# MULTI-OBJECTIVE OPTIMIZATION OF HIGH PERFORMANCE RESIDENTIAL BUILDINGS USING A GENETIC ALGORITHM

Prepared By: **Kelvin Y.H. Liu**

Supervised By: **Dr. Fitsum Tariku**

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# Abstract


**Multi-Objective Optimization of High Performance Residential Buildings Using a Genetic Algorithm**

Kelvin Liu, EIT

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Traditional methods of design and construction of residential buildings are common practice, and in most cases, are required by building codes. However, these design practices do not necessarily yield the most optimized designs in terms of cost, environmental impact, and occupant thermal comfort. Typically, the owner or investor hires an architect that designs the building based on the client's requirements, and then technical designs, such as enclosure and HVAC systems, are tasked to construction and mechanical engineers to satisfy the original design without consideration to energy consumption and environmental impacts. Those who are energy and environmentally conscious rely on an iterative trial and error method using energy simulation tools, and this method consumes much time and resources. To address this problem, this research presents the development and implementation of a simulation-based optimization tool that relies on a genetic algorithm to systematically improve the building design at a conceptual stage based on a set of objective functions. For the purpose of this research, the objective functions include the life-cycle costs, life-cycle global warming potential, and occupant thermal comfort. More specifically, occupant thermal comfort (measured in PPD) acts that the constraint objective.

In this study, a multi-objective optimization genetic algorithm was implemented to find optimal residential building enclosure assemblies that minimizes the life-cycle costs, life-

cycle global warming potential, and keeps occupant thermal comfort within check. Based on the design variables and objective functions, a software tool consisting of four modules is used for optimization: the input and input parameter database files; the genetic algorithm optimization software (jEPlus+EA); the energy simulation program (EnergyPlus) and the optimized output files. All required software and simulation programs can be acquired free of charge from the internet, with the exception of proprietary database files such as material and construction assembly libraries.

For validation, the optimization tool is implemented on a benchmark study, which demonstrates its application and capabilities. The benchmark study is based on ANSI/ASHRAE Standard 140-2001 BESTEST calibration and validation test case 600. The optimization results in multiple Pareto optimal solutions that gives the user a detailed look at the trade-off between the objective functions when high performance building systems are used. The optimization tool is then applied to a case study where an actual single family home (Harmony House) is modeled and important building design parameters are identified and discussed.

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# Table of Contents

## List of Figures

## List of Tables

## Nomenclature

BCIT – British Columbia Institute of Technology

CP – Crossover Probability

EIFS – Exterior Insulation Finishing System

EPD – Environmental Product Declarations

FCB – Fiber Cement Board

FEMP – Federal Energy Management Program

GDP – Gross Domestic Product

GEN - Generation

GHG – Green House Gas

GWP – Global Warming Potential

ICF – Insulated Concrete Forms

ILAS – Ideal Loads Air System

LCA – Life Cycle Assessment

LCC – Life Cycle Cost

LCCA – Life Cycle Cost Analysis

LCEA – Life Cycle Environmental Assessment

LCEI – Life Cycle Environmental Impact

LCGWP – Life Cycle Global Warming Potential

MP – Mutation Probability

NIST – National Institute of Standards and Technology

OSB – Oriented Strand Board

POP – Population

PPD – Percentage of People Dissatisfied

SIP – Structural Insulated Panel

# Chapter 1 Introduction

## 1.1 Research Background

Barriers are required for the protection of human beings from the potentially harsh conditions of the environment. The barrier refers to buildings or facilities that protect people from environmental elements such as sunlight, wind, rain, or snow. On a fundamental level, buildings provide shelter and are a basic necessity, but its impact on the environment, economy, society, and health is often not systematically quantified. As of 2009, the residential and commercial sector combined accounts for 28% of the total Canadian energy demand with a predicted increase rate of 0.6% and 1.0% per year for residential and commercial sectors respectively (National Energy Board 2011). The combined building sector, which includes but is not limited to single/multi-family homes, offices, warehouses, hospitals, and government institutions, consumes large amounts of energy and in turn increases our dependence on natural resources such as fossil fuel, coal, or hydro (National Energy Board 2011).

In addition to the increasing rate of natural resource depletion, there is implicit and explicit energy usage from the manufacturing of building products and the construction of buildings, which in turn releases greenhouse gasses (GHG) and various toxic chemicals back to the environment that people are being sheltered from. As of 2010, the residential building sector contributes 11.4% or 79 megatons of equivalent carbon dioxide ($CO_2$-eq) to total Canadian GHG emissions (Environment Canada 2012). The large energy consumption of the buildings and the building sector itself in Canada not only affects the environment, but it can potentially impact the national economy and society as well.

The construction industry is an important part of the Canadian economy; it creates jobs for engineers, architects, construction workers, and investors. In fact, the construction industry accounts for approximately 7.1% of the national gross domestic product (GDP) compared to the 1.6% contributed by the agriculture, forestry, fishing, and hunting industry combined (Statistics Canada 2013b). The statistics alone cannot fully describe the importance of buildings and the construction industry to the national economy and society. By designing better buildings and facilities with higher energy efficiency that decrease energy consumption, natural and monetary resources can be saved and diverted to other economic sectors that may improve the national economy. Furthermore, a country with a strong economy usually prospers socially as well.

Buildings and facilities not only provide basic shelter, but it is where the majority of individuals do their work, spend time with family and friends, and accomplish various daily activities. The U.S. EPA estimates that typical Americans spend close to 90% of their time indoors where concentrations of certain pollutants are 2 to 5 times higher than normal outdoor environments (U.S. Environmental Protection Agency 2008). Since so much time is spent indoors, and the same can be said for Canadians, it only makes sense that buildings are designed with occupant comfort and health in mind.

Although technology is advancing and efficiencies of construction and building related products are improving, the data shows that there is still room for improvement and the building sector is still responsible for a large proportion of energy consumption and GHG emissions. To solve this problem, engineers, architects, and investors alike must collaborate with greater efficiency and take advantage of advanced design strategies with the help of computer simulations and analysis.

In response to the problems created by the building sector, engineers, architects, and other industry-related professionals have begun to incorporate the concept of Green Buildings into the design process. According to the U.S. EPA, "green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction [while expanding and complementing] the classical building design concerns of economy, utility, durability, and comfort" (U.S. Environmental Protection Agency 2012). The main goal for green buildings is to analyze the life-cycle processes and impacts associated with the building and to find a way to reduce them.

The environmental and social benefits of green buildings are widely acknowledged, but there is concern over the implications of increased up-front costs associated with a premium green building design. Nonetheless, when considering the life-cycle of a building, there can be both environmental and economic benefits from green buildings (Kats et al. 2003). Building developers and owners often shy away from green building designs because of a wrong perception about the method's high initial costs with no immediate benefits; therefore, it is important to consider economic feasibility and environmental performance through a life-cycle perspective (Wang 2005). Moreover, occupant comfort should be considered as a measure of a building's performance because the purpose of buildings and facilities is to serve the needs of its occupants. Life-cycle cost, life-cycle global warming potential, and occupant thermal comfort should all be considered as design objectives when using green building strategies, but the question is how to implement the objectives into the design process without disrupting the workflow of building design and construction.

## 1.2 Thesis Report Organization

The organization of this thesis report will be described as follows:

**Chapter 2** This chapter provides the literature review of previous studies conducted on building assessment methods and multi-objective building optimization. The papers reviewed include surveys on past literature, framework developments, and model validations and applications. The advantages and limitations for each literature is examined and identified to justify this research thesis. A problem statement will also be provided in this chapter in addition to a brief description of research objectives and the research methodology. This chapter will also provide a brief introduction and explanation in terms of the problem statement, research objectives, methodology, and scope of work.

**Chapter 3** This chapter reviews the findings from the literature review chapters and attempts to identify the gaps and limitations of previous research and studies.

**Chapter 4** Based on the gaps and limitations of previous research and studies, this chapter will define the research objectives. The research objectives are what will drive the structure and direction of the methodology, which is also presented in this chapter. Once the methodology is discussed, the scope of work will be defined as well. The scope of work deals with the extent of problems through which this research will attempt to address.

**Chapter 5** The main purpose of this chapter is to provide the basis and assumptions made for the selection of the objective functions. This chapter also goes in-depth with regards to the concepts and formulas used to determine each objective function for use in an optimization environment.

**Chapter 6** The goal of this chapter is to provide detailed information about the optimization parameters that are selected. There will be some basic assumptions and explanations for why each optimization parameter is incorporated into the research. More specifically, the optimization parameters can be anything from a wall assembly to a window glazing type. For each of the parameters, detailed list of variables selected for optimization will be provided.

**Chapter 7** This chapter will further discuss the simulation environment in which the optimization of several case studies can occur. This chapter will first provide a brief overview of what the environment will look like, and then the simulation and optimization software will be introduced. Furthermore, this chapter will go into detail about the input and output files and programs that is required for successful optimization of the pre-selected case studies. The optimization modules, which represents the core of the simulation environment, will be explained thoroughly, followed by additional details with regard to the energy model and optimization pre-configurations.

**Chapter 8** This chapter intends to validate the simulation environment developed in the previous chapter by using a simplified simulation model based on the BESTEST Case 600 model validation requirements. A baseline case is simulated for comparison purposes in order to validate the accuracy of the solutions generated by the optimization framework.

Chapter 8 also deals with a case study based on a commissioned and fully-operating single-family residential building (Harmony House) is conducted in order to test the application of the optimization framework on a real life model. The building is optimized based on life-cycle cost, life-cycle global warming potential, and life-cycle energy consumption. The results are presented and analyzed to identify any issues with the model and any trends in the solutions.

**Chapter 9** This chapter will summarize the findings of the research and provide a conclusion based on these findings. Suggestions for future work are provided based on the limitations of the research thesis.

# Chapter 2 Literature Review

Life cycle building assessment is an important part of building optimization and design, so there are numerous studies conducted on the assessment of sustainable buildings, and this chapter will review the studies. Assessment methods will be divided into Life Cycle Cost Analysis (LCCA) and Life Cycle Environmental Assessment (LCEA), and then the following section will review studies that attempt to integrate the two assessment methods.

Based on the assessment methods reviewed above, studies conducted on general building optimization methods will be reviewed. There are various building optimization methods available, so each method will be analyzed to identify its advantages, drawbacks, and limitations. Lastly, studies based on multi-objective optimization methods using genetic algorithms are reviewed and its limitations are identified in order to justify the purpose of this research.

## 2.1 Literature Review on Building Performance Assessment

In order to address the issues of global warming and other environmental issues, there is a growing demand to accurately and consistently measure the performance of a building. Life Cycle Assessment (LCA) is created to fulfill the task of generating consistent and measurable results for a building. LCA is a method for assessing the cost and environmental impacts of any building system, and that includes the construction of commercial and residential buildings throughout a pre-defined range of life-cycle phases. LCA evaluates all stages in a product life cycle, from raw material extraction, material transportation, manufacturing, and disposal (Curran 2006). LCA can be divided into the life-cycle cost analysis (LCCA) of a building from construction to operation to demolition, and the life cycle environmental assessment (LCEA) of a building through all its life cycle stages (i.e. crade-to-grave).

### 2.1.1 Building Life Cycle Cost Analysis

LCCA is an economic model or cost representation of a building where all costs associated with material procuring, constructing, owning, operating, maintaining, and disposing are considered. LCCA is useful in determining the trade-off between different design alternatives that affect building performance, safety, occupant comfort, and aesthetics. The LCCA method can also be used to figure out where to allocate investments if certain objectives are to be fulfilled based on the building owner or developer. There are many LCCA measures such as Net Savings (NS), Savings-to-Investment Ratio (SIR), and Adjusted Internal Rate of Return (AIRR), that can help developers and designers make an informed decision (Fuller & Petersen 1996). For the purpose of this study, the focus is on the life-cycle cost (LCC), which basically involves the summation of total life cycle costs associated with owning, operating, maintaining, and ultimately disposing of a building system and is shown in Eq. 2- 1 (Fuller & Petersen 1996).

LCC* = initial investment cost + maintenance and repair cost + energy consumption cost + replacement cost – salvage value　　Eq. 2- 1

The common perception of sustainable design and high performance buildings is that it costs significantly more than traditional methods of building development. There are several obstacles to sustainable and high performance buildings which include: incomplete integration within and between projects, lack of life cycle cost analysis, and insufficient technical information related to the cost of sustainable building design.

Some developers are hesitant in sharing cost information and many available cost data do not show the difference between green and traditional building components (Kats et al. 2003). However, careful research and analysis shows that incorporating performance and sustainability into a building can produce significant savings if the LCC and not initial investment cost is considered. For instance, when the Pennsylvania Department of Environmental Protection's Cambria Office Building is designed, developers looking for a return on investment initially balked at the $15,000 increase in costs associated with installing triple glazed windows; however, further analysis shows that the HVAC system sizes can be significantly reduced to save a total of $30,000 (Deru & Torcellini 2005).

There are a large number of case studies on the LCC of buildings throughout the world. For example, a hotel building located in Paris, France, has been analyzed using the LCCA method where several heating and cooling mechanical systems are compared. The research concluded that energy and maintenance cost associated with this type of building accounts for approximately 30-50% of the total LCC (Kosonen et al. 2010). Another case study focuses on the LCC and benefit analysis of vegetated roof systems. After conducting a case study on the Tanyard Branch, the results indicate that there are slight to significant cost benefits of using a vegetated roof system both in the private and public sector (Carter & Keeler 2008). Most studies done on the LCC of high performance or green buildings compared with traditional building designs show that there are social and economic benefits and monetary profits to be made by taking advantage of a sustainable design. However, a common barrier to a wide adaptation of LCC is the difficulty in acquiring accurate and reliable data in order to conduct a LCCA. Regional databases are rarely available or usable and collecting data manually is resource and time consuming (Levander et al. 2009). By applying LCCA to a more advanced application, Schoch & Prakasvudhisarn (2010) used the LCC approach to optimize building geometry and volume. The results from the research indicate that LCC is a quick and efficient method for optimizing building volume and geometry, given that a justified life cycle period is chosen. In other words, different LCC analysis periods can result in different optimal solutions, so the decision maker must take this time dependent parameter into account.

In terms of software tools, there are several available from the National Institute of Standards and Technology (NIST), the most popular being Building Life Cycle Cost 5 (BLCC5), which is a life cycle cost analysis calculator based on the Federal Energy Management Program (FEMP) analysis method along with various other methods such as OMB and MILCON analysis (Fuller 2005).

### 2.1.2 Building Life Cycle Environmental Assessment

LCEA is a comprehensive methodology that can be used to quantify the environmental impacts of a product created during the material extraction, production, operation, and disposal phase of a product life cycle (Blom et al. 2010). This methodology is a systematic and phased approach that consists of four major sub-components: goal definition and scoping, inventory analysis, impact assessment, and interpretation. LCEA is useful when comparing alternatives by considering environmental impacts throughout the entire life cycle of a product, so the decision-maker can design a building by incorporating products or processes with the least total environmental impact (Curran 2006). Table 1 shows the major components of the LCEA methodology with a brief description of each category and Table 2 shows a list of commonly used life cycle environmental impact assessment measures.

| **LCEA Component** | **Description** |
|---|---|
| **Goal Definition and Scoping** | Definition and description of the product, process, or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment. |
| **Inventory Analysis** | Identification and quantification of energy, water, and materials used and its associated environmental discharge or releases (i.e., air emissions, solid waste disposal, waste water discharge). |
| **Impact Assessment** | Assessment of the potential human and ecological effects of energy, water, and material usage, and the environmental releases identified in the inventory analysis. |
| **Results Interpretation** | Evaluation of the results from the inventory analysis and impact assessment to determine the best option of product, process, or service. The decision-maker must have a clear understanding of the uncertainty and assumptions used to generate the results. |

Table 1: List of major LCEA components with brief descriptions (Curran 2006).

Table 2: List of commonly used life cycle impact categories (Curran 2006).

| **Impact Category** | **Scale** | **Examples of LCI Data** | **Common Characterization Factor** | **Description of Characterization factor** |
|---|---|---|---|---|
| **Global Warming** | Global | Carbon Dioxide ($CO_2$)<br>Nitrogen Dioxide ($NO_2$)<br>Methane ($CH_4$)<br>Chlorofluorocarbons (CFCs)<br>Hydro chlorofluorocarbons (HCFCs)<br>Methyl Bromide | Global Warming Potential (GWP) | Converts LCI data to carbon dioxide ($CO_2$) equivalents (GWP can be 50, 100, or 500 year potentials) |

| | | | | |
|---|---|---|---|---|
| | | ($CH_3Br$) | | |
| **Stratospheric Ozone Depletion** | Global | Chlorofluorocarbons (CFCs)<br>Hydro chlorofluorocarbons (HCFCs)<br>Halons<br>Methyl Bromide ($CH_3Br$) | Ozone Depleting Potential | Converts LCI data to trichlorofluoromethane (CFC-11) equivalents |
| **Acidification** | Regional<br>Local | Sulfur Oxides (SOx)<br>Nitrogen Oxides (NOx)<br>Hydrochloric Acid (HCL)<br>Hydrofluoric Acid (HF)<br>Ammonia ($NH_4$) | Acidification Potential | Converts LCI data to hydrogen (H+) ion equivalents |
| **Eutrophication** | Local | Phosphate ($PO_4$)<br>Nitrogen Oxide (NO)<br>Nitrogen Dioxide ($NO_2$)<br>Nitrates<br>Ammonia ($NH_4$) | Eutrophication Potential | Converts LCI data to Phosphate ($PO_4$) equivalents |
| **Photochemical Smog** | Local | Non-methane Hydrocarbon (NMHC) | Photochemical Oxidant Create Potential | Converts LCI data to ethane ($C_2H_6$) equivalents |
| **Terrestrial Toxicity** | Local | Toxic chemicals with a reported lethal concentration to rodents | $LC_{50}$ | Converts $LC_{50}$ data to equivalents; uses multi-media modeling, exposure pathways |
| **Aquatic Toxicity** | Local | Toxic chemicals with a reported lethal concentration to fish | $LC_{50}$ | Converts $LC_{50}$ data to equivalents; uses multi-media modeling, exposure pathways |
| **Human Health** | Global<br>Regional<br>Local | Total release to air, water, and soil | $LC_{50}$ | Converts $LC_{50}$ data to equivalents; uses multi-media modeling, exposure pathways |
| **Resource Depletion** | Global<br>Regional<br>Local | Quantity of minerals used<br>Quantity of fossil fuels used | Resource Depletion Potential | Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve |
| **Land Use** | Global<br>Regional<br>Local | Quantity disposed of in a landfill or other land modifications | Land Availability | Converts mass of solid waste into volume using an estimated density |

| | | | | |
|---|---|---|---|---|
| **Water Use** | Regional Local | Water used or consumed | Water Shortage Potential | Converts LCI data to a ratio of quantity of water used versus quantity of resource left in reserve |

LCEA is widely accepted as a means of measurement of the environmental impacts of a particular product (Haapio & Viitaniemi 2011). There are many examples of LCEA approach being incorporated into the design and assessment of buildings and its subsystems. For instance, a LCEA is conducted on various commonly used building materials, and an obvious conclusion is that materials such as steel, cement, and other mineral materials contribute large amounts of environmental degrading toxins into the environment in addition to consuming significant amounts of energy during the material extraction and production phase. Moreover, in order to facilitate a wide use of LCEA, the process of inventory analysis can be simplified if material manufacturers provide Environmental Product Declarations (EPDs) (Zabalza Bribián et al. 2011). The lack of EPDs results in a bottleneck in the industry. Another study focuses on the environmental impacts of the use and maintenance of heating and ventilation systems in a Dutch environment. The experimental results show that heat pumps, even though they are considered as high performance sustainable products, are not actually more environmental friendly than gas-fired boilers because heat pumps often require supplemental heating in the case that the heating coils do not provide sufficient heat into a building. Also, the most effective way to reduce energy consumption is to decrease the overall heat demand of a building rather than using more mechanicals systems which greatly influences the environmental impact of the building (Blom et al. 2010).

Haapio & Viitaniemi (2011) conducted a comprehensive survey and analysis of the more popular types of environmental assessment tools currently available and came to the conclusion that there needs to be more user-based surveys conducted on the use of LCEA tools. Furthermore, building LCEA tools often take the assumed service life of buildings for granted without further analysis and this may significantly affect the results. A list of commonly used LCA tools is shown in Table 3.

Table 3: List of commonly used LCEA tools including information about their respective developers and database sources (Haapio & Viitaniemi 2011).

| Name of Tool | Developer | Database Source |
|---|---|---|
| **ATHENA™ Environmental Impact Estimator** | ATHENA Sustainable Material Institute; Canada | ATHENA Institute |
| **BEAT 2002** | Danish Building Research Institute (SBI), Denmark | Danish Building and Urban Research (DBUR) |
| **BeCost** | VTT, Finland | Environmental profiles of building materials produced in Finland |
| **BEES 4.0** | U.S NIST, USA | Generic data and brand specific |
| **BREEAM** | Building Research Establishment (BRE), UK | Green Guide |
| **EcoEffect** | Royal Institute of Technology, Sweden | Database for energy and materials |
| **EcoProfile** | Norwegian Building Research Institute (NBI), Norway | No Database |
| **Eco-Quantum** | IVAM, Netherlands | Compilation of publicly available generic data sources such as BUWAL, APME, and ETH and data from LCA's conducted by IVAM |
| **Envest 2** | Building Research Establishment (BRE), UK | UK based data on service life, exposure factor, energy and water consumption benchmarks, LCA data for materials and Ecopoints |
| **Environmental Status Model** | Association of the Environmental Status of Buildings, Sweden | No Database named |
| **EQUER** | Ecole des Mines de Paris, Centre d'Energetique et Procedes, France | Product databases of Swiss and German origin, Okoinventare |

| | | |
|---|---|---|
| **GaBi** | Pe-International, Germany | Priopprietary |
| **LEED** | U.S. Green Building Council, USA | No Database (LEED rating system and reference guide) |
| **LEGEP** | University of Karlsruhe, Germany | SIRADOS, ECOINVENT, GEMIS, Baustoff Okoinventare, and LEGEP database |
| **PAPOOSE** | TRIBU, France | No Database |
| **SimaPro** | Pre Consultants, Europe | Proprietary |
| **TEAM™** | Ecobilan, France | DEAM Starter Kit |

Out of all of the commonly used life-cycle environmental impact categories mentioned in Table 2, global warming potential (GWP) is the most useful measure because it allows users to compare environmental impact of different building components or designs at a global scale rather than restricting the results to a local one. Also, using GWP for LCEA analysis allows users to convert different measures of environmental impact such as acidification or ozone depletion into a single consistent measure in terms of kilograms of carbon-dioxide equivalent. That is why GWP will be studied in further detail. Eq. 2- 2 shows the definition of GWP by a formula according to Forster et al. (2007). Based on this equation, gasses such as methane ($CH_4$) has a GWP of 25 kg$CO_2$-eq and nitrous oxide ($N_2O$) has a GWP of 298 kg$CO_2$-eq, meaning $CH_4$ has 25 times and $N_2O$ has 298 times the radiative forcing abilities compared to $CO_2$ respectively. Naturally, carbon dioxide ($CO_2$) has a factor of 1 since it is compared to itself (Forster et al. 2007).

$$GWP_i = \frac{\int_0^{TH} RF_i(t)dt}{\int_0^{TH} RF_r(t)dt} = \frac{\int_0^{TH} a_i[C_i(t)]dt}{\int_0^{TH} a_r[C_i(t)]dt} \qquad \text{Eq. 2- 2}$$

Where,

TH: Time horizon for which the impacts are considered.

RF: Global mean radiative forcing effects.

$a_{i/r}$: RF per unit mass increase in atmospheric abundance of component $i$ compared to $r$ (radiative efficiency).

$[C_{i/r}(t)]$: Time-dependent abundance of $i$, and the corresponding quantities for the reference gas $r$ in the denominator.

$i$: Greenhouse gas to be measured in comparison to reference gas.

$r$: Reference gas (all GWPs use $CO_2$ as the reference gas).

### 2.1.3 Integrated LCCA and LCEA Environment

The previous sections introduced and examined LCCA and LCEA as separate methods with differing purposes, applications, and goals. However, the decision makers using LCEA, and more specifically life-cycle global warming potential (LCGWP), must also eventually consider economic consequences through the use of LCCA, and to be more specific, life-cycle cost (LCC). In reality, LCCA is not commonly addressed and used in conjunction with LCEA, even the LCEA methodology standard set by ISO 14040 does not consider economic analysis (Norris 2001). As a result, there are three main consequences if life cycle economic analysis is not considered in conjunction with life cycle environmental assessment. First, practicality is reduced if only LCEA is considered without regards to LCCA. There are limited resources, so building projects are often constrained by a monetary budget that renders achieving the best design through LCEA impractical from the project owner/investors' perspective. Second, assessments based on a non-integrated approach prevent decision makers from understanding important trade-off relationships between cost and environmental impacts. Lastly, using an integrated assessment approach can assist designers and decision makers in discovering hidden cost or revenues that might otherwise be overlooked if only an LCCA is used (Norris 2001). Table 4 shows the similarities and differences between the life cycle economic analysis LCCA and the life cycle environmental analysis LCEA.

Table 4: A comparison between LCCA and LCEA (Norris 2001).

| **Tool/Method** | **LCEA** | **LCCA** |
| --- | --- | --- |
| **Purpose** | Compare relative environmental performance of alternative product systems for meeting the same end-use function, from a broad, societal perspective | Determine cost-effectiveness of alternative investments and business decisions, from the perspective of an economic decision make such as a manufacturing firm or a consumer |
| **Activities which are considered part of the 'Life Cycle'** | All processes causally connected to the physical life cycle of the product; including the entire pre-usage supply chain; use and the processes supplying use; end-of-life and the processes supplying end-of-life steps | Activities causing direct costs or benefits to the decision maker during the economic life of the investment, as a results of the investment |
| **Flows considered** | Pollutants, resources, and inter-process flows of materials and energy | Cost and benefit monetary flows directly impacting decision maker |
| **Units for tracking flows** | Primarily mass and energy; occasionally volume, other physical units | Monetary units (e.g. dollars, euros, etc.) |
| **Time treatment and scope** | The timing of processes and their release or consumption flows is traditionally ignored; impact assessment may address a fixed time window of impacts (e.g. 100 year time horizon for assessing global warming potentials) but future impacts are generally not discounted | Timing is critical. Present valuing (discounting) of costs and benefits. Specific time horizon scope is adopted, and any costs or benefits occurring outside that scope are ignored. |

There are many attempts to combine LCCA and LCEA, and several studies have been conducted to examine the practicality and effectiveness of integrated approach. An early attempt to integrate LCA and LCC is introduced by (Norris 2001), which introduces “PTLaser” and “TCAce.” PTLaser. Both of these methods developed by Norris (2001) have been used by multinational corporations, universities, and the US EPA, but is no longer available. TCAce is a joint development by ten multinational companies and the American Institute of Chemical Engineers’ Center for Waste Reduction Technologies and is a comprehensive manual for decision making (Little 2000). In addition, Schau et al. (2011) conducted an integrated LCA and LCC assessment on the remanufacturing of alternators on a global scale. Although the subject of examination is not a building, the same principles apply, and the research concludes that energy consuming systems must be designed for higher efficiency, reduced transportation of materials, and keeping the product in a closed loop. Another research done by Liu (2009) focuses on the integration of LCA and LCC for application in the sustainable building industry. The study indicates that further development of integrated environmental and economic assessment tools is necessary to raise decision maker’s trust in the results given that the data used in the analysis is both reliable and accessible. Additional issues preventing widespread adoption of an integrate LCA and LCC approach include: data insufficiency, contractual policy disagreement, labor intensive analysis, and lack of standardization (Liu 2009). Furthermore, a review on the integrated sustainable life cycle design method by Ramani et al. (2010) also concludes that this approach requires further collaborative research by educational, government, private and commercial institutes. A comprehensive assessment standard that incorporates life cycle management and interoperability between different life cycle assessment models is essential for practical implementation in the construction industry (Ramani et al. 2010).

The general conclusion is that the integrated LCCA and LCEA approach is necessary in the design industry, including buildings, for decision makers to fully understand the economic, environmental, and social impacts of their design. This integrated approach has benefits such as discovering hidden revenues, reducing environmental impacts and costs in addition to health and social well-being. Unfortunately, additional research is required and more policies and standards need to be addressed. Also, a more accessible, comprehensive, and standardized technical database of economic, environment, and social information are necessary to promote the use of the integrated assessment approach in the building design industry.

## 2.2 Literature Review on Optimization Methods

LCCA and LCEA are crucial tools for designers and decision makers, and numerous studies have been conducted on these methods, but these tools only provide a comparative measure for designers and decision makers to consider during the design phase of a building. The assessment tools reviewed in the previous sections do not have the ability to improve a building design or to suggest potentially optimal solutions. Therefore, a method of analyzing building assessment results and applying it to the design process by means of optimization is required.

To address the gap between results obtained from building assessment tools and the design process, several optimization methods have been introduced and validated.

Furthermore, multiple assessment tools with different and often conflicting objectives are a challenge for designers and decision makers to decide on a final solution. The method of searching for an optimal solution to the design problem is another obstacle because there is no standardized method for objective optimization (Andersson 2000).

The following sections review the various methods of objective oriented optimization that is applicable to building design.

### 2.2.1 Weight Global Criterion Method

The Weighted Global Criterion Method is one of the most common general scalar methods available for multi-objective optimization. In brief, this method combines all objective functions into a single function, which simplifies the problem. However, there are several disadvantages with using this method. Firstly, setting one or more of the individual weights within the single function can produce weak Pareto optimal points in the set of solutions. Weak Pareto optimality occurs when the set of solutions do not represent the true set of solutions considering all variables in the objective function. Secondly, there is often a compromise to be made by the decision maker regarding the utopia point and the final solution. Utopia point refers to the optimal solution or set of solutions that is theoretically most representative of the true solution considering all permutations of design variables. In addition, searching for the utopia point requires substantial calculation power and is very inefficient in terms of time and resource consumption. Fortunately, a quicker and more efficient alternative is to search for an approximate utopia point that some may call as aspiration point, reference point, or target point (Marler & Arora 2004a). Based on Eq. 2- 3, 'U' usually represents the achievement function or the target result. If the weights are considered fixed, another problem may occur where the local utopia point is not within feasible solution space; thus, one must minimize the weighted criterion function (Wierzbicki 1982). Furthermore, increasing the exponential variable $p$ can increase the effectiveness in finding the complete Pareto optimal solution. In summation, the Weighted Global Criterion method involves transformations of the original objective functions into a single objective function for simplification. Also, one may think of this method as a means to minimize the distance between the solution point and the utopia point within the local or global criterion space (Marler & Arora 2004a).

$$U = \sum_{i=1}^{k} w_i [F_i(x)]^p$$ Eq. 2- 3

Where,

U: Pareto optimality

*p*: Exponential variable used to increase effectiveness in finding Pareto optimality

w: vector of weights typically set by the decision maker;

F:  objective functions with variable x

*i*: Initial and subsequent number of objective functions

$k$ : Maximum number of objective functions

### 2.2.2 Weighted Sum Method

Similar to the Weighted Global Criterion Method, the Weighted Sum Method is the most common approach to multi-objective optimization. With the exception of the exponential term $p$=1 (refer to Eq. 2- 3), it has the same form as the Weight Global Criterion Method. Eq. 2- 4 shows the modified equation, which essentially eliminates the exponential factor. One advantage of using this method is the guaranteed Pareto optimality if all weights within the function are positive. In other words, the minimum of U is the Pareto optimal point when there are no variables that produce negative results (Marler & Arora 2004a). In addition, this method is simple to use, but the objective functions with different magnitudes might have to be normalized beforehand (Andersson 2000). There are many variations of the Weighted Sum Method, all of which follow the same concept but with slightly altered methodologies. For instance, by grouping original objective functions into sets with common characteristics, the number of original objective functions is reduced. Each set is used to form an independent weighted sum function with specialized weights; also called the Partial Weighting Method developed by Koski & Silvennnoinen (1987). Other examples include: a mathematical relation between decision maker's preference function and weights (Steuer 1986), a ranking method where different objective functions are ordered by importance (Hwang & Yoon 1995), a method based on fuzzy set theory to determine weights (Rao & Roy 1989), an algorithm that determines weights based on aspiration and utopia points, and last but not least an matrix method that uses the eigenvalue of a function matrix to yield pairwise comparisons between different objective functions (Saaty 1990).

$$U = \sum_{i=1}^{k} w_i F_i(x) \qquad \text{Eq. 2- 4}$$

The numerous sub-methods of the Weighted Sum Method are advantageous for the user; however, despite the many methods for determining weights, this type of priori selection of weights does not guarantee an optimal solution. For instance, the weighted sum can only represent the decision maker's preference function accurately if the weights are functions of the original objectives and not constants (Marler & Arora 2004a). Also, it is virtually impossible to produce points on non-convex portions of the Pareto optimal set in the criterion space (Andersson 2000). Most importantly, even if the weights are calibrated consistently and continuously, it may not result in an even distribution of Pareto optimal points. Without a consistent method relating weights and subsequent Pareto points, the results may never accurately represent the complete Pareto optimal set (Marler & Arora 2009). In spite of these disadvantages, the Weighted Sum Method is an ad-hoc method with no clear relation between the weights and the set of solutions.

### 2.2.3 Lexicographic Method

The Lexicographic Method is a method where objective functions are arranged in order of importance, and is similar to the works of (Hwang & Yoon 1995). This method relies heavily on the preference and judgment of the decision maker so a major drawback is the inability to optimize all objectives. The objectives are ranked by the decision maker, so if the solutions have no comparable values, lower level objectives will not be optimized. Eq. 2- 5 simply shows that each objective function should be minimized based on the users judgment on the weight factor applied to each objective function. Moreover, the

Lexicographic method is not commonly used on its own, but is rather combined with other methods such as Goal Programming (Andersson 2000).

$$\min_{x \in X} F_i(x) \qquad \text{Eq. 2- 5}$$

Subject to $F_j(x) \leq F_j(x_j^*)$

Where,

$j = 1,2, \dots, i-1, i > 1$

$i = 1,2, \dots, k$

### 2.2.4 Weighted Min Max Method

This method, also called the Weighted Tchebycheff Method, is also widely accepted by many industries that require a systematic decision making tool. The Weighted Min-Max Method reaches the limits of the extensions of the Weighted Global Criterion Method where the variable $p$ reaches infinite (Marler & Arora 2004a). Furthermore, this method guarantees a necessary condition for Pareto optimality and can accurately provide a complete Pareto optimal set of solutions (Eskelinen et al. 2008). However, there is still a chance that a weak Pareto optimal solution set is generated; therefore, the Augmented Weighted Tchebycheff Method is created by Kaliszewski (1987) and Ralph E Steuer & Na (2003). This augmented method is shown in Eq. 2- 6.

$$U = \max_i \{w_i [F_i(x) - F_i^\circ]\} \qquad \text{Eq. 2- 6}$$

### 2.2.5 Exponential Weighted Criterion

As previously explained regarding the Weighted Sum Method's inability to produce Pareto optimal points on a consistent basis due to non-convex portions of the Pareto optimal criterion space, Athan & Papalambros (1996) propose the use of the Exponential Weighted Criterion method to address these problems. Eq. 2- 7 shows that objective functions and variable $p$ are raised to an exponent.

$$U = \sum_{i=1}^{k} (e^{pw_i} - 1)e^{pF_i(x)} \qquad \text{Eq. 2- 7}$$

### 2.2.6 Weighted Product Method

Objective functions often have different orders of magnitude compared to one another, and must be transformed for unification. The transformations have a high probability of augmenting the set of Pareto optimal solutions. In order to resolve this problem, the Weighted Product Method is introduced by Bridgman (1922) and is presented in Eq. 2- 8. Initially, this method is called a Product of Powers Method, and Gerasimov & Repko (1978) has successfully applied this method to the multi-objective optimization of a truss and refers to it as a valid compromise. In the multi-objective truss problem, they managed to minimize the weight, material displacement, and difficulty of construction. Although this problem solves the problems with the Weighted Sum Method, it is not widely used because of potential nonlinearities in the utility function that can cause computational challenges (Marler & Arora 2004a)

$$U = \prod_{i=1}^{k} [F_i(x)]^{w_i} \quad \text{Eq. 2- 8}$$

Where,

$w_i$: Weights indicating the relative significance of the objective functions.

### 2.2.7 Goal Programming Method

Unlike the Weighted Sum Method, the Goal Programming Method relies on goals specified for each objective function and the total deviation from the goals is minimized. More specifically, this method, developed by Charnes, Cooper, & Ferguson (1955) attempts to calculate the difference in results between the objective functions and the predefined goals. The difference is categorized into positive and negative counterparts, which represents underachievement and overachievement. This method, in theory, is similar to compromise programming and can be considered as a form of global criterion method (Romero et al. 1988). Unfortunately, despite the method's widespread use and convenient applicability, it does not guarantee a Pareto optimal solution. The Goal Programming Method consists of additional variables with nonlinear equality constraints, which can become exponentially difficult to solve with larger problems and more objective functions (Marler & Arora 2004a). As with many multi-objective optimization methods, there are often alternative sub-methods that are derived from the main method's core concept. In this case, there are two primary subclasses of goal programming, which comprises of the Archimedean Goal Programming and the Lexicographic Goal Programming method. The Archimedean Goal Programming method assigns weights to the deviations of each objective from its perspective goal, and the Lexicographic Goal Programming method orders the objective into priorities (Charnes & Cooper 1977). Additionally, Zeleny (1982) introduces the Multi-Goal Programming method, which uses a vector optimization program to minimize multiple objective functions independently.

### 2.2.8 Bounded Objective Function Method

Many function optimization methods rely on the concept of minimizing the objective functions defined by the decision maker, and the Bounded Objective Function Method is no exception. This particular method minimizes the most important objective function based on the decision maker's preferences, and all other objective functions are used as constraints to produce a Pareto optimal solution set (Marler & Arora 2004a). Haimes, Lasdon, & Wismer (1971) introduces the e-constraint method where an algorithmic variation of objective function constraints yields a set of Pareto optimal solutions. Another subclass method integrates the Bounded Objective Function Method with the Goal Programming method and is able to produce Pareto optimal solutions with a larger number of objective functions (Dauer & Krueger 1980).

### 2.2.9 Physical Programming Method

The Physical Programming method is developed by Messac (1996), and defines classifications for goals and objective functions by verbally expressing preferences to a utility function. This method attempts to provide a means of assigning preferences to functions without the need to use a relative weighing system like the Weighted Global Criterion Method and the Weighted Sum Method (Marler & Arora 2004a). One major advantage of this method is to ability to effectively optimize objective functions with different orders of magnitude, which is a problem for many other optimization methods (Messac et al. 2004). Physical Programming is considered to be superior to the Weighted Sum Method and the Goal Programming method because it guarantees a complete Pareto optimal solution set, which is important to all optimization schemes (Marler & Arora 2004b).

The Physical Programming method developed by (Messac 1996) is originally designed for priori articulation of preferences; however, physical programming can also be used for posteriori articulation of preferences as well. The advantage of using this method is its ability to accurately represent the complete Pareto optimal set of solutions even if the Pareto surface or front is non-convex (Messac & Mattson, 2002; Martinez *et. al.*, 2001). Non-convex Pareto surfaces often create challenges for more popular methods such as the weighted sum method. In the case of posteriori physical programming, the decision maker specifies constants that delineate the numerical ranges of objective functions and constraint values. More specifically, a unique utility function is formed by associating numerical ranges with different degrees of user preferences relative to each objective metric (Marler & Arora 2004b).

### 2.2.10 Normal Boundary Intersection Method

The normal boundary intersection method is a direct response to the disadvantages of the weighted sum approach, which is developed by Das & Dennis (1996). This method determines an even distribution of Pareto optimal points with respect to consistent variations in the user-supplied parameter vector $w$, especially for non-convex Pareto optimal sets (Marler & Arora 2004b). Another method called the Normal Constraint Method is a directed improvement on the Normal Boundary Intersection method which eliminates non-Pareto optimal solutions altogether. However, this method must be used with normalized objective functions and with a Pareto filter. There are several advantages to the Normal Constraints approach. Firstly, the decision maker's design objective scales do not affect the performance of this method. Secondly, this method provides a set of evenly spaced Pareto optimal points in the criterion space.

### 2.2.11 Genetic Algorithms

Most optimization methods described till this point involve transforming multi-objective functions into a single objective function for simplification. However, the weighting system required for transformation often decreases the accuracy and reliability of Pareto optimal solution points and the efficiency of the method are hindered by complex problems with more than two objective functions. Genetic Algorithms (GA) are heavily influenced by biological evolution and is based on Darwin's theory of natural selection (Marler & Arora 2004b). This method is originally introduced by Holland (1975). Initially, a population is randomly generated to represent a group of potential solution points. This is the first batch of possible contestants, which will be filtered out based on the decision maker's criterion. In mathematical terms, an algorithmic iteration of the population selection represents generations, a design point represents chromosomes, and a design vector is similar to that of genetic code. Details with regards to the step-by-step process of a genetic algorithm is provided in Table 5.

Table 5: The overall genetic algorithm process described in a step-by-step format (Malhotra et al. 2011).

| | |
|---|---|
| Step 1 | (Start) Generate random population of chromosomes, that is, suitable solutions for the problem. |
| Step 2 | (Fitness) Evaluate the fitness of each chromosome in the population. |
| Step 3 | (New Population) Create a new population by repeating following steps until the new population is complete.<br>a) (Selection) Select two parent chromosomes from a population according to their fitness. Better fitness, the bigger chance to be selected to be the parent.<br>b) (Crossover) With a crossover probability, cross over the parents to form new offspring, that is, children. If no crossover was performed, offspring is the exact copy of parents.<br>c) (Mutation) With a mutation probability, mutate new offspring at each locus.<br>d) (Accepting) Place new offspring in the new population. |
| Step 4 | (Replace) Use new generated population for a further run of the algorithm. |
| Step 5 | (Test) If the end condition is satisfied, stop, and return the best solution in current population. |
| Step 6 | (Loop) Return to Step 2 until end of generation has been met. |

Furthermore, the fundamental process of optimization using a genetic algorithm is relatively simple. Random initial populations of parameter chromosomes are generated, the solutions are then repeatedly evaluated and the most optimal solutions are selected for combination with the next generation of parameter chromosomes. This process is repeated until all solutions have been found or until a pre-defined number of generations have been reached (Zhang 2012). Figure 1 is a flow chart that represents the optimization process using a genetic algorithm.

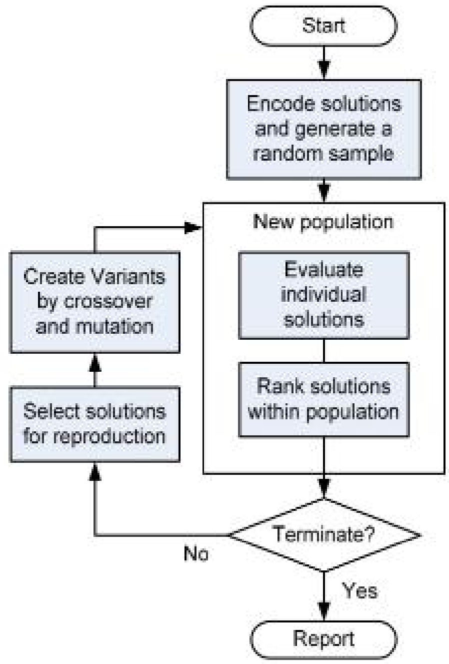



Figure 1: Flow chart representing the design optimization process (Zhang 2012)

For each generation, the selected solutions are better suited for their environment than the solutions that they are created from, and this can be attributed to the crossover and mutation operators (Kalogirou 2007). To clarify, the crossover rate refer to the percentage of the original chromosome genes that is replaced by another chromosome genes, while the mutation rate defines the percentage of the original chromosome genes that is randomly mutated to ensure a broad range of possible design chromosomes. Mutation rate essentially reduces the probability of redundant results after numerous combinations.

One of the major advantages of using Genetic Algorithms is its ability to be tailored to solve multi-objective optimization problems directly. The main challenges of this method is defining appropriate fitness evaluation functions, determining which solutions points shall be passed on to the next iteration, and how to ensure Pareto optimality. Unfortunately, one potential issue with GAs is the lack of embedded Pareto optimality. In other words, the GA approach does not guarantee Pareto optimality in any solution set so Pareto sets are often approximated (Marler & Arora 2004b).

Despite the limitations that prevent GAs from reaching true Pareto optimality, GAs are very robust and can handle all type of solution landscapes, and they also allow a mixture of real and discrete parameter inputs. Moreover, multi-objective GAs can be designed to converge at a Pareto optimal front rather than one optimal solution (Andersson 2000). Another advantage of genetic algorithms is its ability to search from a population of points and thus the probability of searches getting trapped in a local minimum is significantly reduced (Caldas & Norford 2003). Given these advantages, GAs are extremely suitable for applications in multi-objective optimization of building designs.

In most genetic algorithms, a variable is coded using a fixed-length string of bits consisting of 0's and 1's. The number of binary bits required to define a variable depends on the precision and the interval for a continuous variable, and it also depends on the number of alternative values for a discrete variable. The binary code for each variable is concatenated to form a binary string (chromosome), and is then decoded to reveal the solution (Wang 2005). However, the genetic algorithm used in jEPlus+EA is integer encoded rather than binary encoded. The reason integer encoding is used rather than binary encoding is because binary encoding is limited to single-objective optimization and applies to continuous variables only. Marler & Arora (2004b) notes that binary encoding is the most common method, but integer coding is most practical for combinatorial problems. Also, integer encoding has the ability to represent discrete variables, which can reduce the total number of solutions in the design space and reduce simulation time.

## 2.3 Literature Review of Objective Based Building Optimization

The goal of this section is to provide a literature review on a broad spectrum of works regarding objective based building optimization. Each reviewed studies are summarized in the first following subsection and is presented in table format. The majority of reviewed literature is related to multi-objective optimization, but there are several single-objective optimization studies. As a conclusion, the limitations of single and multi-objective building optimization studies will be discussed.

### 2.3.1 General Outline of Previous Related Optimization Studies

This subsection provides a summary that reviews the optimization studies conducted on buildings at a whole-building systems level rather than a component level. There are, however, several studies that focus on a particular component of the building. They are included in the review to study the application of the optimization algorithm. For example, the overhang components of a building are optimized in a study by Manzan & Pinto (2009), and while it focuses on one component of building, the use of a genetic algorithm is emphasized in the study.

Table 6 provides a list of previous work on optimization of building systems, and is presented in alphabetical order based on primary author's name. The first column on the left of the table contains a list of authors and the publication year. The second and third columns lists the major objective functions and variables considered in the study and any additional information that is critical to the study is shown as well. The fourth column categorizes the study based on its application or case studies on either commercial or residential buildings. The fifth and sixth column shows the simulation and optimization software tools used by the studies. The last column categorizes the study based on implemented optimization method and provides optimization parameter details if a genetic algorithm is used by the author(s).

Table 6: List of previous work on objective based building optimization.

| Author(s) | Objective Function(s) | Variables | Building Type | Simulation Program | Optimization Program | Optimization Method |
|---|---|---|---|---|---|---|
| **(Aurélio et al. 2009)** | 1-Environmental Impacts<br>2-Resource Use and Waste<br>3-Occupant Comfort<br>4-Life Cycle Costs | Enclosure type, HVAC system type, HVAC controls | Commercial | TRNSYS<br>OpenLCA | | Genetic Algorithm |
| **(Bichiou & Krarti 2011)** | 1-Life Cycle Cost (demolition, maintenance, and repair costs not included)<br>(30 year study period) | Building orientation, building aspect ratio, building shape, foundation insulation type, wall type, roof type, air infiltration rate, window type and area, shading type, thermal mass type, heating set point, cooling set point, heating efficiency, HVAC system type | Residential | DOE-2 | | Hybrid Genetic Algorithm, Particle Swarm Optimization, and Sequential Search Method |
| **(Caldas & Norford 2003)** | 1-Life Cycle Cost<br>2-Life Cycle Energy Consumption | Building material type, building shape and dimensions, HVAC size, HVAC controls, heating and cooling set points, HVAC flow rates | Commercial<br>Residential | | | Genetic Algorithm |
| **(Diakaki et al. 2010)** | 1-Operating Primary Energy Consumption<br>2-Operating Annual Carbon Dioxide Emissions<br>3-Initial Investment Cost | Door type, window type, roof type, wall type, floor type, insulation type, heating/cooling system type, DHW system type, solar collector type | Residential | | | Compromise Programming |
| **(Ellis et al. 2006)** | 1-Initial Construction Cost<br>2-Energy Consumption | Wall type, roof type, floor type, window type, HVAC system type | Commercial | EnergyPlus | Opt-E-Plus | Sequential Search Method |
| **(Evins et al. 2011)** | 1-Heating Load<br>2-Cooling Load | Double skin façade system, double skin façade controls, ventilation controls, glazing type, heating set points, cooling set points | Commercial | | | |
| **(Fesanghary et al. 2012)** | 1-Life-Cycle Cost<br>2-Life-Cycle Global | Wall type, roof type, floor type, window type | Residential | EnergyPlus | | Harmony Search |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Warming Potential | | | | | |
| **(Fialho et al. 2012)** | 1-Energy Consumption<br>2-Construction Cost<br>(annual study period) | Building orientation, insulation type, insulation thickness | Commercial | EnergyPlus | Hype | Evolutionary Algorithm<br>POP=40<br>GEN=75<br>CP=0.8<br>MP=0.1 |
| **(Flager et al. 2011)** | 1-Life Cycle Cost<br>2-Life Cycle Global Warming Potential<br>(demolition and transportation phase not included)<br>(30 year study period) | Building orientation, glazing percentage, glazing type | Commercial | eQuest | ModelCenter | Genetic Algorithm |
| **(Hamdy et al. 2011)** | 1-Operating Carbon Dioxide Equivalent Emissions<br>2-Initial Investment Cost | Insulation thickness, window type, heat recovery type, shading type, building air-tightness level, heating/cooling system type | Residential | IDA ICE | MATLAB | Genetic Algorithm<br>POP=40<br>GEN=18 |
| **(Hamelin & Zmeureanu 2012)** | 1-Life Cycle Primary Energy Use<br>2-Life Cycle Cost<br>(demolition phase not included)<br>(Combined into single objective)<br>(50 year study period) | Wall insulation thickness, wall insulation type, roof insulation thickness, roof insulation type, floor insulation thickness, floor insulation type, window area, flooring type, basement wall insulation thickness, basement wall insulation type | Residential | TRNSYS | GenOpt 3.0.3 | Particle Swarm Algorithm<br>POP=30<br>GEN=80 |
| **(Hani & Koiv 2012)** | 1-Net Energy Consumption | Window area, glass solar factor, window cardinal directions | Commercial | IDA ICE | GenOpt | Hybrid Generalized Pattern Search, Particle Swarm Optimization, and Hooke Jeeves Algorithm |

| | | | | | | |
|---|---|---|---|---|---|---|
| **(Hasan 2010)** | 1-Life Cycle Cost<br>(demolition phase not included)<br>2-Primary Energy Consumption<br>3-$CO_2$ Emissions<br>4-Indoor Discomfort<br>(20 year study period) | Wall insulation thickness, roof insulation thickness, floor insulation thickness, window thermal transmittance, heat recovery unit efficiency | Residential | | | Hybrid PSO and Hooke and Jeeves Algorithm |
| **(Hopfe & Emmerich 2012)** | 1-Annual Net Energy Consumption<br>2-Indoor Thermal Comfort | Window Area, Room Size, Occupant Internal Gain, Lighting Internal Gain, Equipment Internal Gain, Wall thickness, wall conductivity, roof conductivity, window type, infiltration rate | Commercial | | | Metalmodel-Assisted Robust SMS-EMO Algorithm |
| **(Kusiak et al. 2011)** | 1-Total Energy Consumption<br>2-Indoor Air Quality<br>(Combined into one objective) | HVAC Sizing, HVAC controls | Commercial | | | Strength Pareto Evolutionary Algorithm with Local Search<br>POP=100<br>GEN=150 |
| **(Magnier 2008)** | 1-Total Energy Consumption<br>2-Thermal Comfort<br>3-Visual Comfort | Window area, insulation thickness, cooling capacity, heating set point, cooling set point | Commercial | ESP-r/Radiance<br>TRNSYS | GenOpt/MATLAB | Genetic Algorithm |
| (Manzan & Pinto 2009a) | 1-Primary Energy Consumption | Shading device type (angle, dimensions) | Commercial | ESP-r/Radiance | ModelFRONTIER | Genetic Algorithm |
| **(Milajić et al. 2013)** | 1-Initial Construction and Operating Cost<br>2-Initial Construction and Operating Environmental Impact (cumulative exergy)<br>(20 year study period) | Building orientation, building shape, enclosure structure type, wall type, wall layer type, roof type, roof layer type, floor type, floor layer type, overhang type, overhang depth, window type, window ratio | Commercial | EnergyPlus | | Genetic Algorithm<br>GEN=500<br>POP=50<br>CP=0.85<br>MP=0.008 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **(Nielsen & Svendsen 2002)** | 1-Life Cycle Cost<br>2-Energy Consumption<br>3-Indoor Environmental Quality<br>(30 year study period) | Exterior wall type, interior wall type, deck type, roof type, glazing type, window type and area, ventilation system type. Lighting system type | Commercial<br>Residential | MATLAB | MATLAB | Direct Search Simulated Annealing |
| **(Palonen et al. 2009)** | 1-Differential Life Cycle Cost<br>2-Annual Space Heating | Building enclosure types, HVAC system type | Commercial | | GenOpt | Genetic Algorithm<br>POP=40<br>GEN=100<br>CP=0.8<br>MP=0.03 |
| (Peippo et al. 1999a) | 1-Intial Construction and Operating Costs<br>(annual study period) | Building shape, building orientation, solar collector inclination, wall insulation thickness, window type and area, thermal mass, solar thermal collector type and area, PV system capacity, energy storage volume, lighting type, lighting control type, exhaust air heat recovery type | Commercial | | | Hybrid Cyclic Coordinate, Hooke and Jeeves, Golden Section Algorithm |
| **(Rysanek & Choudhary 2011)** | 1-Initial Construction Cost<br>2-Return-on-investment<br>3-Greenhouse Gas Emissions | Lighting sensors, lighting type, building infiltration rate, heating set point, roof U-value, glazing U-value, HVAC type | Commercial | TRNSYS | MATLAB | Sequential Search Method |
| **(Sahu et al. 2012)** | 1-Net Energy Consumption | Roof type, wall type, glazing type, building orientation, building shape | Commercial<br>Residential | TRNSYS | MATLAB | Admittance Method and Genetic Algorithm<br>POP=20<br>GEN=50<br>CP=0.6<br>MP=0.03 |
| (Schoch & Prakasvudhisarn 2010a) | 1-Life Cycle Cost | Floor area, wall area, window area | Commercial | | ILOG OPL Studio 6.1.1 | Constraint Programming |

| | | | | | | |
|---|---|---|---|---|---|---|
| **(Wang et al. 2005)** | 1-Life Cycle Environmental Impacts (natural resource consumption, global warming potential, acidification, ozone depletion, cumulative exergy)<br>2-Life Cycle Cost<br>(demolition, maintenance, and replacement phase not included)<br>(40 year study period) | Building orientation, aspect ratio, window type, window-to-wall ratio, wall type, wall layer type, roof type, roof layer type | Commercial | Custom based on ASHRAE | Custom | Genetic Algorithm<br>GEN=200<br>POP=40<br>CP=0.9<br>MP=0.02<br>Elite=10 |
| **(Wright & Loosemore 2001)** | 1-Initial construction cost<br>2-Operating cost<br>3-Thermal discomfort | Enclosure construction weight type, glass type, window area, HVAC size, HVAC controls | Commercial<br>Residential | | | Genetic Algorithm<br>POP=200<br>GEN=1000 |
| **(Wright et al. 2013)** | 1-Annual Carbon Emissions<br>2-Overheating Hours | Wall type, insulation thickness, glazing type, infiltration and ventilation rate, building orientation, climate type | Residential | EnergyPlus | jEPlus+EA | Genetic Algorithm |

### 2.3.2 Limitations of Single Objective Optimization Studies

Bichiou & Krarti (2011) has conducted a study on the optimization of a single-family residential building by considering building orientation, building aspect ratios, building shape, enclosure materials, and HVAC system types. Even though this study uses several different types of optimization algorithms such as a genetic algorithm, a sequential search algorithm, and a particle swarm algorithm, the author mentions that the genetic algorithm is the most efficient method in terms of overall optimization time. This research is focused more on comparing different optimization algorithms rather than implementing one to find the most optimal set of solutions for a particular case. This study is also focused on life-cycle costs such as initial material costs and operational costs and does not consider other objective functions such as environmental impact or occupant comfort. Although this study considers standard fiberglass batt insulated walls and exterior insulated walls, it does not consider other forms of high-performance walls such as ICFs or SIPs. Furthermore, this study does not consider the effects of window frame type on the overall optimization of the building.

An IDA Indoor Climate and Energy building simulation model is successfully combined with GenOpt to optimize building facades through the work of Hani & Koiv (2012). This study optimizes a building's facades in terms of orientation and window-to-wall ratio. Despite the obvious limitation of only considering building energy consumption as a single objective function, this study also does not consider the effects of building enclosure material types, assembly types, or mechanical system types. With exceptions to building orientation and window-to-wall ratio, this study does not provide much insight into the actual optimization of detailed design parameters.

One of the unique aspects of the study conducted by Manzan & Pinto (2009) is its focus on the optimization of window shading devices. This study certainly succeeds in its attempt to find the relationship between sun-shading device configurations and total building energy consumption; however, this study neglects many factors that can potentially affect the justification of even implementing a shading device as a building system. For instance, this study lacks the consideration of cost and environmental impacts of using sun-shading devices, both of which are critical objective functions when designing building shading devices. Although this study has taken into consideration different glazing systems in conjunction with shading devices, it only considers the thermal performance of these systems and does not consider cost, environmental impact, or occupant comfort. In addition, shading devices are primarily used in commercial buildings and have minimal applications in a single-family residential building case.

The study by Peippo et al. (1999) focuses on the single-objective optimization of a commercial office building in terms of initial construction and operational costs. This study considers various building design parameters such as building geometry, orientation, PV system capacity, lighting type, window type, etc. However, this study does not consider the effects of varying insulation type and thickness or various tilt angles for the PV panels. This study implements several different optimization methods including a Hybrid Cyclic Coordinate algorithm, a Hooke Jeeves algorithm, and a Golden Section Algorithm. This study does not consider genetic algorithms or other evolutionary type algorithms even though these methods were available at the time of the study. As a result, this study found that the optimization methods used, such as the Hooke Jeeves algorithm, exhibited slow convergence and was largely inefficient in search of global optimal solutions.

The work by Sahu et al. (2012) is similar to the study by Manzan & Pinto (2009) in that they both focus on optimizing building energy efficiency. However, Sahu et al. (2012) focuses more on building orientation, building shape, and building enclosure assemblies such as wall insulation or window glazing type. One of the major limitations of this study is that it does not consider the economic factors of applying the alternative design parameters, which can lead to results that are extremely energy efficient, but may result in extremely high initial investment costs. Another limitation of this study is in the nature of the building enclosure alternative design parameters. The wall and roof assemblies have been pre-assembled prior to inserting it as design parameters in the optimization process. The problem with this approach is that it only considers very limited number of wall and roof assembly types. In other words, the individual layers within each wall and roof type assembly has been pre-combined and thus cannot be fully optimized.

Schoch & Prakasvudhisarn (2010) has provided a comprehensive study on the optimization of building volumes and enclosure areas relative to life-cycle costs. One of the limitations of this research is that it is more applicable to commercial buildings rather than single-family residential buildings since the latter has a tighter constraint in terms of the allowable building dimensions due to a smaller allowable building area. The previous limitation also leads to the second limitation, which is in the lack in the depth of building optimization. Building volume optimization is an upper-level optimization that focuses more on the general architecture rather than actual building components such as insulation type, window glazing type, or mechanical system type, etc. The study by Schoch & Prakasvudhisarn (2010) uses a constraint programming method, which may lead to difficulties in finding truly optimal solutions, since there must be a finite design search space. In other words, using a constraint programming method often leads to locally optimal solutions rather than globally optimal ones.

The study conducted by Hamelin & Zmeureanu (2012) improves upon the works of (Hani & Koiv 2012; Manzan & Pinto 2009a; Sahu et al. 2012) by adding LCC and life cycle energy use objectives. The study also includes a larger variety of building parameter variables, but the two objectives considered in the study are combined into a single-objective using predetermined weight factors. One of the main disadvantages of combining multiple objectives into a single objective is the determination of the pre-assigned weights. This requires that the decision maker understand the relative importance of each objective at an early stage. Furthermore, this study uses GenOpt as the optimization tool which has the same limitations of only optimization based on single-objectives. TRNSYS (Anon 2013) is a flexible simulation tool that has a graphical user interface (GUI) that simulates transient systems, but it is also a commercial software that must be purchase for full functionality. An additional study by Kusiak et al. (2011) substitute LCC with indoor air quality (IAQ) as one of the primary objective functions, but it is limited to variables related to HVAC systems and controls, while building enclosure components are not optimized.

### 2.3.3 Limitations of Multi-Objective Optimization Studies

One of the more comprehensive multi-objective optimization studies has been conducted by Aurélio et al. (2009). This study has attempted to combine environmental impacts, investment costs, occupant thermal comfort, and energy consumption into a single optimization package that uses genetic algorithms. Despite the success in implementing an optimization tool that considers all of the mentioned objective functions, this study is focused mainly on commercial buildings and does not include design parameters suitable for a single-family residential building. For instance, this study focuses more on the thermal performance of commercial-grade insulation and their corresponding costs and environmental impacts, however, these insulation types and enclosure assemblies are not appropriate for use in a single-family residential home. Moreover, this study is limited in its ability to optimize individual layers within enclosure assemblies because it also uses a pre-combined set of exterior enclosure assemblies.

Caldas & Norford (2003) has also used a genetic algorithm to optimize a commercial building based on life-cycle costs and life-cycle energy consumption. This study has attempted to optimize the building shape, dimensions, HVAC size, HVAC controls, HVAC flow rates, and building materials. One of the limitations of this study is that is it focused more on the optimization of HVAC systems and their controls while there is very little in terms of building enclosure design alternatives. For example, the only possible exterior enclosure materials available for optimization are expanded polystyrene, expanded polyurethane, and light/medium weight concrete blocks. This study also does not consider environmental impacts or occupant thermal comfort even though their inclusions have been mentioned in the future works section.

Diakaki et al. (2010) has proposed to use compromise programming to systematically optimize a multi-objective building design. Operating primary energy consumption, operational annual Carbon Dioxide emissions, and initial investment costs are the three main objective-functions for this study. The main limitation with this study is with the use of a compromise programming method. This method requires the three objective functions previously mentioned to be combined into a single criterion. The problem with this approach is that even though the solutions will be the most optimal solutions for any given case, it is difficult for the user to conduct a trade-off analysis based on the three objective functions since they have been augmented into a single objective function prior to the optimization process.

Ellis et al. (2006) introduces the use of a sequential search algorithm to optimize a building exterior enclosure assemblies and HVAC systems based on two objective functions: initial construction cost and energy consumption. A possible limitation with this study is the lack of consideration for environmental impacts and occupant comfort. Another possible limitations, which is mentioned by the authors themselves, is the possibility for deficiencies in the sequential search algorithm under certain scenarios. For instance, competing design options can sometimes result in true optimum solutions not being correctly identified. There is also an issue with having only one degree of freedom allowed by this optimization method.

Fesanghary et al. (2012) uses EnergyPlus and a Harmony Search algorithm to optimize building enclosure related design parameters for a single-family residential building located in the U.S. The study focuses on optimizing the building design parameters based on life-cycle cost and life-cycle global warming potential. The authors use the two objective functions to conduct a trade-off analysis. However, one of the few limitations of this study is the lack of occupant thermal comfort as an objective function. Without considering occupant thermal comfort as an objective function, or at least an objective constraint, it is difficult to determine if the optimized building satisfies minimum occupant thermal comfort requirements as specified by ASHRAE Standards 55. Another limitation of this study by Fesanghary et al. (2012) is that is does not consider all possible wall or roof assembly types applicable to a residential building. In other words, this study only focuses on insulation in the walls and roofs as a single layer, but does not consider the fact that there are many high-performance wall and roof assembly configurations such as advanced framing, EIFS, double-stud, etc. Furthermore, this study only considers one type of window frame material (i.e. aluminum) and does not consider the effects of other window framing types such as wood or fiber-glass.

Fialho et al. (2012) attempts to optimize building orientation, insulation type, and insulation thickness by using an evolutionary algorithm and EnergyPlus. More specifically, the authors have introduced the Hype methodology for systemically optimizing building design parameters. One of the main limitations with this study is the fact that it only considers the energy consumption of a building over the course of one year in addition to initial construction costs. This study does not consider the effects of optimizing a building based on its life-cycle stages; therefore, it is difficult for potential users to see the long term effects of selecting certain design parameters specified by the authors. In addition, this work only takes into accounts objectives related to the reduction of energy consumption in a passive way and does not address energy saving in an active way such as the optimization of mechanical systems.

Flager et al. (2011) uses a genetic algorithm to optimize building orientation, glazing percentage, and glazing type based on life-cycle costs and life-cycle global warming potential. The main software tools used by this study is eQuest and ModelCenter and is primarily targeted towards commercial applications. One of the problems with this method of building optimization is the additional time required to setup the proposed method compared to conventional design processes. This study only considers one validation case based on a single case-study involving a particular building type in a particular climate. It is also important to note that this study considers very few building design parameters and it also does not incorporate occupant thermal comfort as an objective function.

A single-family residential building is optimized using IDA ICE and MATLAB through the implementation of a genetic algorithm. This study, conducted by Hamdy et al. (2011), takes into consideration operating carbon dioxide equivalent emissions and initial investment costs. The authors have attempted to incorporate insulation thickness, window type, heat recovery type, shading type, building air-tightness levels, and heating/cooling system types as the main design parameters. Even though this study provides a clear relationship between investment costs and carbon dioxide equivalent emissions for several mechanical system types, it does not show the long term effects of using the same design parameters. In other words, this study only considers initial cost and not costs associated with the operational phases of the optimized mechanical systems in conjunction with various other building enclosure related variables. Furthermore, this study does not consider environmental impacts associated with the materials production, mechanical systems manufacturing, and the initial construction of the building.

The study by Hamelin & Zmeureanu (2012) attempts to optimize a single-family residential building using a Particle Swarm algorithm. The objective functions considered are life-cycle energy usage and life-cycle cost over a 50-year study period, but without the consideration for the demolition phase. One of the key aspects for this study is the wide variety of building enclosure related design parameters considered for optimization. However, the biggest limitation with this study is the fact that the Particle Swarm algorithm requires the user to combine all objective functions into a single objective function. The problem with combining multiple objective functions together is that the user must then assign weights to each objective function prior to the actual optimization process. Even though this method can produce optimal or near-optimal solutions, it does not give the user the ability to conduct a multi-objective trade-off analysis of the optimal design solutions.

Hasan (2010) has attempted to optimize net-zero buildings by using a hybrid Particle Swarm and Hooke-Jeeves algorithm by including following objective functions: life-cycle cost, primary energy consumption, carbon-dioxide emissions, and indoor discomfort. One of the problems with this study is that the author combines the objective functions mentioned above into either a single objective function or two objective functions. This requires the user to assign weights to each objective function in order to combine them. Even though the author mentions the incorporation of occupant discomfort as an objective function, the results do not seem to include occupant comfort as a design consideration. All remaining multi-objective studies mentioned in Table 6 have similar problems and limitations as the studies mentioned in this section and will thus not be discussed in further detail.

# Chapter 3 Problem Statement

There are several problems with the current state of research in terms of multi-objective optimization of residential building design parameters. First, most of the proposed optimization methods use either proprietary software written by researchers themselves or the software tools are not publicly available and often require users to be familiar with a particular programming language to use. Second, many of the reviewed studies have neglected occupant thermal comfort and have not considered it as an objective function. Although occupant thermal comfort is a complex topic that is largely qualitative and subjective, it should not be disregarded in the optimization process and it should at least be considered as a constraint objective. Third, there currently no studies on the multi-objective optimization, in terms of LCC, LCGWP, and occupant thermal comfort, of high-performance single-family residential buildings by integrating EnergyPlus with a NSGA-II genetic algorithm. Lastly, the majority of research on multi-objective optimization present their findings on new optimization methods and techniques that the authors have developed without applications to single-family residential buildings. It is important that multi-objective optimization is applied to single-family residential buildings, especially in the Canadian climate, where there is a large proportion of single-family residential buildings in Canada and significant savings in life-cycle cost, and life-cycle environmental impacts can be discovered. Furthermore, few studies have focused on the optimization of high-performance single-family building enclosures such as double-stud walls, EIFS walls, ICFs, SIPs, etc.

Despite the limitations in the scope of previous works involving objective based building optimization, it remains a powerful and efficient tool that has many advantages over the other methods previously mentioned. Regardless of which algorithm the user chooses to implement, multi-objective optimization can consistently discover true global optimal or near global optimal solutions for a predefined design space. Thus, this method can produce results more effectively compared to designers experience or a heuristic design approach. Furthermore, rather than relying on the traditional trial-and-error optimization approach, which can consume large quantities of time and resources, optimization algorithms can carry out simulations automatically without repetitive effort by the designer. Algorithmic optimization also gives designers the flexibility of choosing appropriate design objectives and variables depending on the direction and purpose of the optimization. In addition, a trade-off analysis can be easily determined based on the results provided by this method. Given the numerous advantages of objective based algorithmic optimization, this method remains largely unexploited because of the initial complexity in understanding the methodology and how to apply it in practice. This research work attempts to optimize single-family residential buildings in terms of the LCC, LCGWP, and occupant thermal comfort. The main design parameters considered for optimization are wall assemblies, window systems, roof assemblies, and mechanical system sizes. In addition, each individual sub-component of each assembly mentioned above will be optimized separately. The optimal solutions can then be used for trade-off analysis by comparing LCC with LCGWP.

# Chapter 4 Research Approach

## 4.1 Research Objectives

The overall objective of this research is to optimize a specific set of design parameters for single-family residential building. More specifically, the design parameters are primarily related to wall assemblies, window systems, roof assemblies, and mechanical system sizes as well as performance-related characteristics of the mechanical system. Based on the limitations and shortcomings of previous studies related to multi-objective optimization of both residential and commercial buildings, this research will attempt to incorporate three essential objective functions: life-cycle cost (LCC), life-cycle global warming potential (LCGWP), and occupant thermal comfort. More specifically, occupant thermal comfort will be used as a constraint objective to eliminate solutions that are above minimum acceptable thermal comfort levels as defined in ASHRAE Standards 55. These objective functions are selected based on literature review and the need to address these three factors during the design phase of buildings. Additionally, this research work will attempt to identify the specific factors and design parameters that can potentially affect the three objective functions mentioned above.

In order to achieve the first objective, a cost, environmental impact, and material properties database that focuses on materials and components used for standard and high-performance single-family residential buildings must be created. In order to create this database, various sources and other databases must be researched and referenced. Furthermore, this research work will attempt to develop a variety of wall, window, and roof assemblies based on the cost and environmental impact database. LCC and LCGWP data for an air-sourced heat pump system will also be included. Based on these building design parameters, another objective is to develop a set of input parameter optimization modules that can allow users to easily interchange between different design parameters depending on the user's requirements and optimization scope. The ability to interchange between different design-parameters provides flexibility and adaptability to the optimization software tool.

The final objective of this research is to analyze the optimized building design parameters in terms of the trade-offs between the objectives; primarily between LCC and LCGWP. More specifically, various Pareto optimal solutions within the same wall or roof type solution sets will be compared to one another according to LCC and LCGWP. Based on the optimized results, the most commonly selected parameters will also be analyzed and their level of impact on the objective functions can be realized.

## 4.2 Methodology

In order to accomplish the objectives stated above, several processes must be designed and employed. First a literature review is to be conducted to further understand the fundamentals of this research topic and to identify the limitations of previous research work. This will be accomplished through the use of the BCIT Library and various online resources such as *Google Scholar* and *Science Direct*. Using these resources, numerous articles can be reviewed and the most important and relevant articles and research papers will be gathered and consolidated using a reference manager software called *Mendeley*. Additional research on objective functions considered for optimization by other authors will also be conducted. Based on the summarized literature review, the objective functions will be selected by process of elimination. In other words, by breaking down each secondary research into their primary use of objective functions and by comparing one study to another, uncommonly used objective functions will be eliminated.

The second step in the process of this research work is to develop a cost and environmental impact database specifically for the purpose of this research. In other words, the cost and environmental impact database will be limited to materials and components required to optimize specific types of walls, windows, roofs, or mechanical systems considered for this research. The majority of the database will consist of building materials such as insulation, cladding, windows, etc., as well as mechanical systems, such as different sizes and types of heat pump systems. The cost database will be created based on a variety of sources such as construction cost databases and various online sources. The majority of construction and material cost information will be derived from the *RSMeans Building Construction Cost Data 2013* which was published by *Reed Construction Data Inc.* Other sources include the *Craftsman Cost Estimating Guide 2013* and the *Marshall & Swift Residential Cost Handbook 2013*. The environmental impact data, on the other hand, will be also consolidated by referencing various environmental impact databases, including the *International Environmental Agreements (IEA) Database*, *Data for Environmental Analysis and Management (DEAM)*, and the *Athena Sustainable Materials Institute (ASMI) Impact Estimator Database.*

Based on the cost and environmental impact database, this research will then identify and create a set of building design parameters by combining various materials together. For instance, a standard wall assembly may consist of various cladding, sheathing, insulation, and drywall materials. The building design parameters will comprise of only components that have direct impact on the thermal properties. For example, the waterproofing membrane typically installed on the exterior surface of the wood sheathing will not be considered for optimization because it has minimal contributions in terms of thermal conductivity or heat capacity.

One of the critical aspects of this research is to customize the integration of an energy simulation program with a genetic algorithm program in such a way that LCC, LCGWP, and occupant thermal comfort can all be considered for optimization. Assuming a successful integration, the optimization tool will then implemented on an ASHRAE Standards 140 benchmark model. In addition, the same optimization tool will then be applied to a case-study using real-world design parameters based on a single-family residential building located in Western Canada. The results generated by the optimization will then be extracted using a combination of *Microsoft Excel* and *SQLite* database queries. The optimal design solutions will be identified and extracted to Excel for further analysis by means of scatter plots and tabular data consisting of results in terms of the objective functions and their respective combinations of input parameters.

## 4.3 Scope of Work

Since the building design parameters (i.e. insulation thickness, window glazing type, etc) and its service systems parameters (i.e. HVAC system type, mechanical system size, heating and cooling set points, etc.) can only be determined early in the design phase, this research considers the building enclosure and HVAC system sizing as part of the optimization scope. Not only does making alterations to the building design too late in the design process create significant issues, but choosing which life cycle stages of a building to optimize may also inherit the same issues. To be more specific, the types of wall assemblies considered are standard framing wood-stud walls, advanced framing wood-stud walls, double-stud walls, exterior insulated finishing system (EIFS), insulated-concrete forms (ICF), and structural-insulated-panels (SIPs). The roof assemblies considered are the standard rafter-type roofs and high-performance roofs that have exterior insulation in addition to a standard rafter-type roof. Window framing material types and glazing types are both considered for optimization. The optimization of mechanical system sizing will be within the scope of work as well.

All life cycle phases of a building contribute to its energy performance, environmental impact, and thermal comfort. However, due to the high degree of uncertainty in determining accurate levels of energy consumption and environmental impact associated with the maintenance and demolition phases of a building's life-cycle, they are not considered in optimization process. Table 7 shows precisely which life cycle stages are considered (and which stages are not) for optimization in both LCCA and LCEA for the purpose of this research.

Table 7: Scope of life cycle stages considered for both LCCA and LCEA in this research.

| **Life Cycle Phase** | **Activity** | **Consideration** | | **Sources and Methods** |
|---|---|---|---|---|
| | | **LCCA** | **LCEA** | |
| [a] Manufacturing Phase | Building material production | Yes | Yes | RS Means Cost Data, ATHENA Impact Estimator, Manufacturer Data |
| | Transport | No | Yes | |
| | Building construction and future replacement | Yes | Yes | |

| | | | | |
|---|---|---|---|---|
| [b] Usage Phase | Use of electricity and fuels for heating, cooling, ventilation, and lighting | Yes | Yes | EnergyPlus, Local Utility Data |
| [c] Demolition Phase | Building Demolition | No | No | ATHENA Impact Estimator |
| | Transport | No | No | |
| | Recycling | No | No | |
| [d] Life Cycle Energy | Total energy use of the building in its life cycle | Yes | Yes | Phase a+b+c |
| [e] Life Cycle Assessment | life cycle material and energy flow estimation | n/a | Yes | ATHENA Impact Estimator, Phase a+b+c |
| | Impact assessment of building on its environment | n/a | Yes | |

For the LCCA, all activities within the manufacturing phase are lumped into one cost because RSMeans, the main cost data source for this research, considers material, transport, and construction costs as one *Overhead and Project* (O&P) fee (Reed Construction Data Inc. 2013). The O&P cost also includes costs associated with replacement costs depending on the life expectancy of the material or system which are adjusted for inflation as a Net Present Value (NPV) cost. The EnergyPlus building energy simulation software is used to calculate the amount of energy, in terms of electricity and natural gas, used within a year. By referencing current utility rates from local energy provider (i.e. BC Hydro and Fortis BC), the LCC can be calculated in terms of NPV over a specified study period (BC Hydro 2013; Fortis BC 2013). Also, the maintenance, repair, and demolition phases are not included in the LCCA because there is a lack of information and data that covers costs associated with these phases of the buildings, and there are too many uncertainties surrounding the assumptions made to determine maintenance, repair, and demolition costs. For instance, technology, labor costs, and local policies may change during the life-time of the building, which affects how maintenance, repair, and demolition costs are calculated. Figure 2 represents the scope of life-cycle stages that are considered for economic analysis and optimization. Maintenance, repair, and replacement (MRR) costs suggested by Flager et al. (2011), are not considered because this research focuses on the first 30 years of a residential building's life-cycle. Most major components in the building such as the structure, cladding, insulation, etc. is expected to last beyond the 30 year scope. Electrical and mechanical systems may require repairs or replacements throughout the 30 year scope, but they are unpredictable and difficult to determine the costs associated with repairs or replacements. The majority of electrical and mechanical components' expected life depends largely on the type of system used and how well they are maintained throughout their service lives.

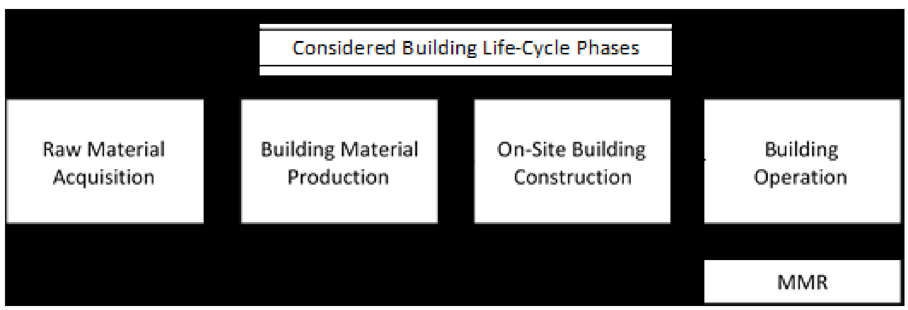



Figure 2: The life-cycle stages considered for economic analysis (MMR: Maintenance, Repair, and Replacement) (Flager & Basbagill 2012).

The main focus of this research is on the optimization of explicit building designs, such as material and systems that have a direct impact on the economic, energy, environmental, and thermal comfort performance. Therefore, the only building geometry related variable is the orientation of the entire building structure. The geometry of the building geometry is pre-determined and remains the same throughout the optimization process.

Structural design, with respect to external and internal force load calculations, is not part of the scope of this research project. The structure does, however, have an impact on the objective functions defined in Chapter 5 and should not be disregarded. More specifically, the structure refers to the framing system in the case of single-family residential buildings, which include wood, steel, or concrete. This research is limited to wood stud framing, insulated concrete structures, and structural insulated panels because steel framing and other building structural methods are not typically found in single-family residential buildings in a Canadian climate.

# Chapter 5 Objective Functions

In context of solution optimization and statistical decision making, an objective function, or a loss function as applied in mathematics, is a non-negative function indicating the cost and trade-off in a particular solution space given a particular decision (Nikulin 2013). In the case of building optimization, objective functions can be considered as quantifiable performance criteria. The performance criteria for this research consist of economic performance, environmental performance, and thermal comfort performance. These performance criteria are evaluated by the following major objective functions respectively: life-cycle cost, life-cycle global warming potential, and occupant thermal comfort rating.

## 5.1 Life Cycle Cost

LCCA is the method used to calculate the total net present value (NPV) cost associated with a given building or system over a pre-defined study period. Eq. 3- 1 is adopted with some modifications.

$$LCC_{PV} = CC_{PV} + EC_{PV} + OMC_{PV} + RRC_{PV} \qquad \text{Eq. 3- 1}$$

Where,

$LCC_{PV}$: Net present value of life-cycle costs

$CC_{PV}$: Net present value of construction costs

$EC_{PV}$: Net present value of energy costs

$OMC_{PV}$: Net present value of operation and maintenance (OM) costs

$RRC_{PV}$: Net present value of repair and renovation (RR) costs

However, according to the scope of research defined in the previous section, OM and RR costs shall be excluded from the equation due to the lack of accurate data and high degree of uncertainty. The OM and RR costs are replaced by a material and system replacement (MSR) cost. Furthermore, demolition costs and salvage value are excluded from the LCCA because of the lack of usable data and the high degree of uncertainty in determining those values. Non-fuel operating costs such as water consumption are not included because water is a free resource in most Canadian locations, and cost related to design, land acquisition, and other pre-construction fees are also excluded because they are assumed to be constant between all optimization alternatives of the same case. Therefore, a modified equation based on the assumptions stated is represented in Eq. 3- 2, and it is also the primary measure for the LCC objective function. The LCC objective function is separated into two objective functions in terms of initial construction and replacement cost as one objective, and life cycle energy consumption cost as another shown in Eq. 3- 2 and Eq. 3- 3. Separating the LCC objective functions provides the designer with explicit information about the trade-offs between different criteria (Caldas & Norford 2003).

$$LCC_{NPV} = ICC + MSR_{NPV} + ECC_{UPV} \quad \text{Eq. 3- 2}$$

$$OF_1 = ICC + MSR_{NPV} + ECC_{UPV} \quad \text{Eq. 3- 3}$$

Where,

$OF_1$: Objective functions that are the main criteria for optimization.

ICC: Initial construction cost of building and its sub-systems including exterior walls, roofs, ground floors, windows, overhangs, and mechanical system along with the components that constitute those subsystems.

ECC: Energy consumption costs associated with the life-cycle operation of the building.

MSR: Material and system related replacement costs throughout the expect life of the building.

NPV: Subscript that denotes the net present value dollar worth accounting for the life-cycle of the system.

UPV: Subscript that denotes the uniform present value dollar worth accounting for the life-cycle of the system.

The ICC and $MSR_{NPV}$ include costs associated with materials and labor. Eq. 3- 4 determines the total ICC based on these variables. The NPV formula, represented in Eq. 3- 5, is calculated based on LCC manual by Rushing et al. (2010).

$$ICC_{NPV} = ICC_{wall} + ICC_{roof} + ICC_{window} + ICC_{HVAC} \qquad \text{Eq. 3- 4}$$

$$MSR_{NPV} = (MSR_{wall} + MSR_{roof} + MSR_{window} + MSR_{HVAC}) * NPV_t \qquad \text{Eq. 3- 5}$$

Where,

Wall: Subscript that denotes the material and construction costs associated with the wall assembly, including the different sub-layers such as cladding, framing, insulation, sheathing, and drywall.

Roof: Subscript that denotes the material and construction costs associated with the roof assembly, including the different sub-layers such as shingles, insulation, sheathing, framing, and drywall.

Window: Subscript that denotes the material and construction costs associated with window systems, including the different components such as glazing, gas fill, and framing.

HVAC: Subscript that denotes the system and installation costs associated with heating and cooling mechanical systems, including components such as heat pumps, air-conditioners, gas furnaces, and electric resistance heaters.

$$ICC_i = UC_i * \begin{cases} A_i, & \textit{systems calculated based on area} \\ S_i, & \textit{systems calculated based on system size} \end{cases} \qquad \text{Eq. 3- 6}$$

$$MSR_i = UC_i * \begin{cases} A_i, & \textit{systems calculated based on area} \\ S_i, & \textit{systems calculated based on system size} \end{cases} \qquad \text{Eq. 3- 7}$$

Where,

$UC_i$: Unit cost per area (\$/m$^2$) or unit cost per system size (\$/kW) of the material or system *i*

$A_i$: Area (m$^2$) of the material or system *i.*

$S_i$: Size (kW) of the mechanical system *i*.

In the case where the area of the wall is required to be calculated, the area of windows and doors are subtracted from the gross area of the wall. This is a special case only applicable to walls and other areas that contain openings. Eq. 3- 8 indicates how to calculate wall area.

$$A_{wall} = A_{wall,gross} - \sum A_{window} \quad \text{Eq. 3- 8}$$

Where,

$A_{wall,gross}$: The gross area of the wall to be considered in the cost calculation.

$A_{window}$: The area of windows on the same plane as the wall to be considered.

$$NPV_t = \frac{1}{(1+d)^t} \quad \text{Eq. 3- 9}$$

Where,

NPV: Subscript that denotes the net present value dollar worth accounting for the life-cycle of the system.

*d*: Annual discount rate including inflation.

*t*: Relevant study period (years) during which the cost occurs.

Energy consumption cost (ECC) incorporates costs associated with energy consumption, so any systems that use electricity, natural gas, or other fuel sources must be included in the calculation. Eq. 3- 10 represents the calculation for costs associated with energy consumption of the building systems. Eq. 3- 11 accounts for the annual energy consumption of the target building, and Eq. 3- 12 determines the uniform present value factor for recurring fuel costs as formulated by Rushing et al. (2010).

$ECC_{UPV} = \sum ECC_{fuel} * UPV_t$ Eq. 3- 10

Where,

$UPV_t$: Uniform present value factors for finding the value of annually recurring costs such as fuels or other resource consumption with a constant escalation rate.

$ECC_{fuel}$: Energy consumption costs associated with fuels such as electricity or natural gas.

*t*: Time period (years) for which the recurring costs occur

$ECC_{fuel} = AEC_{fuel} * UC_{fuel}$ Eq. 3- 11

Where,

AEC: Annual energy consumption of a building in units of (kWh) for a particular fuel type.

$UC_{fuel}$: Unit utility cost of energy source in units of (\$/kWh) at base-date prices.

$UPV_t = (\frac{1+e}{d-e})(1 - \left(\frac{1+e}{1+d}\right)^N) \qquad (d \neq e)$ Eq. 3- 12

Where,

*d*: Discount rate depending on location.

*e*: Escalation rate depending on location.

*N*: Number of time periods (years) over which $ECC_{fuel}$ recurs.

The building is assumed to have mandatory electricity demand rate, but the natural gas demand rate depends on whether the building uses mechanical equipment that consumes natural gas. Thus, for a building that does not incorporate natural gas mechanical equipment, the building is assumed to have no natural gas charges. For the purpose of this research, the rates used to calculate UPV fuel costs, the real discount rate (*d*) *is* assumed to be at 5% (nominal discount rate = 4%, inflation rate = 1%), and the fuel price escalation rate (*e*) is assumed to be at 4%. These rates are only projections and can be validated and changed at the designer's discretion.

As explained in the previous chapters, EnergyPlus is the building energy simulation software used to calculate the energy demand of a particular building design. The annual on-site operating energy consumption includes energy required for heating, cooling, lighting, and equipment. Eq. 3- 13 represents the overall energy demand depending on the fuel types required by the mechanical system(s). Eq. 3- 14, Eq. 3- 15, and Eq. 3- 16 calculates the energy demand of the building for the heating, cooling, and lighting/equipment systems, respectively (Wang 2005). Unless the building consists of only a single zone, the total building energy demand is calculated by summing the energy demand for each zone (i.e. zone 1, zone 2, …, zone n) within the building.

$AEC_{fuel} = AEC_{heating} + AEC_{cooling} + AEC_{lighting/equipment}$ Eq. 3- 13

Where,

$$AEC_{heating} = \sum_{zone=1}^{n} \sum_{timestep=1}^{t_{heating}} \left[\frac{Q_{system}}{COP_{heating}}\right]$$ Eq. 3- 14

$$AEC_{cooling} = \sum_{zone=1}^{n} \sum_{timestep=1}^{t_{cooling}} \left[\frac{-Q_{system}}{COP_{cooling}}\right]$$ Eq. 3- 15

$$AEC_{lighting/equipment} = \sum_{zone=1}^{n} \sum_{timestep=1}^{t_{annual}} \left[PD_{lighting} + PD_{equipment}\right](FA)$$ Eq. 3- 16

Where,

$t_{heating}, t_{cooling}$: Time period (depending on pre-defined length of time-step) for the heating and cooling season, respectively.

$Q_{system}$: System load required for heating or cooling (W) in particular zone.

$COP_{heating}, COP_{cooling}$: Coefficient of performance (dimensionless) depending on type of heating or cooling system, respectively.

PD: power density ($W/m^2$) for lighting or equipment.

FA: Total zone floor area ($m^2$) or total floor area in the case of a single zone building.

## 5.2 Life Cycle Global Warming Potential

Global warming is a significant issue that is partially affected by the release of GHGs into the atmosphere because it traps heat that contributes to the rise of global surface temperatures. In turn, the global warming will affect building operations and influences the energy consumption of buildings leading to a further increase in the production of GHG emissions (Radhi 2010). According to Jones & Trenberth (2007), global mean surface temperatures have risen by 0.74℃ ∓0.18℃ between the years 1906 and 2005, and the rate of global warming is expected to increase at 0.3℃ per decade. Global warming is a serious global issue and can be measured

According to the British Columbia Ministry of Environment, Global Warming Potential (GWP) is an environmental impact factor that enables the comparison of the ability of different Green House Gasses (GHGs) to trap heat in the atmosphere by radiative forcing (British Columbia Ministry of Environment 2012). GWP is measured in equivalent unit weight of carbon dioxide (kg$CO_2$-eq). Moreover, the term radiative forcing refers to the amount of heat-trapping potential for a particular GHG as measured in power per unit area ($W/m^2$). The reason GWP is chosen as the primary measure of environmental impact for this research is because GWP is assumed to have a direct impact on global warming. Also, other environmental impact factors are assumed to have a linear relationship in comparison with GWP. If required, other environmental impact factors can be calculated by multiplying GWP by a certain factor, but is not calculated in this report.

Eq. 3- 17, Eq. 3- 18, and Eq. 3- 19 present a way to calculate the environmental impact objective function and the results are expressed in units of kg-$CO_2$-eq. As with the objective functions for LCC, the objective functions for construction GWP and energy consumption GWP shall be optimized separated in order to analyze the trade-offs between different criteria (Caldas & Norford 2003).

$$LCGWP_{total} = LCGWP_{construction} + LCGWP_{energy} \quad \text{Eq. 3- 17}$$

$$OF_2 = LCGWP_{total} \quad \text{Eq. 3- 18}$$

Where,

$OF_2$: The second main objective function that serve as the main criteria for optimization.

LCGWP: Life-cycle global warming potential.

Construction: subscript that denotes the life-cycle GWP effects of construction, materials, and systems used in the building.

Energy: subscript that denotes the life-cycle GWP effects of energy consumption by the building; mainly the consumption of electricity and natural gas.

$$LCGWP_{construction} = LCGWP_{wall} + LCGWP_{roof} + LCGWP_{window} + LCGWP_{HVAC} \quad \text{Eq. 3- 19}$$

Wall: subscript that denotes the material, transport, and construction GWP associated with the wall assembly, including the different sub-layers such as cladding, framing, insulation, sheathing, and drywall.

Roof: subscript that denotes the material, transport, and construction GWP associated with the roof assembly, including the different sub-layers such as shingles, insulation, sheathing, framing, and drywall.

Window: subscript that denotes the material, transport, and construction costs associated with window systems, including the different components such as glazing, gas fill, and framing.

HVAC: subscript that denotes the system GWP associated with heating and cooling mechanical systems, including components such as heat pumps, air-conditioners, gas furnaces, and electric resistance heaters.

$LCGWP_i = UGWP_i * A_i$ Eq. 3- 20

Where,

$UGWP_i$: GWP per unit area measured in ($kqCO_2$-eq/$m^2$) for the material or system *i.*

$A_i$: Area of the material or system as designed in the building; measured in ($m^2$).

Some systems such as heating and cooling mechanical systems are not measured by a unit area basis; rather, it is measured as entire combined system. Systems that are measured as an entire unit can be calculated using Eq. 3- 20 as well, but the $UGWP_i$ will have units of $kgCO_2$-eq/unit and the unit $A_i$ will have a value of 1. The GWP created by the energy consumption of the building and its sub-systems can be calculated by using Eq. 3- 21.

$$LCGWP_{energy} = 0.108 * AEC_{fuel}\left(\frac{EF_{CO2,fuel} * FF_{CO2,fuel} + EF_{CH4,fuel} * FF_{CH4,fuel} + EF_{NOx,fuel} * FF_{NOx,fuel}}{1000}\right) * \mathrm{t}$$

Eq. 3- 21

Where,

$AEC_{fuel}$: Annual energy consumption of a particular fuel type in units of (Wh).

EF: Emissions factor that converts a particular GHG into equivalent $CO_2$ units; measured in ($gCO_2$-eq/gGHG).

FF: Fuel factor that determines the amount of GHG emitted per unit energy consumption; measured in (g/MJ).

Fuel: subscript that denotes the type of fuel used by the building, mainly electricity and natural gas.

CO2: subscript that denotes carbon dioxide gas.

CH4: subscript that denotes methane gas.

NOx: subscript that denotes nitrous oxide gas.

*t*: Time period (years) for which the LCEA is conducted.

The annual energy consumption of the building is calculated by EnergyPlus using the same method described in the previous section. However, the energy consumption calculated in the previous section uses units of (Wh or kWh), but the unit factors for GWP calculations require the energy consumption in units of (MJ). Hence, $AEC_{fuel}$ must be multiplied by a factor of $0.108$; where, $0.108 = (30 * 3.6)/1000$ to convert Wh to MJ.

## 5.3 Occupant Thermal Comfort Rating

Thermal comfort is generally defined as the state of mind in which the occupant expresses satisfaction with the thermal environment (ISO 2005). This measure is important because the modern man spends most of the day indoors (Hoof et al. 2010), and the ultimate purpose of a building is to serve its occupants with a comfortable shelter from the outdoor environment. However, thermal comfort is a very complex interdisciplinary field of study that involves building science, physiology, and psychology (Hoof et al. 2010). The complexity of this subject give rise to various attempts to model thermal comfort, such as Fanger PMV, Pierce Two-Node, KSU Two-Node, and an Adaptive Model based on EU Standard EN15251-2007 (LNBL 2012). The Fanger PMV model is chosen to calculate thermal comfort rating for the purpose of this research because it is the most well-known model and is the easiest to implement by using well established formulas and charts. This objective function is used as a constraint objective, which will be discussed in further detail.

In order to understand how thermal comfort is rated, the scales that represent different levels of occupant comfort sensation must be defined. Table 8 and Table 9 represent the two different thermal sensation scales used by many of the thermal comfort models.

Table 8: Seven point Thermal Sensation Scale (LNBL 2012).

| Sensation | Description |
|---|---|
| **3** | Hot |
| **2** | Warm |
| **1** | Slightly Warm |
| **0** | Neutral |
| **-1** | Slightly Cool |
| **-2** | Cool |
| **-3** | Cold |

Table 9: Nine point Thermal Sensation Scale (LNBL 2012).

| Sensation | Description |
|---|---|
| **4** | Very Hot |
| **3** | Hot |
| **2** | Warm |
| **1** | Slightly Warm |
| **-0** | Neutral |
| **-1** | Slightly Cool |
| **-2** | Cool |
| **-3** | Cold |
| **-4** | Very Cold |

Based on the Thermal Sensation Scales, the thermal model can be created to determine the overall comfort of occupants based on a qualitative scale. Now, a human being's thermal sensation is strongly correlated to the thermal balance of his or her body as a whole (ISO 2005), so the thermal properties of the humans must be calculated as well in terms of a metabolic rate. Metabolic rate is the measure of the internal heat production rate of an occupant per Dubois body surface area ($m^2$), shown in Eq. 3- 22.

$$A_{Du} = 0.202 * \left(W_{occupant}\right)^{0.425} * \left(H_{occupant}\right)^{0.725} \qquad \text{Eq. 3- 22}$$

Where,

$W_{occupant}$: Weight of the occupant to be modeled in (kg).

$H_{occupant}$: Height of the occupant to be modeled in (m).

The metabolic rate of the occupant can be calculated depending on various factors including skin temperature, clothing insulation, air temperatures, etc. Eq. 3- 23 represents the formulas developed by Fanger to determine metabolic rate.

$$M = L = Q_{res} + Q_{dry} + E_{sk} + WE, \text{ at thermal steady state} \qquad \text{Eq. 3- 23}$$

Where,

$Q_{res}$: Rate of respiratory heat loss ($W/m^2$).

$Q_{dry}$: Sensible heat flow from skin ($W/m^2$).

$E_{sk}$: Total evaporative heat loss from skin ($W/m^2$).

WE: Rate of heat loss due to work efficiency (W/m$^2$).

$$Q_{res} = E_{res} + C_{res} = 0.0023M(44 - P_a) + 0.0014M(34 - T_a). \qquad \text{Eq. 3- 24}$$

Where,

$E_{res}$: Rate of latent respiratory heat loss (W/m$^2$).

$C_{res}$: Rate of dry respiratory heat loss (W/m$^2$).

$M$: Metabolic rate per unit Dubois area (W/m$^2$).

$P_a$: Water vapor pressure in ambient are (Torr).

$T_a$: Air temperature (°C)

$$Q_{dry} = h_c f_{cl}(T_{cl} - T_a) + f_{eff} f_{cl} \varepsilon\sigma(T_{cla}^4 - T_{ra}^4) \qquad \text{Eq. 3- 25}$$

Where,

$f_{cl}$: Ratio of clothed body.

$f_{eff}$: Fraction of surface effective for radiation (typical = 0.72).

$T_{cl}$: Clothing surface temperature (°C).

$T_{cla}$: Clothing surface temperature in absolute degrees (K).

$T_{ra}$: Mean radiant temperature of surrounding (K).

For $H > 58.2, E_{rsw} = 0.42(H - 58.2)$ Eq. 3- 26

For $H \leq 58.2, E_{rsw} = 0$ Eq. 3- 27

$E_{diff} = 0.4148(P_{sk} - P_a) = E_{sk} - E_{rsw}$ Eq. 3- 28

$P_{sk} = 1.92(35.7 - 0.028H) - 25.3$ Eq. 3- 29

Where,

$H$: Internal heat production rate of an occupant per Dubois area (= $M - WE$)(W/m$^2$)

$E_{rsw}$: Rate of heat loss from the evaporation of regulatory sweating at the state of comfort (W/m$^2$)

$P_{sk}$: Saturated water vapor pressure at required skin temperature (Torr)

By using Eq. 3- 23 to Eq. 3- 29, the Fanger Predicted Mean Vote (PMV) can be calculated using Eq. 3- 30 and the Percentage People Dissatisfied (PPD), which estimates the percentage of occupants who express signs of discomfort, can be determined as well using Eq. 3- 31. Furthermore, Figure 3 shows a graph that represents the relationship between PMV on a seven point scale and PPD. Most importantly, the PPD scale does not reach below 5%, implying that satisfying 100% of the occupants is virtually impossible. For the purpose of this research, all solutions with a PPD above 20% is assumed to be beyond the comfortable limits specified by ASHRAE Standards 55 and will thus be discarded from the set of optimal solutions.

$$PMV = 3.155(0.303e^{-0.114M} + 0.028)L \qquad \text{Eq. 3- 30}$$

$$PPD = 100 - 95e^{-0.03353*PMV^4 - 0.2179*PMV^2} \qquad \text{Eq. 3- 31}$$

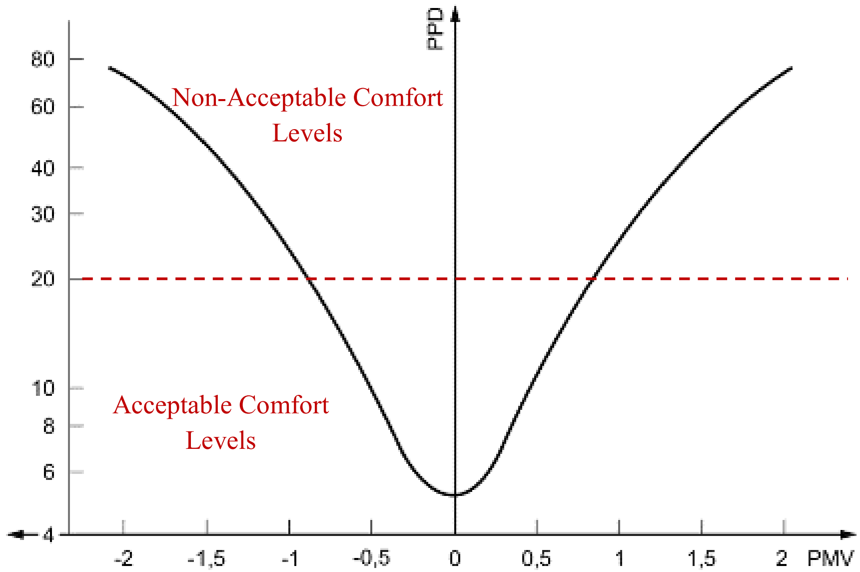



Figure 3: PPD (%) as a function of PMV where the dashed line represents the occupant thermal comfort limit (ISO 2005)

As a final step to convert PPD into a meaningful objective function, the PPD is averaged through a period of one year of energy simulation. Eq. 3- 32 determines the objective function to be used as a criterion for optimization.

$$OF_3 = \frac{\sum_{timestep=0}^{t_{annual}} PPD}{t_{annual}} \qquad \text{Eq. 3- 32}$$

Where,

$t_{annual}$: Time period (depending on length of timestep) over the course of one year.

## 5.4 Summary

This research project focuses mainly on the building enclosure (i.e. wall assembly, roof assembly, window systems, etc.) and mechanical systems (i.e. heating and cooling systems). The scope of LCCA includes all life-cycle stages with exception to building maintenance and demolition because of the high degree in uncertainty of the data and the lack thereof. The LCEA also considers all stages of the building life-cycle with exceptions to the demolition phase as well as certain operational maintenance costs for the same reason as the LCCA. Even though the ATHENA Impact Estimator provides environmental impact data for the entire life cycle including the demolition phase (Athena Sustainable Materials Institute 2013), it provides minimal contributions to the overall life-cycle accumulations so they are eliminated from the optimization for consistency with the LCCA. Furthermore, this research only focuses on the first 30 years of the building's service life, so accounting for the demolition phase is unnecessary. The objective functions are selected based on literature review and the limitations of EnergyPlus and jEPlus+EA in addition to personal judgment, and they are defined by the following equations in Table 10. However, the optimization software is flexible and allows users to define the number and type of objective functions based on their preferences.

Table 10: List of objective functions considered for optimization in this research

| Objective Function | | Description |
|---|---|---|
| **1. LCCA** | = | Life Cycle Cost of Building |
| **2. LCEA** | = | Life Cycle GWP of Building |
| **Occupant Thermal** | = | Average Annual Occupant Thermal Comfort (Constraint |

| | | |
|---|---|---|
| **Comfort** | | Objective) |

In this thesis, the variables are selected based on certain considerations such as its impact on the objective functions, designer's control over the variables, the accessibility of variable data, etc. The concept of structure-related variables allow implicit variables to be defined and for system compatibility between enclosure types. Moreover, all variables are considered as discrete and are constrained by pre-determined parameters in order to maintain a manageable design space. Variables are also flexible and can be changed by the user depending on the purpose and preferences.

# Chapter 6 Optimization Parameters

This sections aims at describing the various wall and roof assembly types that are selected for optimization in this research thesis. For the purpose of this research, 5 different wall assemblies, 2 roof assemblies, various window frame and glazing types, and an air-source heat pump is selected for optimization. The section will provide a detailed description of each wall and roof assembly type as well as their material properties, costs, and environmental impact factors. The assumptions made to obtain specific values related to wall, roof, and window materials will also be mentioned in this section. Although this research work focuses only on an air-source heat-pump, the assumptions made regarding the sizing of the mechanical system will be provided.

## 6.1 Standard and High-Performance Wall Assemblies

This section will discuss in further detail the different wall assemblies that are selected for optimization. The 5 major wall assembly types (i.e. standard wall, exterior insulation finishing system (EIFS), double-stud wall, insulated concrete forms (ICF), and structural insulated panels (SIPs)) are chosen for optimization because they are the most commonly used construction methods in the single-family residential building industry. Although some wall types may be used more often than others, they are all more or less accepted by the industry in addition to having industry approved construction code standards.

### 6.1.1 Standard Wall Construction

The standard wall construction is the most commonly used wood-framed wall assembly in Canada. It typically consists of either 2x4 or 2x6 framing, fiberglass or cellulose cavity insulation between the studs, exterior sheathing, weather barrier, and exterior cladding as shown in Figure 4. Even though this method of construction has been the standard for many years in many places, the 2x4 stud framing with batt insulation wall assembly no longer meets energy code requirements for insulation in many climates throughout North America (Building Science Corporation 2009d). However, this research project has chosen to use both the 2x4 and 2x6 single-stud construction type as the baseline case for comparative analysis because it is the most widely accepted method for constructing a single-family residential building. The vapor control and House-wrap layers are not considered for the optimization because their primary function is moisture control and not thermal regulation.

A variation of the standard wall is the advanced framing wall assembly. The advanced framing wall assembly is fundamentally identical to the standard wall assembly with exception to the spacing between vertical studs. Regardless of the type of stud used (i.e. 2x4 or 2x6), the on-center spacing between vertical studs is 600mm (24 in.) rather than 400mm (12 in.) used in standard framing techniques. Table 11 shows the different framing techniques and stud types considered for optimization.

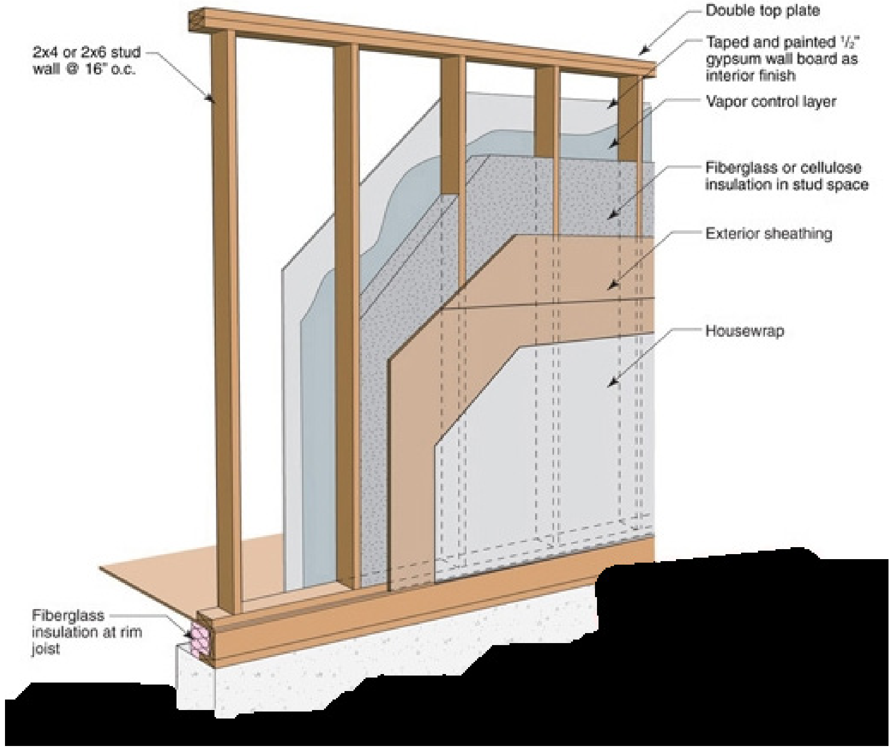



Figure 4: Diagram representing the different layers in a standard wall assembly in addition to the wood stud framing (Building Science Corporation 2009d).

Within the wall assembly, there are individual layers such as cladding, framing, insulation, etc. Each layer having multiple variables, which are also listed in Table 11. With exception to the stud space insulation and wood framing layers, each layer is independent on other layers. The stud space insulations and wall framing types are dependent on each other. For example, if 2x4 wood stud standard framing is chosen as the primary structural framing of the building, only insulation that is thinner than 88.9mm (3.5 in.) can be selected. Additionally, if 2x6 wood stud framing is selected, then an insulation type with appropriate thickness must be selected as well (i.e. 140mm (5.5 in.) Blown Cellulose). A pre-combined list of stud space insulation and wall framing type, along with their corresponding ID codes, is shown in Table 12 . A full list of material properties, cost, environmental impact data, and corresponding EnergyPlus input code is provided in Appendix B. Furthermore, all additional high-performance wall assemblies are based off the standard and advanced wall assembly type with exception to ICF and SIP wall assemblies.

Table 11: List of individual wall layers and each layer having multiple variables which will be considered for standard/advanced wall assembly optimization.

| Wall Layer | Layer Variables |
|---|---|
| **Exterior Cladding** | • Wood Siding (CL1*)<br>• Fiber Cement Siding (CL2)<br>• Residential 30 ga. Steel Siding (CL3)<br>• Stucco on Steel Mesh (CL4)<br>• Common Face Brick (CL5)<br>• Vinyl Siding (CL6) |
| **Exterior Sheathing** | • Softwood Plywood (WS1)<br>• OSB (WS2) |
| **Stud Space Insulation** | • 88.9mm (3.5 in.) Fiberglass Batt. (IN1)<br>• 140mm (5.5 in.) Fiberglass Batt. (IN2)<br>• 88.9mm (3.5 in.) Blown Cellulose (IN10)<br>• 132mm (5.2 in.) Blown Cellulose (IN11)<br>• 88.9mm (3.5 in.) Mineral Wool (IN13)<br>• 140mm (5.5. in.) Mineral Wool (IN14)<br>• 88.9mm (3.5 in.) Spray Polyurethane Foam (Closed Cell) (IN28)<br>• 140mm (5.5 in.) Spray Polyurethane Foam (Closed Cell) (IN31)<br>• No Insulation |
| **Framing Type** | • 2x4 Standard Framing (400mm o.c.)<br>• 2x4 Advanced Framing (600mm o.c.)<br>• 2x6 Standard Framing (400mm o.c.)<br>• 2x6 Advanced Framing (600mm o.c.) |

| | |
|---|---|
| **Interior Drywall** | • Regular Gypsum Board (DW1)<br>• Gypsum-Fiber Board (DW2) |
| ***Implementation of optimization model ID code is discussed in further detail in Chapter 7. Furthermore, a full list of material properties, costs, and environmental data is provided in Appendix A of this report.** | |

Table 12: List of stud spacing, stud dimensions, and insulation type combinations considered for use in the optimization process.

| ID Code | Stud Spacing (mm) | Stud Dimensions (in.) | Insulation Type |
|---|---|---|---|
| **SDIN1** | 400 | 2x4 | Fiberglass |
| **SDIN2** | 400 | 2x4 | Mineral Wool |
| **SDIN3** | 400 | 2x4 | Blown Cell |
| **SDIN4** | 400 | 2x4 | Spray Foam |
| **SDIN5** | 400 | 2x4 | Airspace |
| **SDIN6** | 400 | 2x6 | Fiberglass |
| **SDIN7** | 400 | 2x6 | Mineral Wool |
| **SDIN8** | 400 | 2x6 | Blown Cell |
| **SDIN9** | 400 | 2x6 | Spray Foam |
| **SDIN10** | 400 | 2x6 | Airspace |
| **SDIN11** | 600 | 2x4 | Fiberglass |
| **SDIN12** | 600 | 2x4 | Mineral Wool |
| **SDIN13** | 600 | 2x4 | Blown Cell |
| **SDIN14** | 600 | 2x4 | Spray Foam |
| **SDIN15** | 600 | 2x4 | Airspace |
| **SDIN16** | 600 | 2x6 | Fiberglass |
| **SDIN17** | 600 | 2x6 | Mineral Wool |
| **SDIN18** | 600 | 2x6 | Blown Cell |
| **SDIN19** | 600 | 2x6 | Spray Foam |
| **SDIN20** | 600 | 2x6 | Airspace |

### 6.1.2 Exterior Insulation Finishing System (EIFS)

The exterior insulation finish system (EIFS) wall assembly type is based off of the standard and advanced wall assembly type with the addition of a continuous layer of insulation on the exterior side of the sheathing layer. Even though Figure 5 shows some commonly used components such as 2x6 stud wall and 3 in. to 5 in. EPS insulation, the optimization is not limited to these components. In addition to the wall layers and layer variables discussed on the standard wall construction section and in Table 11 and Table 12, Table 13 shows the list of continuous exterior insulation types that are selected for optimization.

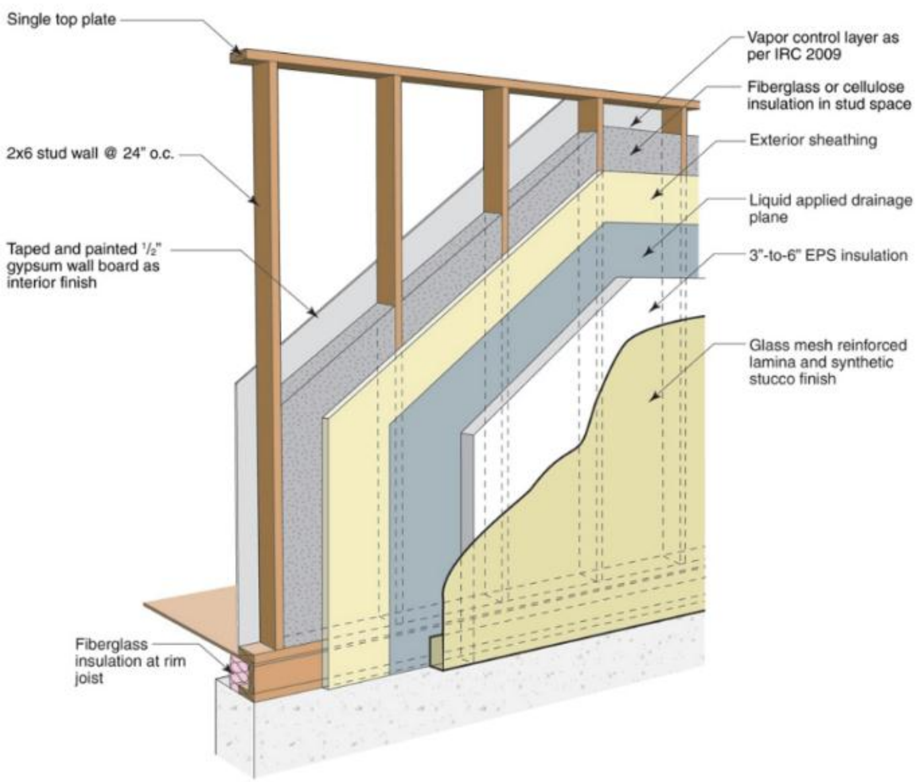


Figure 5: Diagram of an EIFS wall assembly with commonly used components (Building Science Corporation 2009b).

Table 13: List of continuous exterior insulation selected for the optimization of the EIFS wall assembly.

| Wall Layer | Layer Variables |
|---|---|
| **Continuous Exterior Insulation** | • 12.7mm (0.5 in.) Isocyanurate (IN5*)<br>• 25.4mm (1.0 in.) Isocyanurate (IN6)<br>• 50.8mm (2.0 in.) Isocyanurate (IN7)<br>• 76.5mm (3.0 in.) Isocyanurate (IN8)<br>• 102mm (4.0 in.) Isocyanurate (IN9)<br>• 88.9mm (3.5 in.) Mineral Wool (IN13)<br>• 140mm (5.5 in.) Mineral Wool (IN14)<br>• 25.4mm (1.0 in.) EPS Rigid Foam (IN15)<br>• 50.8mm (2.0 in.) EPS Rigid Foam (IN16)<br>• 76.2mm (3.0 in.) EPS Rigid Foam (IN17)<br>• 25.4mm (1.0 in.) XPS Rigid Foam (IN21)<br>• 50.8mm (2.0 in.) XPS Rigid Foam (IN22)<br>• 76.2mm (3.0 in.) XPS Rigid Foam (IN23)<br>• 25.4mm (1.0 in.) Spray Polyurethane Foam (Closed Cell) (IN25)<br>• 50.8mm (2.0 in.) Spray Polyurethane Foam (Closed Cell) (IN26)<br>• 76.2mm (3.0 in.) Spray Polyurethane Foam (Closed Cell) (IN27) |
| ***Implementation of optimization model ID code is discussed in further detail in Chapter 7. Furthermore, a full list of material properties, costs, and environmental data is provided in Appendix A of this report.** | |

### 6.1.3 Double-Stud Wall Construction

The double-stud wall construction is fundamentally similar to the standard wall construction with exception to having two layers of wood framing instead of a single layer. In other words, where there is originally one layer of wood stud framing, there is now two layers. Now, the two layers of vertical studs can either be parallel (with some space in between) or have a staggered orientation. Figure 6 shows the diagram two which the optimization model is based on, with exception to the insulation layer in the gap between framing. For the purpose of this research thesis, the two layers of stud space insulation is assumed to be directly in contact with each other, eliminating the insulation layer in the gap and the studs are assumed to be oriented in a staggered position to allow for thermal breaks between the two framing layers. The stud space insulation parameters are based on Table 12.

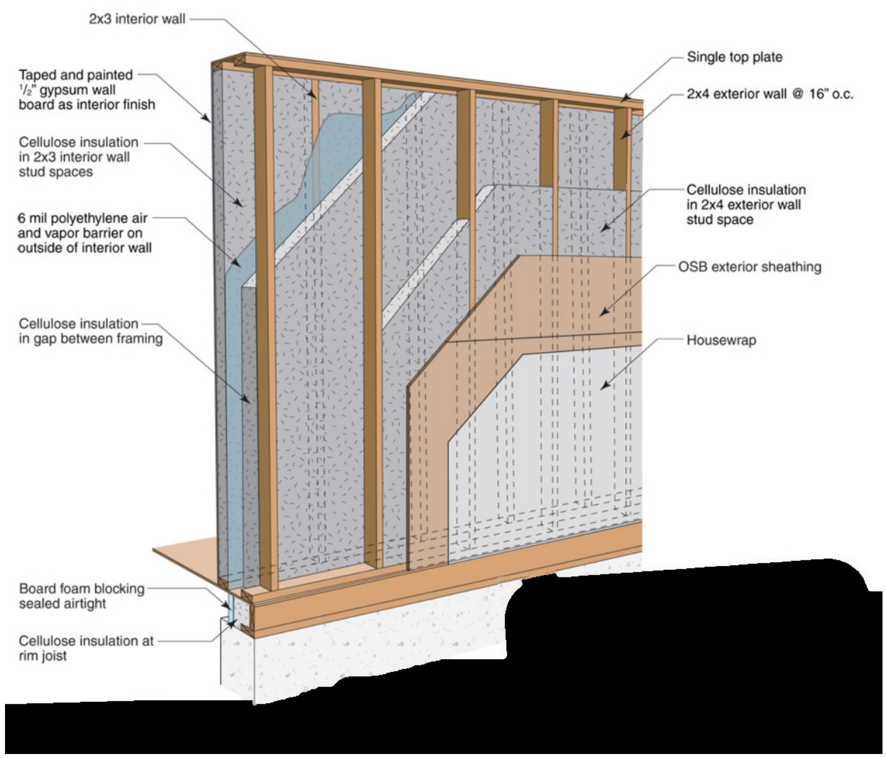


Figure 6: Diagram showing the double-stud wall assembly with commonly used components (Building Science Corporation 2009a).

### 6.1.4 Insulated Concrete Forms (ICF)

The insulated concrete form (ICF) wall assembly is completely different compared to all other wall assemblies discussed to this point. This wall assembly does not contain any wood studs or wood components. Rather, this wall assembly uses concrete sandwiched between two layers of rigid foam insulation. Figure 7 shows how the different layers of materials are put together to create the ICF wall assembly. Additionally, the individual wall layer components selected for optimization are shown in Table 14. The inner and outer insulation layers are assumed to be the same thickness and material type for the purpose of this research. For instance, if a 76mm (3.0 in.) EPS rigid foam is selected for the inner layer, the outer layer must be the same.

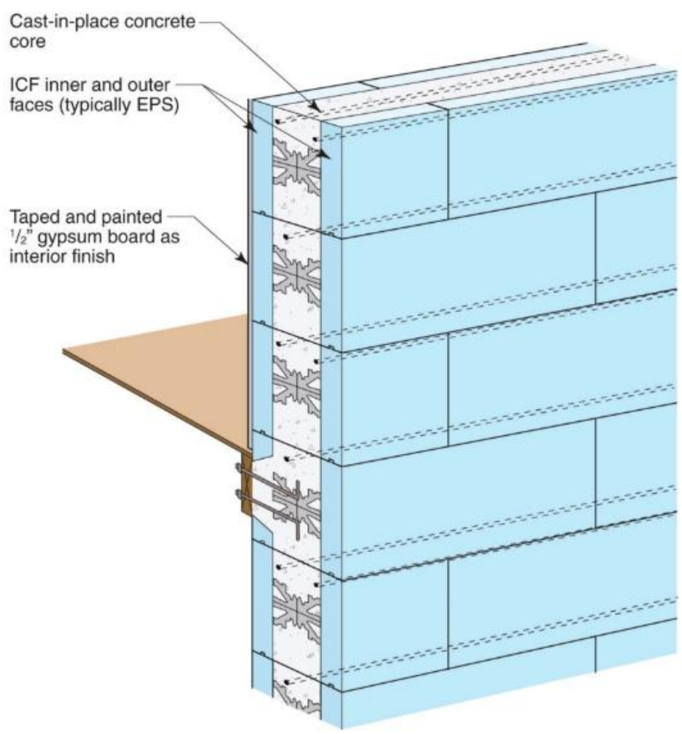



Figure 7: Diagram of a typical ICF wall assembly built with commonly used components (Building Science Corporation 2011).

Table 14: List of wall layers and individual layer variables selected for optimization.

| Wall Layer | Layer Variables |
|---|---|
| **Inner and Outer Insulation Faces** | • 50.8mm (2.0 in.) EPS Rigid Foam (IN16*) |
| **Core** | • 152mm (6.0 in.) Concrete (ICF1)<br>• 203mm (8.0 in.) Concrete (ICF2) |
| **Interior Drywall** | • Regular Gypsum Board (DW1)<br>• Gypsum-Fiber Board (DW2) |
| ***Implementation of optimization model ID code is discussed in further detail in Chapter 7.** | |

**Furthermore, a full list of material properties, costs, and environmental data is provided in Appendix A of this report.**

### 6.1.5 Structural Insulated Panels (SIP)

Structural insulated panels follow a similar concept as the ICF wall assemblies. Instead of rigid foam insulation on the inner and outer faces of the wall, wood sheathing is used (i.e. plywood or OSB). Furthermore, a layer of rigid foam insulation is sandwiched in between the two layers of sheathing to create the SIP. Figure 8 shows the diagram of a SIP with typical components. The House-Wrap layer is not included in the optimization model because it has minimal contributions to the overall thermal performance of the wall assembly. Unlike other wall assemblies, SIP panels are usually factory ordered and pre-assembled before construction. Therefore, the SIPs are not separated into layers, but rather considered as a complete system with several options listed in Table 15. SIP wall assemblies also have a cladding layer and an interior drywall layer that are the same as a standard wall assembly (refer to Table 11).

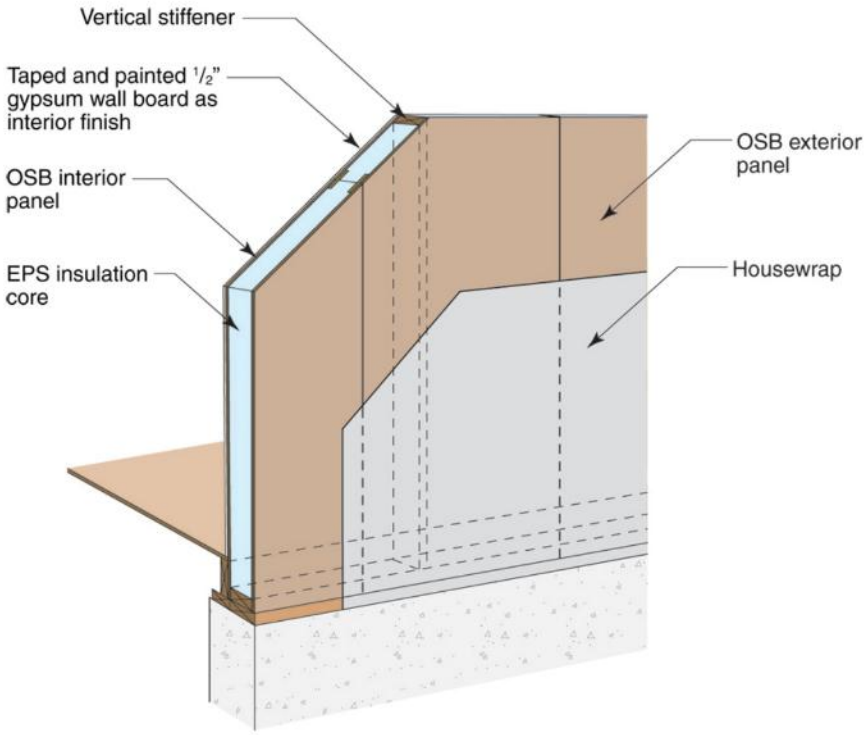



Figure 8: Diagram of a typical SIP wall assembly with commonly used components(Building Science Corporation 2009c).

Table 15: List of SIP wall assemblies with their sheathing and insulation core combinations.

| ID Code | Inner & Outer Sheathing Type | Core Type |
|---|---|---|
| **SIP1** | 11.1mm (0.44 in.) OSB Sheathing | 88.9mm (3.5 in.) EPS Foam |
| **SIP2** | 11.1mm (0.44 in.) OSB Sheathing | 140mm (5.5 in.) EPS Foam |
| **SIP3** | 11.1mm (0.44 in.) OSB Sheathing | 184mm (7.25 in.) EPS Foam |
| **SIP4** | 11.1mm (0.44 in.) OSB Sheathing | 235mm (9.25 in.) EPS Foam |

## 6.2 Standard and High-Performance Roof Assemblies

For the purpose of this research project, roof assemblies are divided into a code standard roof and a high-performance roof. The standard roof refers to a typical building code-compliant flat or rafter-type roof assembly with wood rafters and rafter-space insulation. The high-performance roof, on the other hand, refers to a flat or rafter-type roof assembly with continuous exterior insulation underneath typical roof shingles. The following sections will provide in-depth descriptions of both roof assemblies along with selected variables for optimization.

### 6.2.1 Standard Roof Construction

There are several types of roof assemblies that can fall under the standard roof construction type (i.e. joist, truss, and rafter-type roof assemblies), but this research focuses mainly on the rafter-type roof ceiling assembly. In this case, the roofing is attached directly to the top of the ceiling rafters as is the case for cathedral or sloped ceilings. Figure 9 and Figure 10 represent a flat and sloped roof using the rafter-type roof ceiling assembly. As shown, there are no attic spaces so they are not considered as a layer in the optimization model. The roof assemblies can be represented in EnergyPlus in a similar way as a standard wall construction. In other words, each layer, such as shingles, sheathing, framing, insulation, etc., can be separated into individual layers with numerous layer variables. The layers and layer variables are shown in

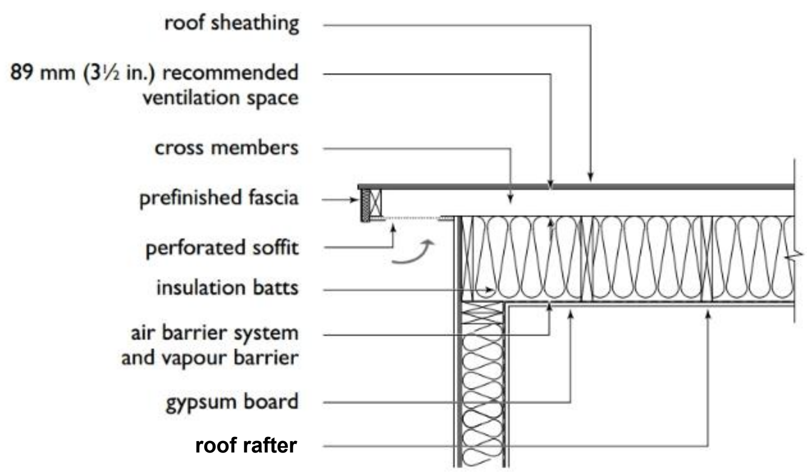



Figure 9: Cross-section view of a rafter-type flat roof assembly with commonly used components (Canada Mortage and Housing Corporation 2013).

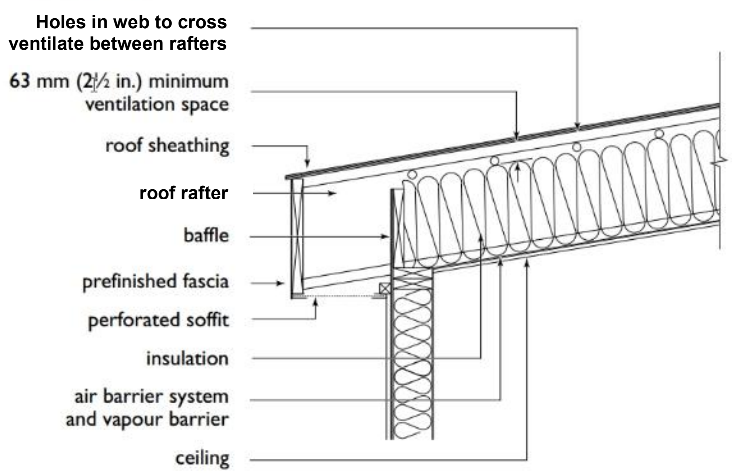



Figure 10: cross-section view of a rafter-type sloped/cathedral roof assembly with commonly used components (Canada Mortage and Housing Corporation 2013).

Table 16: List of individual roof layers with each layer having multiple variables which will be considered for standard roof assembly optimization.

| Roof Layer | Layer Variables |
|---|---|
| **Exterior Roofing** | • Asphalt Roof Shingles (RF1*)<br>• Residential 30 ga. Steel Roof Panels (RF2) |
| **Exterior Sheathing** | • Softwood Plywood (WS1)<br>• OSB (WS2) |
| **Stud Space Insulation** | • 140mm (5.5 in.) Fiberglass Batt. (IN2)<br>• 184mm (7.25 in.) Fiberglass Batt. (IN3)<br>• 286mm (11.25 in.) Fiberglass Batt. (IN4)<br>• 132mm (5.2 in.) Blown Cellulose (IN11)<br>• 165mm (6.5 in.) Blown Cellulose (IN12)<br>• 152mm (6.0 in.) Spray Polyurethane Foam (Closed Cell) (IN31)<br>• 2 x 102mm (4.0 in.) Spray Polyurethane Foam (Closed Cell) (IN29)<br>• 2 x 152mm (6.0 in.) Spray Polyurethane Foam (Closed Cell) (IN31) |
| **Framing Type** | • 2x6 Standard Framing (400mm o.c.)<br>• 2x6 Advanced Framing (600mm o.c.)<br>• 2x8 Standard Framing (400mm o.c.)<br>• 2x8 Advanced Framing (600mm o.c.)<br>• 2x12 Standard Framing (400mm o.c.)<br>• 2x12 Advanced Framing (600mm o.c.) |
| **Interior Ceiling Drywall** | • Regular Gypsum Ceiling Board (DW3)<br>• Gypsum-Fiber Ceiling Board (DW4) |
| ***Implementation of optimization model ID code is discussed in further detail in Chapter 7. Furthermore, a full list of material properties, costs, and environmental data is provided in Appendix A of this report.** | |

Similar to the standard wall construction mentioned in Standard Wall Construction, the standard roof assembly requires a pre-combined set of rafter space insulation in order to simplify the simulation and optimization process by reducing the complexity of implicit EnergyPlus calculations and data extraction. Table 17 represents all the possible spacing, dimensions, and insulation type combinations that are considered for optimization.

Unlike wall assemblies, roof assemblies have deeper rafters and thus thicker roof insulation.

Table 17: List of stud spacing, rafter dimensions, and insulation type combinations considered for use in the optimization process.

| ID Code | Rafter Spacing (mm) | Rafter Dimensions (in.) | Insulation Type |
|---|---|---|---|
| **RFIN1** | 600 | 2x6 | Fiberglass |
| **RFIN2** | 600 | 2x6 | Blown Cell |
| **RFIN3** | 600 | 2x6 | Spray Foam |
| **RFIN4** | 600 | 2x8 | Fiberglass |
| **RFIN5** | 600 | 2x8 | Blown Cell |
| **RFIN6** | 600 | 2x8 | Spray Foam |
| **RFIN7** | 600 | 2x12 | Fiberglass |
| **RFIN8** | 600 | 2x12 | Blown Cell |
| **RFIN9** | 600 | 2x12 | Spray Foam |
| **RFIN10** | 400 | 2x6 | Fiberglass |
| **RFIN11** | 400 | 2x6 | Blown Cell |
| **RFIN12** | 400 | 2x6 | Spray Foam |
| **RFIN13** | 400 | 2x8 | Fiberglass |
| **RFIN14** | 400 | 2x8 | Blown Cell |
| **RFIN15** | 400 | 2x8 | Spray Foam |
| **RFIN16** | 400 | 2x12 | Fiberglass |
| **RFIN17** | 400 | 2x12 | Blown Cell |
| **RFIN18** | 400 | 2x12 | Spray Foam |

### 6.2.2 High-Performance Roof Construction

The high-performance roof assembly is fundamentally the same as the standard roof assembly with the exception to an additional layer of continuous insulation on the exterior face of the sheathing. The additional continuous insulation provides extra thermal performance in addition to a more air-tight building. Although Figure 11does not show any insulation between the rafters, there is indeed rafter-space insulation for the purpose of this research project. Furthermore, the crushed stone or gravel ballast shown is also not considered as a layer variable for the high-performance roof.

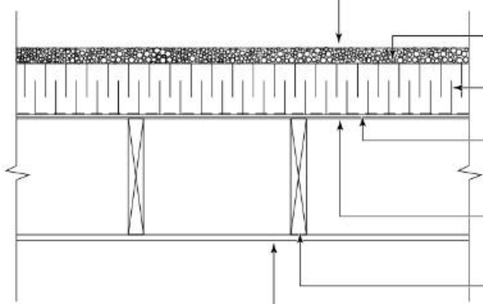



Figure 11: Cross-section view of a rafter-type flat roof assembly with commonly used components (Canada Mortage and Housing Corporation 2013).

In terms of the construction layers for the high-performance roof, the majority of construction layers are the same as the standard roof assembly except for the continuous rigid foam insulation on the exterior face of the roof sheathing. Table 18 shows all the exterior insulation that is considered for optimization of the roof assembly. There are numerous other types of exterior insulation available for application in a roof assembly, but the variables selected below are only a representation of commonly used materials.

Table 18: List of continuous exterior roof insulation selected for the optimization of the high-performance roof assembly.

| Roof Layer | Layer Variables |
|---|---|

| | |
|---|---|
| **Continuous Exterior Insulation** | • 12.7mm (0.5 in.) Isocyanurate (IN5*)<br>• 25.4mm (1.0 in.) Isocyanurate (IN6)<br>• 50.8mm (2.0 in.) Isocyanurate (IN7)<br>• 76.5mm (3.0 in.) Isocyanurate (IN8)<br>• 102mm (4.0 in.) Isocyanurate (IN9)<br>• 102mm (4.0 in.) EPS Rigid Foam Insulation (IN18)<br>• 127mm (5.0 in.) EPS Rigid Foam Insulation (IN19)<br>• 152mm (6.0 in.) EPS Rigid Foam Insulation (IN20)<br>• 102mm (4.0 in.) XPS Rigid Foam Insulation (IN24) |
| ***Implementation of optimization model ID code is discussed in further detail in Chapter 7. Furthermore, a full list of material properties, costs, and environmental data is provided in Appendix A of this report.** | |

## 6.3 Window Frame and Glazing Assemblies

Window assembly parameters are relatively simple compared to wall or roof assemblies because they essentially only consist of the window frame and glazing. Some windows have dividers that are either on-top of a single pane of glazing or dividing the window area into multiple smaller glazing panes. However, for the purpose of simplicity, this research will focus only on windows without dividers. A diagram of the window assembly within a wall being considered for optimization are shown in Figure 12. All window frame parameter variables (i.e. frame width, frame outside projection, and frame inside projection, frame solar absorptance, frame visible absorptance, and frame thermal emissivity) will be kept constant with exception to the frame conductance and frame-edge to center-of-glass ratio. The frame conductance and frame-edge to center-of-glass ratio depends on the window frame material under consideration and these values are referenced from the LBNL THERM and WINDOW programs.

Window glazing assemblies also have several variables pertaining to the number of glass-panes, such as double-glazed or triple-glazed, the window coating (or lack thereof), and the gas-filling between the panes of glass. The parameters and parameter variables mentioned are presented in Table 19 below.

Table 19: List of window frame parameters and parameter variables considered for optimization.

| Window Parameters | Parameter Variables |
|---|---|
| **Window Frame** | • Solid Wood (WF1*)<br>• Vinyl Clad Wood Core (WF2)<br>• Aluminum (WF3)<br>• Vinyl (WF4) |
| **Window Glazing** | • Double-Glazed, Non-Coated, Air-Filled (GZ1)<br>• Double-Glazed, Low-E Coated, Air-Filled (GZ2)<br>• Double-Glazed, Low-E Coated, Argon-Filled (GZ3)<br>• Triple-Glazed, Non-Coated, Air-Filled (GZ4)<br>• Triple-Glazed, Low-E Coated, Air-Filled (GZ5)<br>• Triple-Glazed, Low-E Coated, Argon-Filled (GZ6) |
| ***Implementation of optimization model ID code is discussed in further detail in Chapter 7. Furthermore, a full list of material properties, costs, and environmental data is provided in Appendix G of this report.** | |

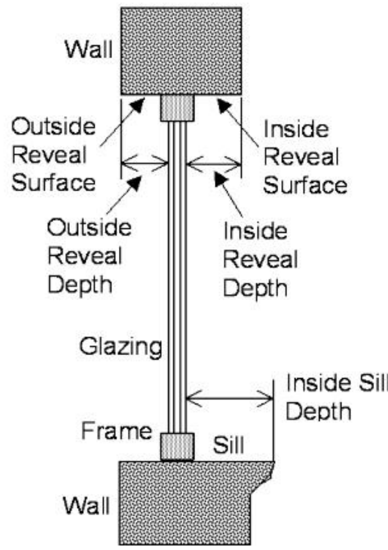
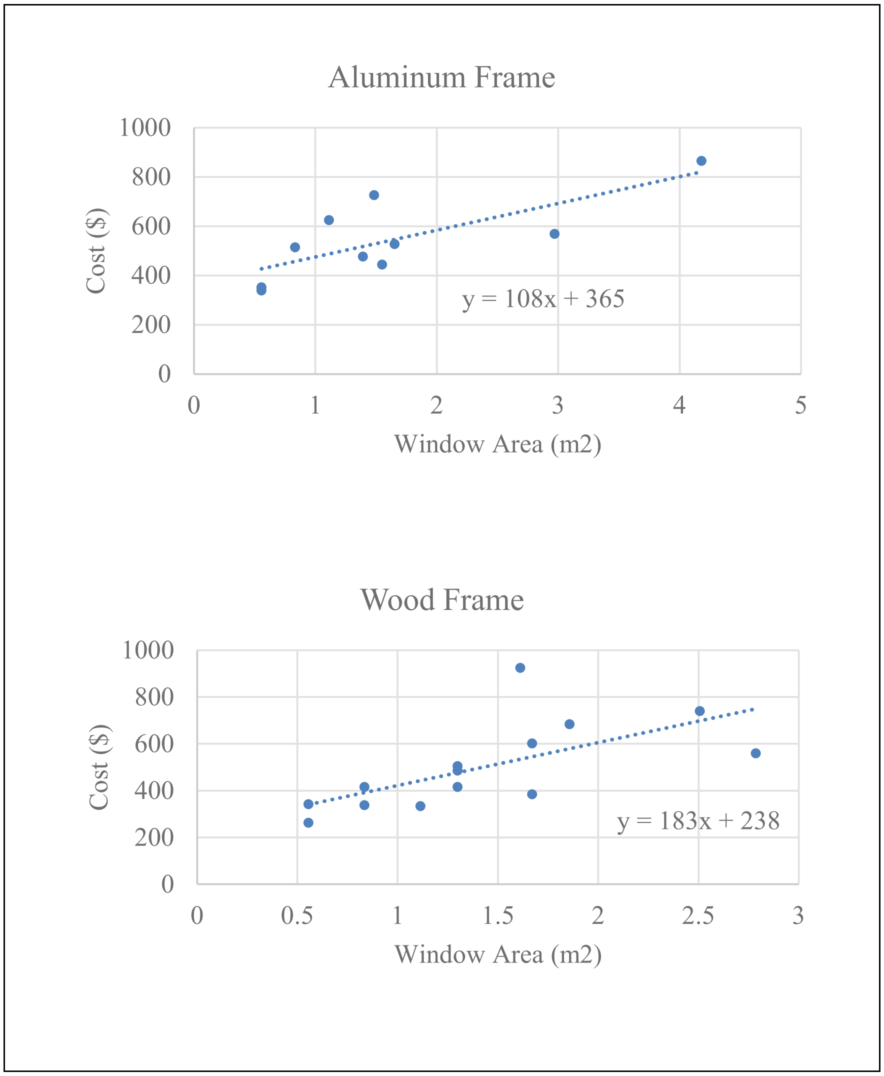



Figure 12: Cross-section view of a sample window assembly with parameters that are considered for optimization (LBNL 2013b).

Unlike wall or roof assembly variables that have cost and GWP data readily available that can be measured in unit costs, such as dollar-per-square meter, window frames and glazing do not have easily accessible data that can be directly applied to this research project. Therefore, the window frames and glazing component costs are calculated using a sample of windows costs of various types and sizes referenced from RSMeans. For instance, an aluminum window frame can have a significantly different cost depending on the size of the window, so the average unit cost can be estimated using a sample of aluminum window frames of different sizes. The method used to calculate the cost of aluminum window frames is shown in Figure 13, along with wood, vinyl-clad wood, and vinyl frames. The unit cost of the glazing is directly taken from RSMeans and can be seen in Window Database. Moreover, the unit environmental impact data is extracted from the ATHENA Impact Estimator using a similar method mentioned above. The

ATHENA Impact Estimator allows users to break down GWP data by materials and this data is provided in Appendix G.



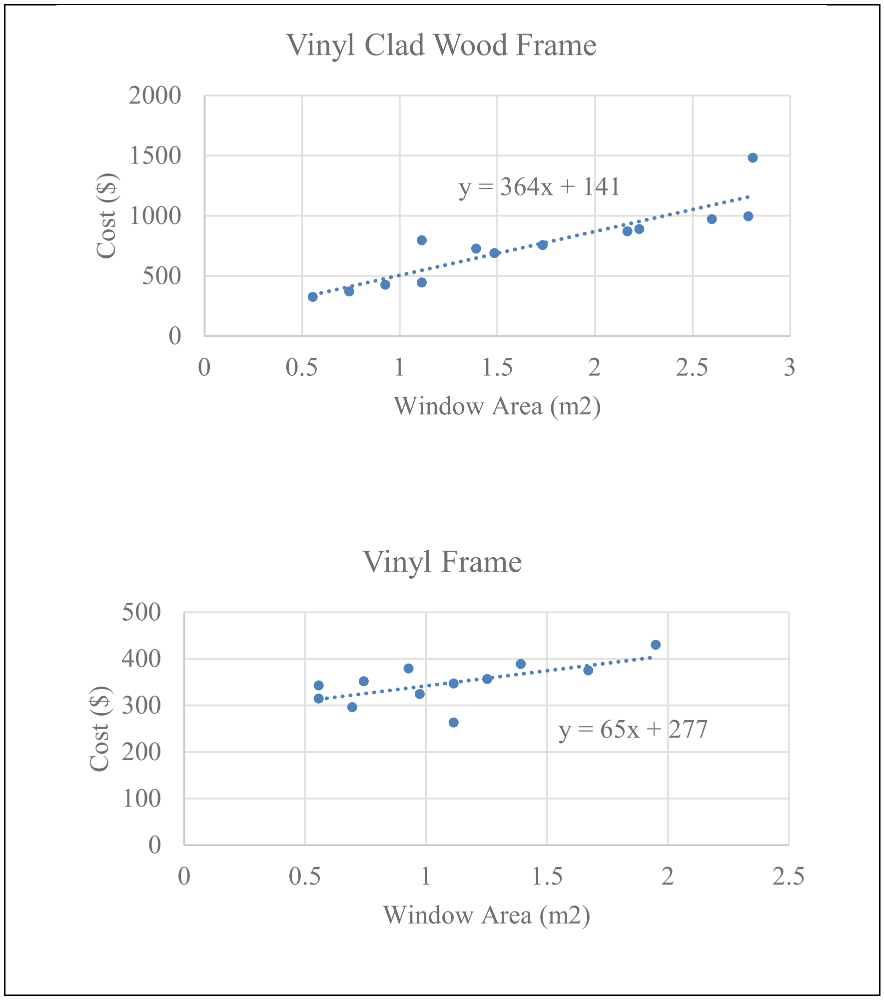



Figure 13: Four scatter-plots used to calculate the unit cost of the different window frame types.

## 6.4 Mechanical System (Air-Source Heat-Pump)

The mechanical system being considered for optimization is an air-sourced heat pump system with constant heating and cooling set-point temperatures. The heating set-point is set at 20 degrees Celsius and the cooling set-point is set at 27 degrees Celsius. Although this research does not consider individual mechanical components of the heat pump as parameter variables, the heating and cooling capacity is auto-sized and is thus considered a variable depending on the other building components being optimized. A full list of mechanical system parameters which are required for the simulation to run correctly is provided in Table 20. The majority of parameters are set at default values provided by EnergyPlus with exception to the heating and cooling set-point temperatures in addition to heating and cooling coefficient-of-performance (COP). These altered values are referenced from the Harmony House project outline provided by CMHC (2011). The BESTEST Case 600 will use default EnergyPlus values provided by Neymark & Nrel (2002).

Table 20: Example list of mechanical system parameters and default values used for Harmony House optimization.

| Mechanical System Parameter | Value |
|---|---:|
| Do Zone Sizing Calculation | Yes |
| Do System Sizing Calculation | Yes |
| Do Plant Sizing Calculation | No |
| Run Simulation for Sizing Periods | No |
| Run Simulation for Weather File Run Periods | Yes |
| Constant Heating Setpoint (C) | 20 |
| Constant Cooling Setpoint (C) | 27 |
| Outdoor Air Flow Rate per Person (m3/s) | 0.00944 |
| Cooling Supply Air Flow Rate (m3/s) | Auto-size |
| Heating Supply Air Flow Rate (m3/s) | Auto-size |
| No Load Supply Air Flow Rate (m3/s) | Auto-size |
| Cooling Coil Type | Single Speed DX Cooling Coil |
| Cooling Coil Availability Schedule Name | Off |
| Heat Pump Heating Coil Type | Single Speed DX Heat Pump |
| Heat Pump Heating Coil Availability Schedule Name | Custom Schedule |
| Heat Pump Heating Coil Rated Capacity (W) | 11722.84 |
| Heat Pump Heating Coil Rated COP | 2.75 |

Similar to the method used to calculate the cost of window frames, the cost of air-sourced heat-pump used for optimized is determined using chart shown in Figure 14. Using the relationship between cost and heat-pump heating output capacity, the total system cost can be estimated depending on the auto-sized heating capacity calculated by EnergyPlus.

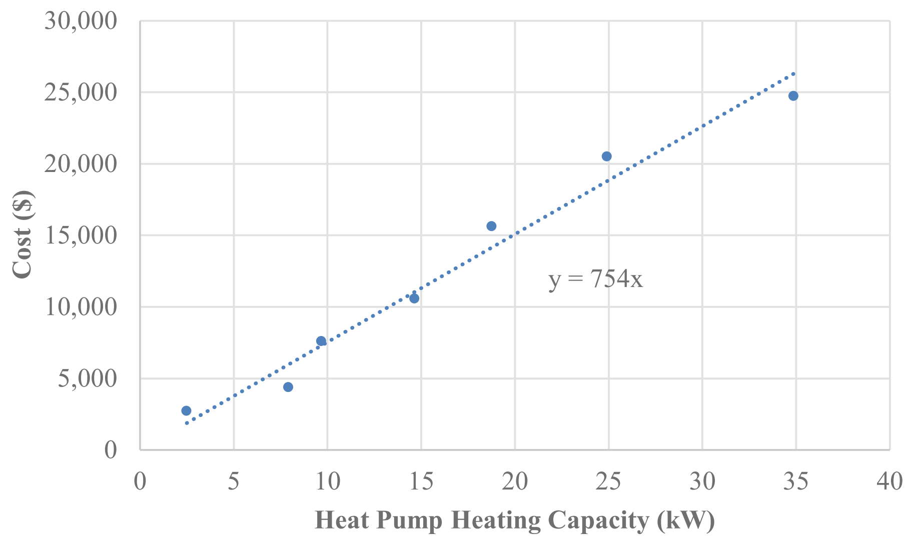



Figure 14: Scatter plot of the cost of air-sourced heat-pump systems relative to heating capacity.

The embodied environmental impact data is taken from several sources from the literature review. In particular, Shah et al. (2008) has done a comprehensive study on the embodied environmental impacts associated with the manufacturing of HVAC systems. For the purpose of this research, the embodied environmental impact of heat pumps will be calculated using the source mentioned above. In the study by Shah et al. (2008), a heat pump system with a system output capacity of 26.4 kW consists of approximately 101 kg of steel, 32 kg of galvanized steel, 17 kg of copper, and 6 kg of R-22 refrigerant. Now, using the embodied environment impact data (shown in Table 21) from several sources such as DEAM, GEMIS, and IIASI, the embodied environmental impact of the heat pump system can be calculated. Based on the collected data, the unit embodied GWP of heat pump systems is approximately 20.2 kg-CO2-eq/kW.

Table 21: List of primary materials, embodied carbon data, and their respective sources used to manufacture typical mechanical systems.

| Material Type | kg CO2 eq./kg-material | Source |
|---|---|---|
| **Aluminum** | 10 | DEAM database |
| **Copper** | 6.1 | DEAM database |
| **Steel** | 3.2 | DEAM database |
| **Steel (galvanized)** | 1.8-2.8 | GEMIS, IIASI |
| **HCFC R-22** | 3.0 | Johnson (2004) |

## 6.5 Summary

The variables are selected based on certain considerations such as its impact on the objective functions, users' control over the variables, the accessibility of variable data, etc. The concept of structure-related variables allow implicit variables to be defined and for system compatibility between enclosure types. Moreover, all variables are considered as discrete and are constrained by pre-determined parameters in order to maintain a manageable design space. Variables are also flexible and can be changed by the user depending on the purpose and preference.

# Chapter 7 Simulation Environment

This chapter introduces the components of the simulation-based optimization system; mainly the simulation program, optimizer program, database, and the input and output files. The simulation environment is presented in the first section to show the relationship and progression between the components. Detailed description of each component and assumptions made for each will be presented in the following sections. Following a detailed description of each core component, a detailed step-based description is also provided for the overall environment.

## 7.1 Simulation Environment Introduction

There are three fundamental forms of simulation-based optimization systems: external simulation, internal simulation, and hybrid external/internal simulation. An external simulation interface uses a translator to communicate between the energy simulation program and the optimizer. An internal simulation interface is used when the energy simulation program and optimizer are programmed simultaneously. In other words, the energy simulation program interacts with the optimizer directly without a translator, and this typically reduces computing resource requirement. The third system employs both internal and external communication protocols between the energy simulator and optimization program, which is only used when multiple programs with different communication protocols are required (Wang 2005). Fortunately, jEPlus+EA provides an integrated communications protocol that imports and exports EnergyPlus input and output files directly without a separate external interface.

The core of the optimization environment requires a close integration and synchronization between three distinct components: the energy simulation program, the optimization program, and the input/output files. Each component serves a unique but essential purpose in the environment and requires careful integration in order to work. First, the energy simulation program, EnergyPlus, calculates the objective functions based on user-defined input and parameter configurations. Depending on the user's preference or intentions, the number of parameters and types of variables are determined. The number and type of objective functions is also dependent on the energy simulation program because objective functions cannot be determined if the energy simulation program does not provide the required outputs to determine the objective functions. Second, the optimization program, jEPlus+EA, processes the energy simulation outputs to optimize the objective functions. In this research, a genetic algorithm optimizes the energy simulation outputs to search for a set of optimal solutions. Last but not least, the input and output are files associated with the energy simulation and optimization programs that determine how the simulation is conducted. The direction and scope of optimization is determined by the input while the output allows users to interpret and analyze the results. For instance, the user can configure the input files to simulate different components of a building design, and the variables associated with the selected components can also be assigned. In addition, the database of material properties, costs, and environmental factors are included in the input files.

Figure 15 provides a visualization of the general workflow between the energy simulation program and the optimizer. The input files enter from the left hand side while the outputs are shown on the right hand side of the diagram. In the case of this research, the jEPlus output is then analyzed by the use of Microsoft Excel. More specifically, the jEPlus output can be converted into tables and graphs that are easier to understand.

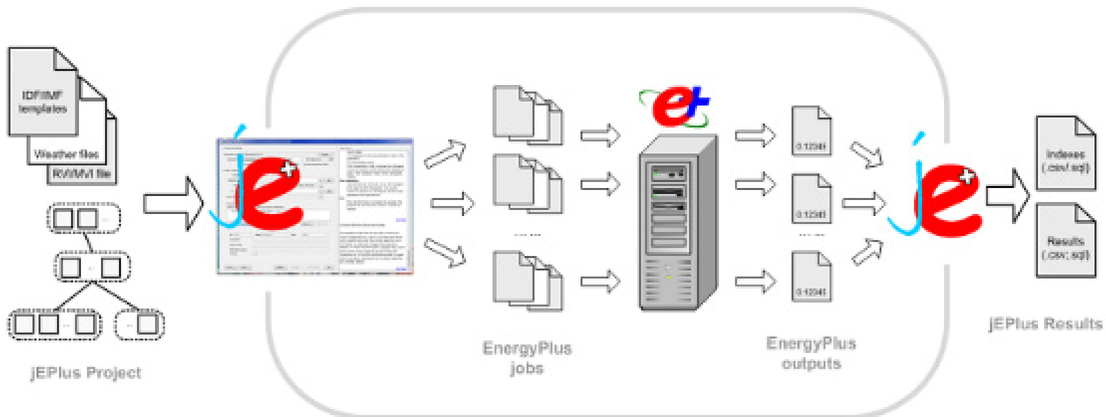



Figure 15: The basic workflow between jEPlus+EA and EnergyPlus (Yi Zhang 2013).

Figure 16 provides a more detailed visualization of the overall optimization process. The region of the graph enclosed in the EnergyPlus simulation box represents an internal process which runs each time the optimization algorithm calls for a new generation of solutions. Moreover, for each wall and roof type combination being optimized, the jEPlus+EA configuration files are reconfigured to optimize the appropriate design parameters. Following the successful multi-objective optimization of each wall and roof combinations mentioned in previous sections, the results are extracted and analyzed.

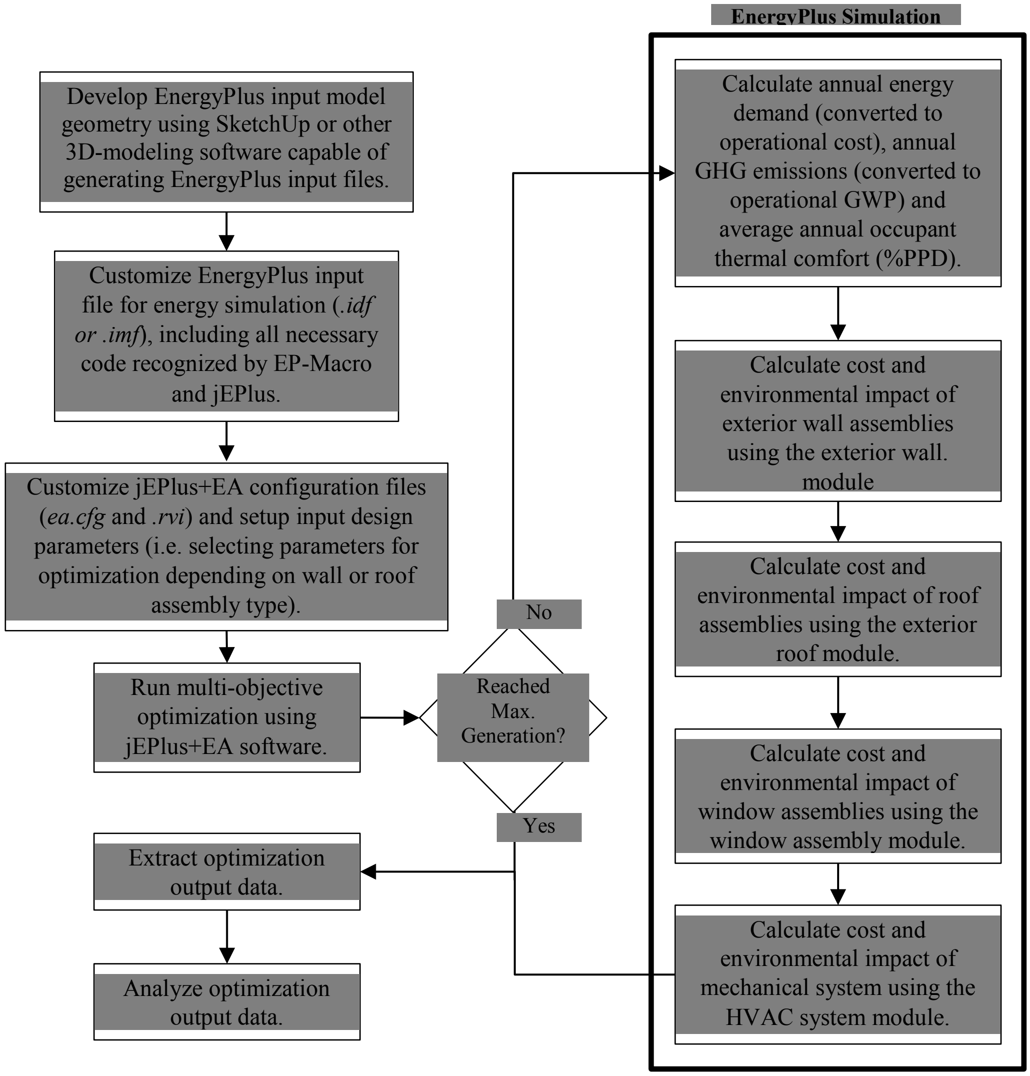



Figure 16: Flow-chart of the general multi-objective optimization process

## 7.2 Energy Simulation Program

### 7.2.1 EnergyPlus

EnergyPlus is an energy analysis and thermal load simulation program with roots in both *BLAST* and *DOE-2* simulation programs. The user defines the geometry and the materials used in the building enclosure and configure the mechanical system to a specific performance requirement. EnergyPlus calculates the heating and cooling loads necessary to maintain thermal set-points based on internal and external loads. The ultimate purpose of EnergyPlus is to provide users with a powerful simulation engine that is capable of modeling as many building systems and components as possible without the need to understand complex computer programming languages, as is often the case with older tools like *BLAST* and *DOE-2*. Moreover, the fast-paced development of HVAC systems requires constant updates and EnergyPlus provides users with the capability of adding additional modules that model complex and state-of-the-art systems without the need to understand the code for the entire program (UIUC 2013). Figure 17 shows the overall schematic for the modules included in EnergyPlus, and it also shows how each module is managed within the environment.

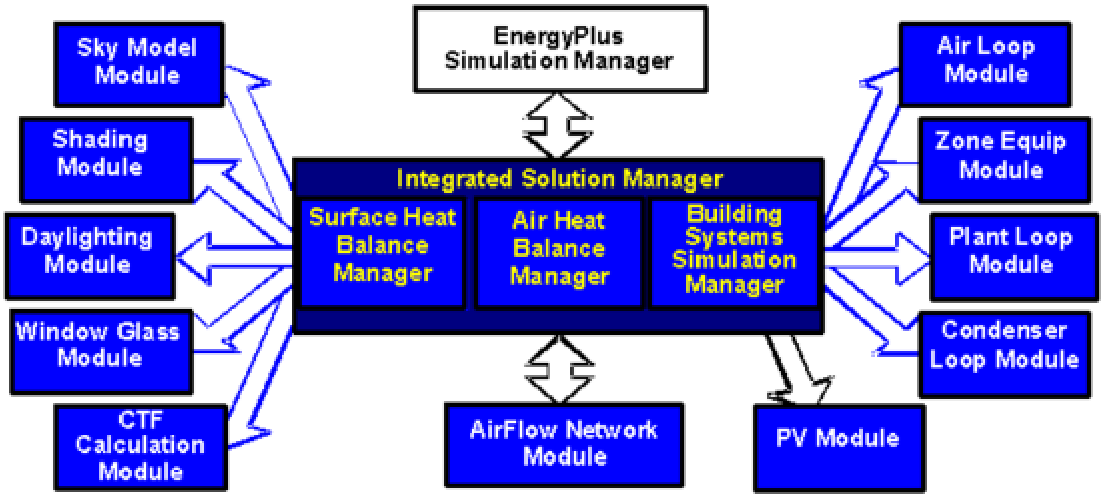



Figure 17: Schematic for the overall EnergyPlus module environment (LNBL 2012)

EnergyPlus is a powerful simulation engine that is capable of modeling complex building systems and components, but understanding the basics to run a simulation can be a difficult and time consuming learning processes for many users because there is no user-friendly graphical user interface (GUI). Despite this drawback, EnergyPlus inherits the following advantages:

- An integrated and simultaneous solutions manager that simulates building response as well as the primary and secondary building systems. All modules within the program are tightly coupled such that iterations can be easily performed when necessary (i.e. multi-objective optimization).
- A user-definable time step configuration for sub-hourly simulations, which allows the user to speed up simulation runs by increasing the interval between each time step.

- ASCII text based weather, input, and output files which are easy to modify and customize once the user is familiar with the object oriented codes associated with the program. With the combination of *EP-Macro*, a text based macro program, advanced simulations can be run for multiple alternatives without having to manually edit the weather and input files.
- A robust heat balance algorithm that allows for parallel calculation of radiant and convective effects for both interior and exterior surfaces at each user-defined time step. This increases model accuracy while decreasing simulation run times because of the simultaneous calculation method.
- A conduction transfer function algorithm that considers the transient effects of heat flow through elements such as walls, roofs, and floors. The effects of thermal mass on thermal lag can be accurately modeled using this algorithm and further improves the accuracy of the overall simulation results.
- Comprehensive thermal comfort models that predict occupant thermal comfort ratings depending on interior conditions such as temperature, activity, relative humidity, etc. This feature allows the user to consider thermal comfort as an objective function for optimization, which many other studies choose to neglect.
- Advanced fenestration calculations for windows, doors, and other openings that take into account the layer-by-layer heat balances of glazing systems. This algorithm accurately models both thermal and solar radiation effects on fenestration materials.
- On-site energy generation model that simulates renewable energy systems such as wind-turbines and photovoltaic panels. The efficiencies can be configured using a

simple or complex model depending on the design phase, and the energy produced can be incorporated into the energy demand network of the building to reduce the need for purchased utilities from external sources.

- An integrated LCA module that can sum the individual costs of building components and calculate the costs associated with energy consumption. This module can be modified, using *EP-Macro*, to take into account environmental effects such as GWP.

In addition to the advantages listed above, the most useful aspect of using EnergyPlus is the text based nature of the input files. EnergyPlus calls upon either an *.idf* or an *.imf* input file which serves as the inputs for simulation purposes. The input file is organized into "object classes" with each class representing a different input parameter for building simulation. For example, the "schedules" object class defines all variables associated with time related parameters such as HVAC or lighting schedules and the "materials" object class defines all materials to be used in the building model and it defines the physical properties of building related materials. Although the text based input file can be difficult to understand initially, but once the user is familiar with the object classes and its input parameters, then the building model can be defined with extreme detail. For instance, the HVAC system can be defined with as much or as few detail as required depending on the stage in the design phase. The HVAC system(s) can be built up manually using individual mechanical components such as boilers, ducts, and fan-coil units, or it can be defined using an HVAC template with much fewer required inputs. More details about creating EnergyPlus input files and implementing EP-Macro for advanced and integrated calculations for the purpose of optimization is provided in section 7.4

### 7.2.2 Whole Building Energy Simulation

The principle of heat balance is used to calculate the heating and cooling loads within each zone of the building. The summation of the total loads from internal loads, zone surfaces, outside air infiltration, and inter-zone air mixing must be balanced by the HVAC system capacity in order to maintain steady conditions within the zone. The heat balance equations must be solved simultaneous for every zone in the building at every time-step for a duration depending on the designer's preference. The zone air heat balance is represented by Eq. 4- 1 (LNBL 2012).

$$-Q_{system} = \sum_{i=1}^{N_{intloads}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) - C_z \frac{dT_z}{dt}$$

Eq. 4- 1

Where,

$\sum_{i=1}^{N_{intloads}} \dot{Q}_i$: Sum of convective internal loads within the zone.

$\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z)$: Sum of convective heat transfer from the zone surfaces.

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$: Sum of heat transfer due to interzone air mixing.

$\dot{m}_{inf} C_p (T_\infty - T_z)$: Sum of heat transfer due to infiltration from outside air.

$C_z \frac{dT_z}{dt}$: Transient energy stored in zone air.

$Q_{system}$: System load (W) required to satisfy zone air heat balance.

Where,

$$C_z = \rho_{air} C_p C_T \qquad \text{Eq. 4- 2}$$

Where,

$\rho_{air}$: Zone air density (kg/m$^3$).

$C_p$: Zone air specific heat capacity (kJ/kg-K).

$C_T$: Sensible heat capacity multiplier.

Calculating the heat balance on the zone surfaces requires further analysis because of both convective and radiative effects from winds and solar exposure. EnergyPlus takes advantage of the Conductive Transfer Function (CTF) module to calculate the heat flux through the zone surfaces. Eq. 4- 3 and Eq. 4- 4 represent the calculations required to determine heat flux on the outside and inside zone surfaces, respectively (LNBL 2012).

Inside surface heat flux:

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta} \qquad \text{Eq. 4- 3}$$

Outside surface heat flux:

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{i,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,t-j\delta} \qquad \text{Eq. 4- 4}$$

Where,

$X_j$: Outside CTF coefficient, j = 0,1,…, nz.

$Y_j$: Cross CTF coefficient, j = 0,1,…, nz.

$Z_j$: Inside CTF coefficient, j = 0,1,…, nz.

$\Phi_j$: Flux CTF coefficient, j = 0,1,…, nz.

$T_i$: Inside surface temperature (K).

$T_o$: Outside surface temperature (K).

$q''_{ko}$: Conduction heat flux on outside surface (W/m$^2$).

$q''_{ki}$: Conductiong heat flux on inside surface (W/m$^2$).

## 7.3 Optimization Program

### 7.3.1 jEPlus+EA

jEPlus is an open-sourced and free-of-charge software package that allows users to run parametric analysis on building designs by coupling itself with EnergyPlus or TRNSYS. By combining the parametric analysis tool with a genetic algorithm optimization algorithm, jEPlus+EA is developed. The software provides a simple yet highly efficient method for building optimization and can significantly reduce the time required for simulation when large design spaces are considered (Zhang 2012).

More specifically, jEPlus by itself is a parametric analysis tool which allows users to define parameters within an EnergyPlus model and generate large populations of different combinations of those parameters. The parametric tool alone is useful in finding a design solution space for projects with a small number of parameters. Unfortunately, the more parameters there are in the model, the larger the design space and thus impacting the practicality of the study. jEPlus creates a project file that stores the definition of parameters of a building model as well as the simulation execution settings. The design parameters are organized in a parameter tree structure as shown in Figure 18. Each level or row in the parameter tree increases the total number of possible parameter combinations because the number of alternatives within each parameter must be multiplied by the number of alternatives in all other parameters.

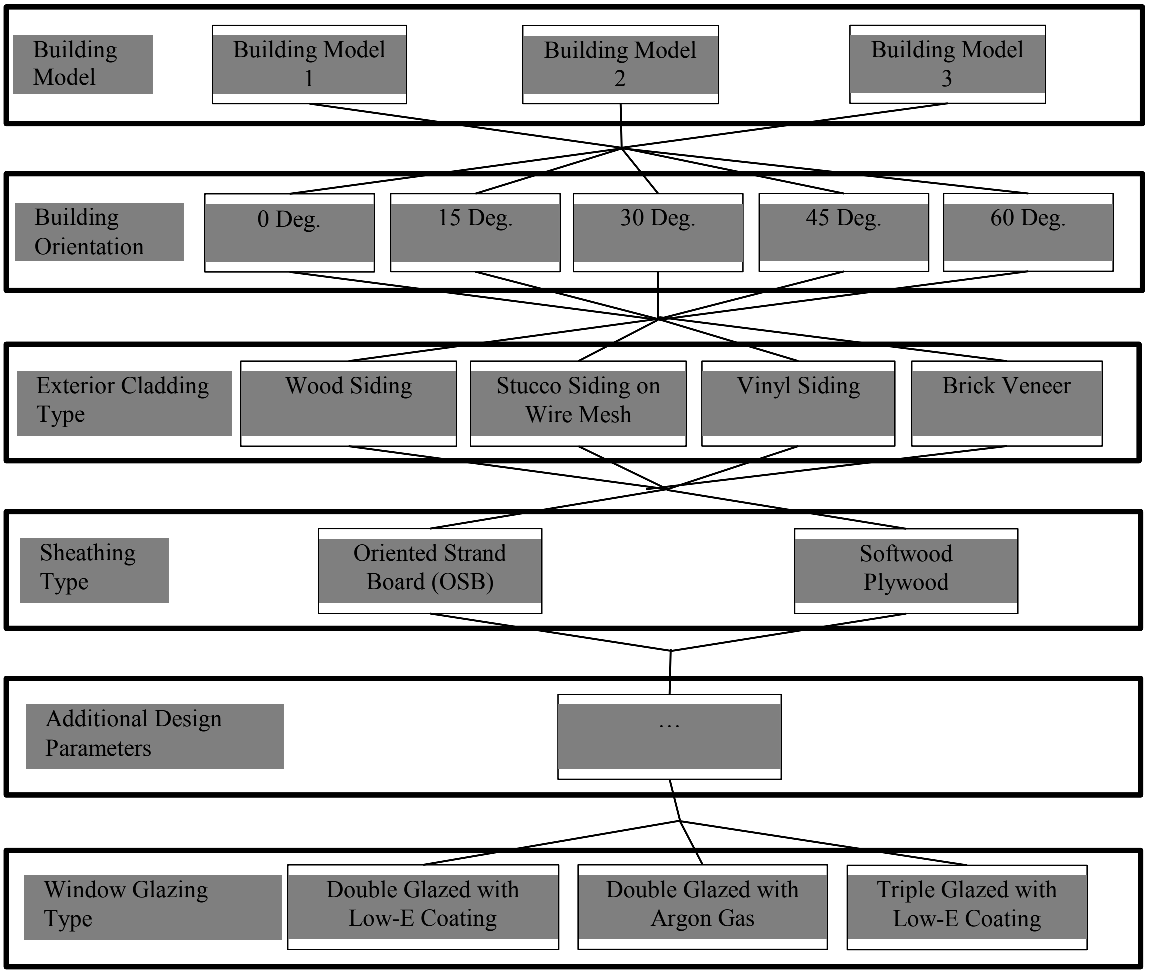



Figure 18: Example diagram of parameter tree to be used for multi-objective optimization.

Each path shown in Figure 18 represents one design solution, and by indexing of each alternative selected in each solution path, an integer chromosome is created for genetic algorithm optimization. Integer encoding has the additional benefit of being highly efficient and can represent the solution space accurately without redundancy or duplication in results. However, the user must still be careful when defining parameters to eliminate any possibility of redundancy or duplication (Zhang 2012). This parametric analysis tool can then be synchronized with a genetic algorithm to search for optimal solutions based on objective functions and constraints rather than searching for the entire solution space, which can take a long time.

## 7.4 Model Design Variables

Design variables refer to the parameters that can be changed during the optimization process in order to minimize the objective functions defined in the previous sections. The selection of building variables significantly affects the optimization results. For instance, choosing to exclude insulation and glazing type as variables can reduce the ability in finding the most optimal results in terms of the defined objective functions. Therefore, the variables must be carefully selected and consideration must be made for those selections. The main considerations and assumptions for selecting variables are discussed in detail within the first section, and then all variables considered for optimization are presented. Furthermore, the variable constraints are presented because of the nature of building variables; some are discrete while others are continuous (i.e. HVAC system type vs. building orientation).

### 7.4.1 Detailed Description of Variables

The following section presents the variables that are considered in the optimization environment. Variables are categorized by their function in the building design, mainly: structure, enclosure configuration, window configuration, and mechanical system related variables. All variables within the EnergyPlus input file that require optimization will be enclosed by a program specific symbol. For example, if exterior wall cladding is a parameter that the user wants to optimize, then the line of EnergyPlus input code will be replaced with @@cladding@@. Each building parameter that is considered for optimization typically has 3 inherent properties related to parameter naming, cost, and GWP factors; therefore, each parameter has 3 inherent property naming conventions. For instance, the cost variable for the cladding parameter mentioned is represented by @@cladding_cost@@ and the environmental impact factor variables is represented by @@cladding_gwp@@. The same variable naming convention is applied to all building parameters selected for optimization.

#### *7.4.1.1 Building Geometry Related Variables*

**Building orientation** (*@@orientation@@*): represents the angle between true geographic north and the building north. The building north is indicated by taking one face of the building as a reference plane, which is indicated by the designer. The orientation is measured in degrees with clockwise direction being positive and is represented as a discrete variable (i.e. 0, 15, 30, 45, … n).

#### *7.4.1.2 Structure Related Variables*

Although structure related variables are present, they are implicitly calculated into enclosure variables and do not have a separate variable name. Even though there are different types of framing system types available, such as advanced 2x6 framing and. standard 2x4 framing, the economic, energy, and environmental impact effects are added into enclosure variables such as the insulation layer within a wall assembly. For example, the unit area cost ($/m2) of different types of framing (i.e. 400mm o.c. vs. 600mm o.c.

stud spacing) is added into the unit area cost of insulation layer materials that come in contact with the structural frame of a building. The same concept is also applied to the environmental impact of the framing materials.

The purpose of this implicit variable is to compare different framing methods and framing material types. Also, this variable ensures that there is continuity and compatibility between different enclosure sections. EnergyPlus does not allow different variations of layers between the same enclosure types. All wall assemblies within the same building, for example, shall have the same number of layers if they are to be interconnected.

**Exterior wall assembly type**

(*@@ewalltype@@*): a discrete variable defining the different wall assembly types that are available for optimization (i.e. advanced framing, standard framing, double stud framing, exterior insulated finishing system (EIFS), etc.). This variable dictates the configuration of individual wall assembly sub-layers.

**Roof assembly type**

(*@@rooftype@@*): a discrete variable representing the type of roof system used in the building design (i.e. vented cathedral roof, SIP, etc.). This variable dictates the configuration of individual roof assembly sub-layers.

#### 7.4.1.3 Enclosure Assembly Configuration Related Variables

The building enclosure system refers to opaque wall, floor, and roof systems. Windows are not considered a part of this category because it has slightly different modeling conventions and characteristics. A building enclosure system is composed of individual sub-layers that have different properties. The sub-layers can include cladding, insulation, sheathing, air cavity, or drywall, and each sub-layer is considered as a discrete variable. The configuration of sub-layers depends on the type of enclosure, and the enclosure type is also considered as a discrete variable. This research project includes the following enclosure configuration-related variables:

**Wall cladding type**

(*@@cladding@@|@@cladding_cost@@|@@cladding_gwp@@*): a discrete variable defining the different cladding materials suitable for residential purposes (i.e. face-brick, vinyl siding, wood siding, etc.). This variable is present in all wall assembly types.

**Exterior insulation type**

(*@@ext_ins@@|@@ext_ins_cost@@|@@ext_ins_gwp@@*): a discrete variable representing the different exterior applied insulation suitable for residential purposes (i.e. EPS, mineral wool, spray foam, etc.). This variable may or may not be used in the wall assembly depending on *@@ewalltype@@*.

**Wall sheathing type**

(*@@sheathing@@|@@sheathing_cost@@|@@sheathing_gwp@@*): a discrete variable representing the various sheathing materials that may be used in residential building construction (i.e. plywood, OSB, gypsum, etc.). This variable may or may not be used in the wall assembly depending on @@*ewalltype*@@.

**Wall stud space insulation**

(@@*stud_ins*@@|@@*stud_ins_cost*@@|@@*stud_ins_gwp*@@): a discrete variable representing insulation filled between the stud space for 2x4 or 2x6 framing (i.e. fiberglass batt, blown cellulose, spray foam, etc.). This variable is only called when @@*ewalltype*@@ uses 2x4 or 2x6 framing within the wall assembly.

**Drywall type**

(@@*wall_drywall*@@|@@*wall_drywall_cost*@@|@@*wall_drywall_gwp*@@): a discrete variable representing the type of drywall often used in the interior of a building (i.e. gypsum and gypsum-fiber). This variable is present in all wall assembly types.

**SIP wall type**

(@@*sip*@@|@@*sip_cost*@@|@@*sip_gwp*@@): a discrete variable representing various SIP wall system types which includes EPS insulation between a layer of OSB sheathing on both surfaces. This variable may or may not be used in the wall assembly depending on @@*ewalltype*@@.

**Roof shingle type**

(@@*shingles*@@|@@*shingles_cost*@@|@@*shingles_gwp*@@): a discrete variable representing the type of shingle used on the exterior surface of the roof assembly (i.e.

asphalt or steel panels). This variable may or may not be used in the wall assembly depending on *@@rooftype@@*.

**Roof rigid foam insulation type**

(*@@roof_rigid_ins@@|@@roof_rigid_ins_cost@@|@@roof_rigid_ins_gwp@@*): a discrete variable representing the rigid foam insulation types typically used in residential construction. This variable may or may not be used in the wall assembly depending on *@@rooftype@@*.

**Roof stud space insulation type**

(*@@roof_stud_ins@@|@@roof_stud_ins_cost@@|@@roof_stud_ins_gwp@@*): a discrete variable representing the types of batt insulation filled between roof joists. This variable may or may not be used in the wall assembly depending on *@@rooftype@@*.

#### *7.4.1.4 Window System Configuration Related Variables*

Window systems are similar to enclosure systems in that it also requires multiple sub-layers of material to create a glazing assembly. The difference is in the window framing assemblies which do not use a layer convention, but rather factors that calculate its thermal properties and how it affects the glazing area.

**Window frame type**

(@@*windowframetype*@@|@@*windowframetype_cost*@@|@@*windowframetype_gwp*@@): a discrete variable representing the material used for window frames (i.e. wood, vinyl, aluminum, etc.).

**Glazing system type**

(*@@glazingtype@@*|*@@glazingtype_cost@@*|*@@glazingtype_gwp@@*): a discrete variable representing the glazing system type used for the building design (i.e. double glazed, double glazed low-e coated, triple glazed, etc.).

#### *7.4.1.5 Mechanical System Related Variables*

HVAC equipment is a complex system that contains many implicit variables that affect the overall performance and characteristics of the system. For instance, changing the COP of the heating and cooling systems can drastically affect the amount of energy consumed by the building. Also, changing the temperature set points can affect how the mechanical systems behave in terms of energy consumption efficiency and operation frequency. Mechanical systems contain large amounts of interconnected systems such as wiring and ductwork, but only the main components of the HVAC system is considered as variables. In other words, only the main power-house of the HVAC system that provides the actually heating or cooling capabilities (i.e. heat pumps, air-conditioners, boilers, etc.) is considered as a variable that effect the optimization results. Other systems such as wiring and ductwork are assumed to be constant between the various alternatives.

**HVAC system type** (*@@hvactype@@*): a discrete variable that determines the type of HVAC system employed in the building (i.e. heat pump with gas furnace, air-conditioner with electric resistance heating, etc.).

### 7.4.2 Variable Constraints

All variables have some form of constraint, and this is to keep the building design space within a finite limit. Certain variables have designer applied constraints, while other have physical or market constraints (i.e. glazing system types). For the purpose of this research, all single variables are defined with selection constraints in order to reduce the total number of variable parameters.

Selection constraints apply to discrete variables and the value of the discrete variables are usually pre-determined by the user. For instance, the window glazing system type can be limited to three systems including double glazed air filled (GZ1), double glazed low-e coated air filled (GZ2), and double glazed low-e coated argon filled (GZ2), which is defined as:

$$@@glazingtype@@ \in \{GZ1, GZ2, GZ3\}$$

### 7.4.3 Assumptions for Selecting Variables

In the case of building optimization, there are discrete and continuous variables both used to describe a building design. Discrete parameters are those that have distinct variations such as glazing system type, wall structure type, or insulation type, and cannot be represented on a continuous scale due to physical and external constraints. Continuous variables usually represent physical properties or characteristics of a parameter. For instance, the building orientation can technically be fixed at any particular angle, between 0 and 360 degrees due north, based on the designer’s preference. The building can either face 0 degrees or 36.24 degrees from north, and there are theoretically no limitations.

However, even though some discrete variables cannot be continuous, all continuous variables can be discrete. Window area is an example where it can be a continuous function of area ($m^2$), but industry availability of window sizes forces this variable to be discrete depending on the manufacturer. For the purpose of this research, all variables are considered to be discrete in order to reduce the size of the design space.

The following assumptions are taken into consideration when selecting variables for this simulation-based optimization study:

1. Variables must be selected based on the scope of research defined in section 4.3. Since the scope is limited to enclosure and mechanical system related parameters, variables that can be changed by the designer at an early phase are selected. Some variables such as photovoltaic systems and window shading devices are considered as well.
2. Only variables that can be changed by the designer are considered because some parameters are beyond the control of the designer. Examples include: building location, discount rate, escalation rate, weather, etc.
3. Variables that have significant impact on the objective functions are selected, and they are based on user experience, guidelines, and sensitivity analysis. For instance, vapor barrier materials are not considered because this research does not take into account the effects of moisture on the thermal performance of the building.
4. Variables that provide designers with explicit information are selected because some variables with implicit value make it difficult for designers to find the true

optimal solution. Even though the thermal resistance of an entire enclosure can be selected as a variable, the optimal solution does not provide the designer with useful information on what materials to use. Hence, it is more efficient and useful to select material layers within the enclosure as variables.

5. Only variables that can be modeled in the energy simulation program (EnergyPlus) are selected. Even though EnergyPlus is a powerful simulation tool capable of modeling a wide range of building parameters, there are still limitations. For instance, EnergyPlus is capable of modeling many types of HVAC systems, but cannot model its effect on indoor air quality.
6. Variables are also selected based on the availability of information. For example, the information on the cost and environmental impacts of certain materials are inaccessible or require further investment to acquire. Since information regarding material properties, cost, and environmental impact of any particular material is frequently taken from various sources, there is often a mismatch between information of the same material or system. Thus, only variables with consistent and accurate information from various sources are selected.

## 7.5 Input and Output

The input and output are files or programs that act as the interface between the user and the optimization system. The input and output files allow the user to customize the simulation program and the optimizer. More specifically, the user has the ability to control which parameters are used for optimization, what the constraints for each parameter are, and how the optimization algorithm operates. The follow section provides a detailed description of the input and output text files.

### 7.5.1 Input Files for Simulation

There are a number of files associated with the input configuration necessary for EnergyPlus simulations. The most important files are the input data file (*.idf*) and the input macro files (*.imf*). The difference between the *.idf* and *.imf* input files is that the *.imf* extension is used for input files containing macro programs. The macro programs are run by an external EnergyPlus program called EP-Macro (programming instructions can be found in LBNL (2013)), which reads the *.imf* file and processes the macro code within the file. Regardless of whether the user wants to utilize macro processes or not, the main *.idf* or *.imf* file shall be named after the project identification (i.e. *"project_name".idf* or *"project_name".imf*). Furthermore, the complete EnergyPlus input files used for optimization of the BESTEST Case 600 and the Harmony House case can be found in Appendix H and Appendix N.

The EP-Macro code for the main *.imf* input file is entered prior to any EnergyPlus input code because EP-Macro must read the macro instructions in order to commence the macro functions. The initial EP-Macro code required for EnergyPlus to calculate macro processes is shown in Figure 19. The first step is to define the file path to where all the macro modules are located (i.e. "##fileprefix K:\Optimization Project\include"). The macro modules refer to individual EP-Macro enabled EnergyPlus input for optimization. For example, the module that combines the layer variables, calculates the life-cycle cost, and determines the life-cycle GWP for exterior wall assemblies can be found in the file named “EWallType.imf.” Optimization modules using EP-Macro are further discussed in Optimization Modules of this Report.

Figure 19 also shows the macro code necessary to configure the individual layer variables within each wall, roof, or window type. “##set1 ewalltype @@ewalltype@@” tells EP-Macro to set the appropriate exterior wall type for optimization using the options provided in the parameter “@@ewalltype@@”, but before any exterior wall type can be selected, the user must first call upon the exterior wall type module by using “##include EWallType.imf.” All other parameters mentioned in Chapter 6, such as roof assembly types and window types, can be selected in the same manner described above. Mechanical systems can also be called upon using EP-Macro but it refers to entire mechanical systems with system parameters (i.e. heating set-points, cooling set-points, system capacity, etc.) rather than individual layer variables. Again, further descriptions for the optimization modules are provided in Optimization Modules of this Report.

```
##fileprefix K:\Optimization Project\include

!=====Macro Definitions=====
!====Exterior Wall=====
##set1 ewalltype @@ewalltype@@

##set1 CLADDING @@cladding@@
##set1 SHEATHING @@sheathing@@
##set1 WALL_DRYWALL @@wall_drywall@@
##set1 EXT_INS @@ext_ins@@
##set1 STUD_INS @@stud_ins@@
##set1 SIP @@sip@@
##set1 AGICF @@agicf@@

##set1 CLADDING_COST @@cladding_cost@@
##set1 SHEATHING_COST @@sheathing_cost@@
##set1 WALL_DRYWALL_COST @@wall_drywall_cost@@
##set1 EXT_INS_COST @@ext_ins_cost@@
##set1 STUD_INS_COST @@stud_ins_cost@@
##set1 SIP_COST @@sip_cost@@
##set1 AGICF_COST @@agicf_cost@@
```

```
##set1 CLADDING_GWP @@cladding_gwp@@
##set1 SHEATHING_GWP @@sheathing_gwp@@
##set1 WALL_DRYWALL_GWP @@wall_drywall_gwp@@
##set1 EXT_INS_GWP @@ext_ins_gwp@@
##set1 STUD_INS_GWP @@stud_ins_gwp@@
##set1 SIP_GWP @@sip_gwp@@
##set1 AGICF_GWP @@agicf_gwp@@

!====Window Systems====

##set1 WINDOW_FRAME @@windowframetype@@
##set1 GLAZING @@glazingtype@@

##set1 WINDOW_FRAME_COST @@windowframe_cost@@
##set1 GLAZING_COST @@glazingtype_cost@@

##set1 WINDOW_FRAME_GWP @@windowframe_gwp@@
##set1 GLAZING_GWP @@glazingtype_gwp@@

!====Roof Type====

##set1 rooftype @@rooftype@@

##set1 SHINGLES @@shingles@@
##set1 RIGID_INS @@roof_rigid_ins@@
##set1 RAFTER_INS @@roof_stud_ins@@
##set1 ROOF_DRYWALL @@roof_drywall@@
##set1 ROOF_SIP @@roof_sip@@

##set1 SHINGLES_COST @@shingles_cost@@
##set1 RIGID_INS_COST @@roof_rigid_ins_cost@@
##set1 RAFTER_INS_COST @@roof_stud_ins_cost@@
##set1 ROOF_DRYWALL_COST @@roof_drywall_cost@@
##set1 ROOF_SIP_COST @@roof_sip_cost@@

##set1 SHINGLES_GWP @@shingles_gwp@@
##set1 RIGID_INS_GWP @@roof_rigid_ins_gwp@@
##set1 RAFTER_INS_GWP @@roof_stud_ins_gwp@@
##set1 ROOF_DRYWALL_GWP @@roof_drywall_gwp@@
##set1 ROOF_SIP_GWP @@roof_sip_gwp@@

##include Materials.idf
##include EWallType.imf
##include RoofType.imf
##include WindowType.imf
##include DesignDay.idf
##include HVAC_@@hvactype@@.imf
```

Figure 19: EP-Macro input code to commence the optimization process.

It is important to note that depending on if EP-Macro is to be used or not, individual object classes of the main input file can be called upon externally or internally. For instance, all objects in the schedule, material, or construction class can be included in the main *.idf* at the cost of a larger input file, or the same object classes can be called upon externally using EP-Macro which reduces the size the main *.imf* file but results in numerous sub-files.

Each of the main EnergyPlus input files for optimization is associated with a weather file. The weather file typically has an *.epw* extension and it contains all data and information regarding the target location coordinates and elevation as well as typical weather data for each hour within a year. The weather or meteorological data defines the temperature, humidity, sky cover and various other meteorological data necessary for design load calculations. The weather file can be named after the project name or any other identification the user requires as long as the weather file is properly linked either using EP-Launch or jEPlus+EA.

With each successful simulation, there are hundreds of possible results outputs available for analysis. Therefore, a separate results visualization input file with extension *.rvi* is required to let EnergyPlus know exactly which result outputs need to be extracted. For the purpose of this research, the extracted results are used as the three major objective functions mentioned in Chapter 5. There are three visualization result types, applicable to building optimization, which EnergyPlus allows for extraction: variables, meters, and SQLite data. The *Output:Variable* object class is used to report results calculated by

EnergyPlus with a list of possible outputs listed in the *eplusout.rdd* file generated following first simulation run. An example of a results output defined by the *Output:Variable* object class is the outdoor dry bulb temperature averaged over a user defined time period (i.e. hour, month, or annual). The typical object class used to extract energy related results is the *Output:Meter* object which calculated the total amount of energy categorized into electricity, gas, and other common fuels types used in building according to different levels. For instance, the meters can be calculated at the facility, building, zone, system, and plant level. Furthermore, the meter outputs can be categorized into energy end use types, which breaks down the energy consumption report in terms of equipment and lighting. Last but not least, the *Output:SQLite* object tells EnergyPlus to create an external SQLite file that can be further processed using spreadsheets or SQLite software such as SQLite Manager (Reference & Input 2012).

```
!-Start EnergyPlus output extraction

eplusout.eso

eplusout.csv

FangerPPD ! c0

Carbon Equivalent:Facility !c1

0

!-End EnergyPlus output extraction

!-Start SQLite extraction

ConCost; Construction Cost [$]; select (select Value FROM TabularDataWithStrings WHERE
(ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and
TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and
Units='' and RowId=1))+(select Value FROM TabularDataWithStrings WHERE
(ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and
TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and
Units='' and RowId=3))+(select Value FROM TabularDataWithStrings WHERE
(ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and
```

```
TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=5))+(select Value FROM TabularDataWithStrings WHERE (ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=6))+(select Value FROM TabularDataWithStrings WHERE (ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=8))+(select Value FROM TabularDataWithStrings WHERE (ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=9))+(select Value FROM TabularDataWithStrings WHERE (ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=10)) !c2

GWP; Global Warming Potential [kg CO2 eq]; select(select Value FROM TabularDataWithStrings WHERE (ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=2))+(select Value FROM TabularDataWithStrings WHERE (ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=4))+(select Value FROM TabularDataWithStrings WHERE (ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=7))+(select Value FROM TabularDataWithStrings WHERE (ReportName='Construction Cost Estimate Summary' and ReportForString='Entire Facility' and TableName='Cost Line Item Details' and RowName='--' and ColumnName='SubTotal ~~$~~' and Units='' and RowId=11)) !c3

Electricity Purchased; Electricity Purchased [$]; select Value FROM TabularDataWithStrings WHERE (ReportName='Economics Results Summary Report' and ReportForString='Entire Facility' and TableName='Tariff Summary' and RowName='ELECTRICITYRATE' and ColumnName='Annual Cost (~~$~~)' and Units='' and RowId=1) ! c4

Electricity Sold; Electricity Sold [$]; select Value FROM TabularDataWithStrings WHERE (ReportName='Economics Results Summary Report' and ReportForString='Entire Facility' and TableName='Tariff Summary' and RowName='ELECTRICITYSOLD' and ColumnName='Annual Cost (~~$~~)' and Units='' and RowId=3) !c5

Gas Purchased; Gas Purchased [$]; select Value FROM TabularDataWithStrings WHERE (ReportName='Economics Results Summary Report' and ReportForString='Entire Facility' and TableName='Tariff Summary' and RowName='GASRATE' and ColumnName='Annual Cost (~~$~~)' and Units='' and RowId=2) ! c6

Gas; Natural Gas [kWh]; select Value FROM TabularDataWithStrings WHERE (ReportName='AnnualBuildingUtilityPerformanceSummary' and ReportForString='Entire Facility' and TableName='End Uses' and RowName='Total End Uses' and ColumnName='Natural Gas' and Units='kWh' and RowId=16) ! c7

!-End SQLite extraction

!-Start objectives calculations

Life Cycle Cost; NPV($); c2+c4*25.81+c6*25.81 ! Study Period=30 Years, Price Escalation Rate=4%,
```

```
Real Discount Rate=5% (Nominal Discount=4%, Inflation Rate=1%)

Life Cycle GWP; kgCO2-eq; c3+c1*30 ! Life Cycle GWP of initial investment

Occupant Thermal Comfort; Average-PPD; c0 ! Average annual thermal comfort

!-End objectives calculations
```

Figure 20: Example *rvi* results extract file that uses both native EnergyPlus extract language as well as *SQLite* results extraction

Figure 20 shows how the *.rvi* results extraction file extracts results and sets up optimization objectives. The first few lines of code between the comment lines "*!-Start EnergyPlus output extraction"* and "*!-End EnergyPlus*" *output extraction*" notifies EnergyPlus to extract certain output files (i.e. *FangerPPD* and *Carbon Equivalent:Facility*) and extract it into a new *.csv* file that can be processed by any spreadsheet program such as Microsoft Excel. The subsequent lines represent code between the comment lines "!-*Start SQLite extraction*" and "*!-End SQLite extraction*" signals the use of SQLite to extract very specific results output from the SQL file generated by EnergyPlus. For example, the subsequent SQL code following "*Electricity Purchased;…*" informs SQLite to output specific values related to the dollar amount of electricity that is demanded from the modeled building. In the case of construction cost and GWP extraction, each *rowId* refers to a particular value that is pre-calculated by EnergyPlus using EP-Macro. For example, if *rowId* is equal to 1, then it will extract the data pertaining to the total construction and material cost associated with the exterior wall. Table 22 shows an example of EnergyPlus output extracted from *eplustbl.csv* which can then be extracted by jEPlus for optimization purposes. To be specific, the formula used to calculate the total initial construction cost represented by the component *ConCost* is expressed through Eq. 5- 1. Moreover, Eq. 5- 2 is used to calculate the total initial GWP of construction and materials. These formulas can then be added to the operational cost in terms of purchased gas and electricity cost and GWP over a 30 year period to achieve LCC and LCGWP. Note that each *rowId* corresponds with the item name and quantities shown in Table 22.

Initial Construction and Material Cost = RowId-1 + RowId-3 + RowId-5 + RowId-6 + RowId-8 + RowId-9 + RowId-10

Eq. 5- 1

Initial Construction and Material GWP = RowId-2 + RowId-4 + RowId-7 + RowId-11

Eq. 5- 2

Table 22: Sample list of EnergyPlus output that are extracted by SQLite for optimization.

| RowId | Item Name | Quantity. | Units | Unit Cost ($) | SubTotal($) |
|---|---|---|---|---|---|
| **1** | Total Initial Cost of Exterior Wall Assembly | 211.25 | m2 | 77.39 | 16348.54 |
| **2** | Total Initial GWP of Exterior Wall Assembly | 211.25 | m2 | 24.14 | 5099.54 |
| **3** | Total Initial Cost of Roof Assembly | 224.83 | m2 | 136.67 | 30727.69 |
| **4** | Total Initial GWP of Roof Assembly | 224.83 | m2 | 68.77 | 15461.64 |
| **5** | Total Fixed Cost of Window System | 1 | Ea. | 65 | 65 |
| **6** | Total Initial Cost of Window System | 57.62 | m2 | 668.95 | 38546.4 |
| **7** | Total Initial GWP of Window System | 57.62 | m2 | 426.17 | 24556.87 |
| **8** | Total Cost of Mechanical System Based on Cooling Capacity | 8.35 | kW (total cooling capacity) | 154 | 1286.2 |
| **9** | Total Cost of Mechanical System Based on Cooling | 13.65 | kW (total heating | 26 | 354.92 |

| | | | | | |
|---|---|---|---|---|---|
| | | | capacity) | | |
| **10** | Total Fixed Cost of Mechanical System | 1 | Ea. | 1935 | 1935 |
| **11** | Total Fixed GWP of Mechanical System | 1 | Ea. | 465 | 465 |

The last section of the *rvi* file configures the output data created in the previous lines in such a way to create objectives for optimization. Essentially, the example in Figure 20 shows three objective functions that are considered for optimization: Life Cycle Cost, Life Cycle GWP, and Occupant Thermal Comfort. Each line of code that is responsible for extracting a particular value is followed by a parameter label starting with the letter "c" followed by the a number (i.e. c1, c2, c3, etc.). This label is to be used by the objective function calculation section of the *.rvi* file. Firstly, the LCC is calculated by adding parameters c2, c4, and c6. Parameter c2 refers to the initial construction cost of a particular optimized building and parameters c4 and c6 are multiplied by a uniform present value factor that converts the annual dollar amount of electricity and gas purchased into LCC over 30 years with a price escalation rate of 4% and a real discount rate of 5% (nominal discount rate = 4% and inflation rate = 1%). The uniform present factor can be calculated using Eq. 3- 12. Secondly, the LCGWP can be calculated by adding parameters c3 (GWP of initial construction materials) and c1 (carbon equivalent emissions of building operations), where parameter c1 is multiple by 30 years. Lastly, parameter c0 does not need to be added to any other parameter, nor does it require a modification factor, because EnergyPlus calculates the occupant thermal comfort internally using the Fanger-PPD model presented in Occupant Thermal Comfort Rating of this Report.

### 7.5.2 Input Files for Optimization

There are several input files required for the optimizer to run properly. First, the optimization program requires the main jEPlus+EA project file with extension (*jep*). The (*jep*) is automatically generated within the same project folder as the *idf/imf* file when a new jEPlus project is created. (*jep*) is a java file that links the weather file (*epw*) and results extraction file (*rvi*) to the main (*idf/imf*) file, which is necessary for a successful EnergyPlus simulation. The (*jep*) file also defines the parameters and the variables within each parameter using a parameter tree.

In terms of configuring the optimizer to suit the optimization problem, the user needs to access the jEPlus+EA optimizer configuration file *ea.cfg*. show in Figure 21. This is a text based file that permits the user to change specific settings related to the genetic algorithm. For instance, the user can set the crossover and mutation rate (0.0-1.0), population size (0-9999), maximum number of generations (0-9999), and various other output log file related settings. It is important that the configuration file be resaved once any changes are made in order for the settings to take effect in subsequent simulations. The full list of optimization software parameters and their default values can be seen in Appendix H.

```
##########################################################################
# GA engine settings file
##########################################################################
# Default GA settings
        GAengine.PMutation = 0.2
        GAengine.PCrossover =0.8
        # Percent of population to be updated in each generation.
        # This parameter is ignored if elitism is used
        GAengine.PPopReplace = 0.95
        GAengine.PopSize = 50
```

```
        GAengine.MaxPops = 500
...
# Output and Log Files
        GAengine.OutputFolder = K:\Output
        GAengine.WriteLogFile = false
        GAengine.LogFileName = GAcore.log
        GAengine.SaveSnapShots = false
        GAengine.SnapShotsGap = 1
        GAengine.SaveProgress = false
        GAengine.ProgressFile = GA_Progress.sco
        GAengine.SaveFamilyStat = false
        GAengine.FamilyStatDumpDir = dump
        GAengine.SaveOpStat = false
        GAengine.OpStatFile = OpStat.sco
        GAengine.SavePopStat = false
        GAengine.PopStatFile = GA_PopStat.sta
        GAengine.SaveEliteList = false
        GAengine.EliteListFile = EliteList.sco
# End of settings
```

Figure 21: jEPlus+EA configuration file that allows users to customize the optimization parameters.

### 7.5.3 Optimization Modules

In addition to using individual input parameters in the main simulation input file as design variables, entire systems can be considered as variables as well. Walls, roofs, floors, and HVAC systems can be considered as a design alternative altogether rather than considering individual construction variables such as insulation thickness or a single HVAC parameter such as the COP. However, in order to include entire systems as a design alternative for optimization, EP-Macro must be used to create external *imf* files. The external *imf* files can be considered as individual modules and is highly customizable according to the user's required study objectives. In this case of this research, the objectives are defined in Chapter 5.

The external modules can be included in the main simulation file by calling upon the external *imf* file. For example, an external file that includes design alternatives for window systems called *windowtype.imf* can be included in the main simulation file by adding the following lines of code:

```
##fileprefix C:\"user_defined_file_path"\

##set1 windowtype @@windowtype@@

##include windowtype.imf
```

Figure 22: EP-Macro code that calls on external window type module and defines the *jEPlus* readable variables to control the external module

The reason the alternative modules are called upon externally is to reduce the complexity and size of *"project_name.imf*." The modules simplify the process required to add or remove design alternatives without having to edit the *"project_name".imf* file itself substantially. In Figure 22, for example, "*##include windowtype.imf"* can be removed by adding the "*!"* symbol before that line of code, which turns that line into a comment and removes the module. The same process can be applied to any module, such as wall assembly types, roof assembly types, or HVAC system types. The individual modules are presented in the following sections.

#### *7.5.3.1 Exterior Wall Assembly Module*

Depending on the wall type selected by the genetic algorithm, EP-Macro is called upon to select the appropriate EnergyPlus *Construction* and *ComponentCost:LineItem* code. The

*Construction* components determine the configuration of individual wall layers depending on the wall assembly type selected. The *ComponentCost:LineItem* components are used to calculate the total initial construction cost and total initial GWP based on the wall assembly selected. Figure 23 shows the complete exterior wall assembly module for all wall types considered for this research and it also shows the *Construction* and *ComponentCost:LineItem* EnergyPlus components. The module (*EWallType.imf*) uses an if-loop to determine which *Construction* and *ComponentCost:LineItem* to use. For instance, if the genetic algorithm from jEPlus+EA selects a double-stud wall assembly to optimize, the parameter variable called "DOUBLE_STUD" will be inserted into parameter input @@ewalltype@@ (converted into *ewalltype[]* once in EP-Macro mode) within the main project file. Once this is done, EP-Macro will then know which *Construction* and *ComponentCost:LineItem* components to use for optimization. All other *Construction* and *ComponentCost:LineItem* components shown under other wall types will not be imported into the main EnergyPlus simulation file, and is thus not considered for optimization.

```
##if #[ewalltype[] eqs SPLIT_INSULATION]

        Construction,
        ewalltype[],
        CLADDING[],
        AL1,
        EXT_INS[],
        SHEATHING[],
        STUD_INS[],
        WALL_DRYWALL[];

        ComponentCost:LineItem,
        Total Cost of Exterior Wall,
        ,
        Construction,
        ewalltype[],
        ,
```

```
	,
	#[#[#[#[CLADDING_COST[] + EXT_INS_COST[]] + SHEATHING_COST[]] +
STUD_INS_COST[]] + WALL_DRYWALL_COST[]];

	ComponentCost:LineItem,
	Total GWP of Exterior Wall,
	,
	Construction,
	ewalltype[],
	,
	,
	#[#[#[#[CLADDING_GWP[] + EXT_INS_GWP[]] + SHEATHING_GWP[]] +
STUD_INS_GWP[]] + WALL_DRYWALL_GWP[]];

##elseif #[ewalltype[] eqs DOUBLE_STUD]

	Construction,
	ewalltype[],
	CLADDING[],
	AL1,
	SHEATHING[],
	STUD_INS[],
	STUD_INS[],
	WALL_DRYWALL[];

	ComponentCost:LineItem,
	Total Cost of Exterior Wall,
	,
	Construction,
	ewalltype[],
	,
	,
	#[#[#[#[CLADDING_COST[] + STUD_INS_COST[]] + SHEATHING_COST[]] +
STUD_INS_COST[]] + WALL_DRYWALL_COST[]];

	ComponentCost:LineItem,
	Total GWP of Exterior Wall,
	,
	Construction,
	ewalltype[],
	,
	,
	#[#[#[#[CLADDING_GWP[] + STUD_INS_GWP[]] + SHEATHING_GWP[]] +
STUD_INS_GWP[]] + WALL_DRYWALL_GWP[]];

##elseif #[ewalltype[] eqs STANDARD_WALL]

	Construction,
	ewalltype[],
	CLADDING[],
	AL1,
	SHEATHING[],
	STUD_INS[],
	WALL_DRYWALL[];
```

```
        ComponentCost:LineItem,
        Total Cost of Exterior Wall,
        ,
        Construction,
        ewalltype[],
        ,
        ,
        #[#[#[CLADDING_COST[] + SHEATHING_COST[]] + STUD_INS_COST[]] +
WALL_DRYWALL_COST[]];

        ComponentCost:LineItem,
        Total GWP of Exterior Wall,
        ,
        Construction,
        ewalltype[],
        ,
        ,
        #[#[#[CLADDING_GWP[] + SHEATHING_GWP[]] + STUD_INS_GWP[]] +
WALL_DRYWALL_GWP[]];

##elseif #[ewalltype[] eqs SIP]

        Construction,
        ewalltype[],
        CLADDING[],
        AL1,
        EXT_INS[],
        WS3,
        SIP[],
        WS3,
        WALL_DRYWALL[];

        ComponentCost:LineItem,
        Total Cost of Exterior Wall,
        ,
        Construction,
        ewalltype[],
        ,
        ,
        #[#[#[CLADDING_COST[] + SIP_COST[]] + WALL_DRYWALL_COST[]] +
EXT_INS_COST[]];

        ComponentCost:LineItem,
        Total GWP of Exterior Wall,
        ,
        Construction,
        ewalltype[],
        ,
        ,
        #[#[#[CLADDING_GWP[] + SIP_GWP[]] + WALL_DRYWALL_GWP[]] +
EXT_INS_GWP[]];

##elseif #[ewalltype[] eqs AGICF]
```

```
        Construction,
        ewalltype[],
        CLADDING[],
        IN16,
        AGICF[],
        IN16,
        WALL_DRYWALL[];

        ComponentCost:LineItem,
        Total Cost of Exterior Wall,
        ,
        Construction,
        ewalltype[],
        ,
        ,
        #[#[#[CLADDING_COST[] + SHEATHING_COST[]] + AGICF_COST[]] +
WALL_DRYWALL_COST[]];

        ComponentCost:LineItem,
        Total GWP of Exterior Wall,
        ,
        Construction,
        ewalltype[],
        ,
        ,
        #[#[#[CLADDING_GWP[] + SHEATHING_GWP[]] + AGICF_GWP[]] +
WALL_DRYWALL_GWP[]];

##else
##endif
```

Figure 23: EnergyPlus/EP-Macro input code for the exterior wall assembly module.

#### *7.5.3.2 Exterior Roof Assembly Module*

The roof assembly module (*RoofType.imf*) is very similar to the exterior wall assembly module in that it uses the same if-loop statements to determine which roof assemblies is to be select for optimization based on the GA (refer to Appendix I). However, instead of the parameter @@ewalltype@@, the roof assembly module uses the parameter @@rooftype@@, which is converted to rooftype[] so it can be read by EP-Macro. The *Construction* and *ComponentCost:LineItem* components shown in Appendix I behaves in the same manner as in the exterior wall assembly module an EP-Macro will process this input code in the same way. However, unlike the exterior wall assembly module, the roof assembly module is dependent on the exterior wall assembly module and not vice-versa. The reason is that if the optimizer decides to select an SIP system for the exterior walls, the typical method is to use an SIP roof as well. Therefore, the roof assembly module reflects this behavior by using a nested if-loop to select the roof assembly. If the GA optimizer selects an SIP wall assembly, then the roof module will take that information and restrict the roof assembly module to only select an SIP roof; otherwise, the roof assembly module will allow the selection of either a standard or high-performance roof as mentioned in Standard and High-Performance Roof Assemblies.

#### *7.5.3.3 Window Assembly Module*

The window assembly module (*WindowType.imf*) is slightly more complex than both the exterior wall assembly and roof assembly modules because the glazing type is dependent on the window frame type. The reason is that the overall performance of the window assembly is dependent on both the window frame and the glazing type that is selected for optimization. Similar to the roof assembly module, the window assembly module uses a nested if-loop to determine the complete window system as shown in Figure 24 (refer to Appendix J for window module EP-Macro input code). The EP-Macro input code simply expresses the relationship between window frames and glazing types. For each of the 4 window frame types mentioned in section 6.3, there are 6 glazing types, which results in a total of 24 window frame and glazing type combinations that make up the overall window assembly.

In terms of calculating the cost and GWP of the window assemblies, the components *Construction* and *ComponentCost:LineItem* behave in the same way as with the exterior wall assembly module and the roof assembly module. The difference is in the *WindowProperty:FrameAndDivider* component, which defines the window frame thickness and width in addition to its thermal properties depending on which window frame type is selected.

```
##if #[WINDOW_FRAME[] eqs WF1]

##if #[GLAZING[] eqs GZ1]
        Construction,
        GZ1,
        Clear,
        Air,
        Clear;

        WindowProperty:FrameAndDivider,
        Wood,
        0.110,
        ,,
        1.73,
        1.08,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , , ;
##elseif #[GLAZING[] eqs GZ2]
        Construction,
        GZ2,
        LowE_Out,
        Air,
        Clear;

        WindowProperty:FrameAndDivider,
        Wood,
        0.110,
        ,,
        1.73,
        1.17,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , , ;
…
##else
        Construction,
        GZ6,
        Clear,
        Argon,
        LowE_Out,
        Argon,
        LowE_In;

        WindowProperty:FrameAndDivider,
        Wood,
        0.110,
        ,,
        1.73,
        1.50,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , , ;
##endif
```

```
ComponentCost:LineItem,
        Total Cost of Window System,
        ,
        General,
        WoodFrame,
        , , , , , ,
        238,
        ,
        1;

        ComponentCost:LineItem,
        Total Cost of Window System,
        ,
        Construction,
        GLAZING[],
        ,,
        #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

        ComponentCost:LineItem,
        Total GWP of Window System,
        ,
        Construction,
        GLAZING[],
        , ,
        #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];
…
```

Figure 24: Sample of EnergyPlus/EP-Macro input code for the window assembly module.

#### *7.5.3.4 Mechanical System Module*

Unlike the three modules presented in the previous sections, the mechanical system or HVAC module (*HVAC_AC_ELEC.imf*) does not have any *Construction* components or if-loops for internal calculation. However, there are still *ComponentCost:LineItem* components that calculate the initial construction and material costs and GWP. The HVAC module represents an entire section of code necessary to define the mechanical system that will be used for optimization, and a condensed sample code is shown in Figure 25. The mechanical system module shown below is also representative of actual parameters used for the optimization of the validation and case study model, the majority of which are default EnergyPlus inputs.

Although the scope of work of this research limits the HVAC to just an air-sourced heat pump, there are still numerous variables that require optimizing. For instance, the HVAC heating or cooling capacity requires optimizing depending on the building enclosure components that are optimized in the other modules. Since EnergyPlus provides an auto-sizing function for the HVAC system, the heating or cooling capacity can be optimized implicitly in EnergyPlus dependent the exterior building enclosure systems. The input parameters that the user should pay special attention to are bolded and underlined in Figure 25.

```
HVACTemplate:Thermostat,
        Zone Thermostat, !- Thermostat Name
        , !- Heating Setpoint Schedule
        20, !- Constant Heating Setpoint {C}
        , !- Cooling Setpoint Schedule
        27; !- Constant Cooling Setpoint {C}

HVACTemplate:Zone:Unitary,
…
        0.00944, !- Outdoor Air Flow Rate per Person {m3/s} or 10 cfm/person
```

```
…
            None, !- Baseboard Heating Type
…

HVACTemplate:System:UnitaryHeatPump:AirToAir,
…
            SingleSpeedDX, !- Cooling Coil Type
            Off, !- Cooling Coil Availability Schedule Name
…
            autosize, !- Cooling Coil Capacity {W}
            autosize, !- Cooling Coil Rated Sensible Heat Ratio
            3.8, !- Cooling Coil Rated COP
            SingleSpeedDXHeatPump, !- Heat Pump Heating Coil Type
            , !- Heat Pump Heating Coil Availability Schedule Name
…
            autosize, !- Heat Pump Heating Coil Rated Capacity {W}
            3.1, !- Heat Pump Heating Coil Rated COP
…
            Gas, !- Supplemental Heating Coil Type
            Off, !- Supplemental Heating Coil Availability Schedule Name
            autosize, !- Supplemental Heating Coil Capacity {W}
…
            NoEconomizer, !- Economizer Type
…
            None, !- Heat Recovery Type
...
            None, !- Humidifier Type
…

ComponentCost:LineItem,
ASHP System Cost, !- Name
…
Coil:DX, !- Line Item Type
HEAT PUMP HEATING COIL, !- Item Name
…
754; !- Cost per Unit of Output Capacity {$/kW}

ComponentCost:LineItem,
Heat Pump System GWP, !- Name
…
Coil:DX, !- Line Item Type
HEAT PUMP HEATING COIL, !- Item Name
…
20.2; !- GWP per Unit of Output Capacity {kg-CO2-eq/kW}
```

Figure 25: Sample EnergyPlus/EP-Macro input code for the HVAC module.

The mechanical system module requires a secondary sub-module in order for EnergyPlus to auto-size the mechanical systems. This secondary module (*DesignDay.idf*) is also called upon in the main EnergyPlus project file by EP-Macro. Figure 26 shows the input code required for the mechanical system to be properly sized by using the component *SizingPeriod:WeatherFileConditionType*. This component basically tells EnergyPlus to size the mechanical system according to a pre-defined summer and winter design day.

For the purpose of this research, a typical summer and typical winter design day is selected. The typical summer and winter design day is create through a heuristic procedure that identifies typical periods in the actual weather file. This component will allow one of those periods to be selected for sizing or load calculations (LBNL 2013b)

```
SizingPeriod:WeatherFileConditionType,
        Typical Summer Weather Period for Design, !- Name
        SummerTypical, !- Period Selection
        SummerDesignDay, !- Day Type
        No, !- Use Weather File Daylight Saving Period
        Yes; !- Use Weather File Rain and Snow Indicators

SizingPeriod:WeatherFileConditionType,
        Typical Winter Weather Period for Design, !- Name
        WinterTypical, !- Period Selection
        WinterDesignDay, !- Day Type
        No, !- Use Weather File Daylight Saving Period
        Yes; !- Use Weather File Rain and Snow Indicators
```

Figure 26: EnergyPlus input code to set the mechanical system sizing period.

### 7.5.4 Simulation and Optimization Output

Once the simulation is completed for each wall and roof type combination, the results can be extracted from jEPlus+EA interface. The optimization software allows users to directly copy and paste the Pareto optimal solution sets from each simulation run. The extracted data consists of raw EnergyPlus and jEPlus input code in the form presented in Appendix A, Appendix F, and Appendix G. Through Microsoft Excel, the raw data input can be converted into user readable form so that unfamiliar users can understand the optimization output without having to learn the proprietary code for the design parameter database.

In addition to the jEPlus+EA output, each solution within the solution set has its own EnergyPlus output folder located in the location pre-defined by the user. There are multiple files located within each output folder, most of which are standard EnergyPlus output files including variable definition and error output files. However, the most important file is the *eplustbl.csv* file located within each output folder which contains a full set of EnergyPlus output data in the form of multiple tables. This file can either be opened using a generic text-based reader or using Microsoft Excel. This file will output critical information regarding each output solution generated by the optimization software such as site and source energy consumption, end-uses, building geometry, etc. The most important output this file provides is the *Cost Line Item Details* object which outputs cost and environmental impact results based on each component defined in the previous section (refer to section 7.5.3). A sample of this section of critical EnergyPlus output is presented in Table 23.

Table 23: Sample EnergyPlus output related to initial cost and environmental impact data.

| Line No. | Item Name | Quantity. | Units | ($) per Qty. | Sub-Total ($) |
|---|---|---|---|---|---|
| **1** | TOTAL COST OF EXTERIOR WALL | 211.25 | m2 | 77.39 | 16348.54 |
| **2** | TOTAL GWP OF EXTERIOR WALL | 211.25 | m2 | 24.14 | 5099.54 |
| **3** | TOTAL COST OF ROOF | 224.83 | m2 | 136.67 | 30727.69 |
| **4** | TOTAL GWP OF ROOF | 224.83 | m2 | 68.77 | 15461.64 |
| **5** | TOTAL COST OF WINDOW SYSTEM | 1 | Ea. | 65 | 65 |
| **6** | TOTAL COST OF WINDOW SYSTEM | 57.62 | m2 | 668.95 | 38546.4 |
| **7** | TOTAL GWP OF WINDOW SYSTEM | 57.62 | m2 | 426.17 | 24556.87 |
| **8** | ASHP SYSTEM COST | 8.35 | kW (total cooling capacity) | 154 | 1286.2 |
| **9** | ASHP SYSTEM COST | 13.65 | kW (total heating capacity) | 26 | 354.92 |
| **10** | HVAC SYSTEM COST | 1 | Ea. | 1935 | 1935 |
| **11** | HVAC SYSTEM GWP | 1 | Ea. | 465 | 465 |

Since each output file is located in a separate folder, it is impractical to manually extract the data for additional results analysis by opening each individual file. Therefore, a custom Visual Basics software is developed to extract the critical solutions from the full list of Pareto optimal solutions. Now, the critical solutions are calculated by determining the Pareto Front in terms of LCC and LCGWP only. Before this can be done, the full list of solutions must first be filtered to eliminate any data that has an occupant thermal comfort level above predefined PPD for reasons provided in section 5.3. Once the raw output data is filtered, the Pareto Front for each solution set can be determined by calculating the number of solutions less than each individual solution. The solutions with no other solutions lower than itself in terms of LCC and LCGWP, then it will be considered to be on the Pareto Front. Once the list of Pareto Front solutions are found, the LCC and LCGWP is further broken down into their initial and operating phases using the software shown in Figure 27 below. With the extracted data for each Pareto optimal solution set, the results can then be analyzed in additional detail by creating scatter plots, bar-charts, and tables, allowing users to compare individual solutions to find one that is most suitable based on their own criterion and weights.

```
Public strFileName As String
Public currentWB As Workbook
Public dataWB As Workbook
Public strCopyRange As String

Sub GetData()
    Dim strWhereToCopy As String, strStartCellColName As String
    Dim strListSheet As String

    strListSheet = "List"

    On Error GoTo ErrH
    Sheets(strListSheet).Select
    Range("B2").Select

    'this is the main loop, we will open the files one by one and copy their data into the masterdata sheet
    Set currentWB = ActiveWorkbook
    Do While ActiveCell.Value <> ""

        strFileName = ActiveCell.Offset(0, 1) & ActiveCell.Value
        strCopyRange = ActiveCell.Offset(0, 2) & ":" & ActiveCell.Offset(0, 3)
        strWhereToCopy = ActiveCell.Offset(0, 4).Value
        strStartCellColName = Mid(ActiveCell.Offset(0, 5), 2, 1)

        Application.Workbooks.Open strFileName, UpdateLinks:=False, ReadOnly:=True
        Set dataWB = ActiveWorkbook

        Range(strCopyRange).Select
        Selection.Copy

        currentWB.Activate
        Sheets(strWhereToCopy).Select
        lastRow = LastRowInOneColumn(strStartCellColName)
        Cells(lastRow + 1, 1).Select

        Selection.PasteSpecial xlPasteValues, xlPasteSpecialOperationNone, Transpose:=True
        Application.CutCopyMode = False
```

```
        dataWB.Close False
        Sheets(strListSheet).Select
        ActiveCell.Offset(1, 0).Select
    Loop
    Exit Sub

ErrH:
    MsgBox "It seems some file was missing. The data copy operation is not complete."
    Exit Sub
End Sub

Public Function LastRowInOneColumn(col)
    'Find the last used row in a Column: column A in this example
    'http://www.rondebruin.nl/last.htm
    Dim lastRow As Long
    With ActiveSheet
    lastRow = .Cells(.Rows.Count, col).End(xlUp).Row
    End With
    LastRowInOneColumn = lastRow
End Function
```

Figure 27: Visual Basics code for Excel that extracts specific EnergyPlus data from the individual output folders.

## 7.6 Summary

This chapter introduces the overall optimization environment to be implemented in the research project. The concepts, fundamental processes and objectives are discussed and the software used to conduct the research is also explained in detail. The software EnergyPlus and jEPlus+EA are introduced and discussed in detail. The capabilities and functionalities of each software are explained and discussed. In summary, EnergyPlus is a powerful building energy simulation tool that uses text based input that can be easily configured by the user once they learn the object-based language. Given the object-based nature of the simulation engine, any parameter within the limitations of the program can be considered as a design variable for genetic algorithm optimization. Also, jEPlus+EA is a free and open-source software that uses the NSGA-II version of the genetic algorithm, which is highly robust and customizable.

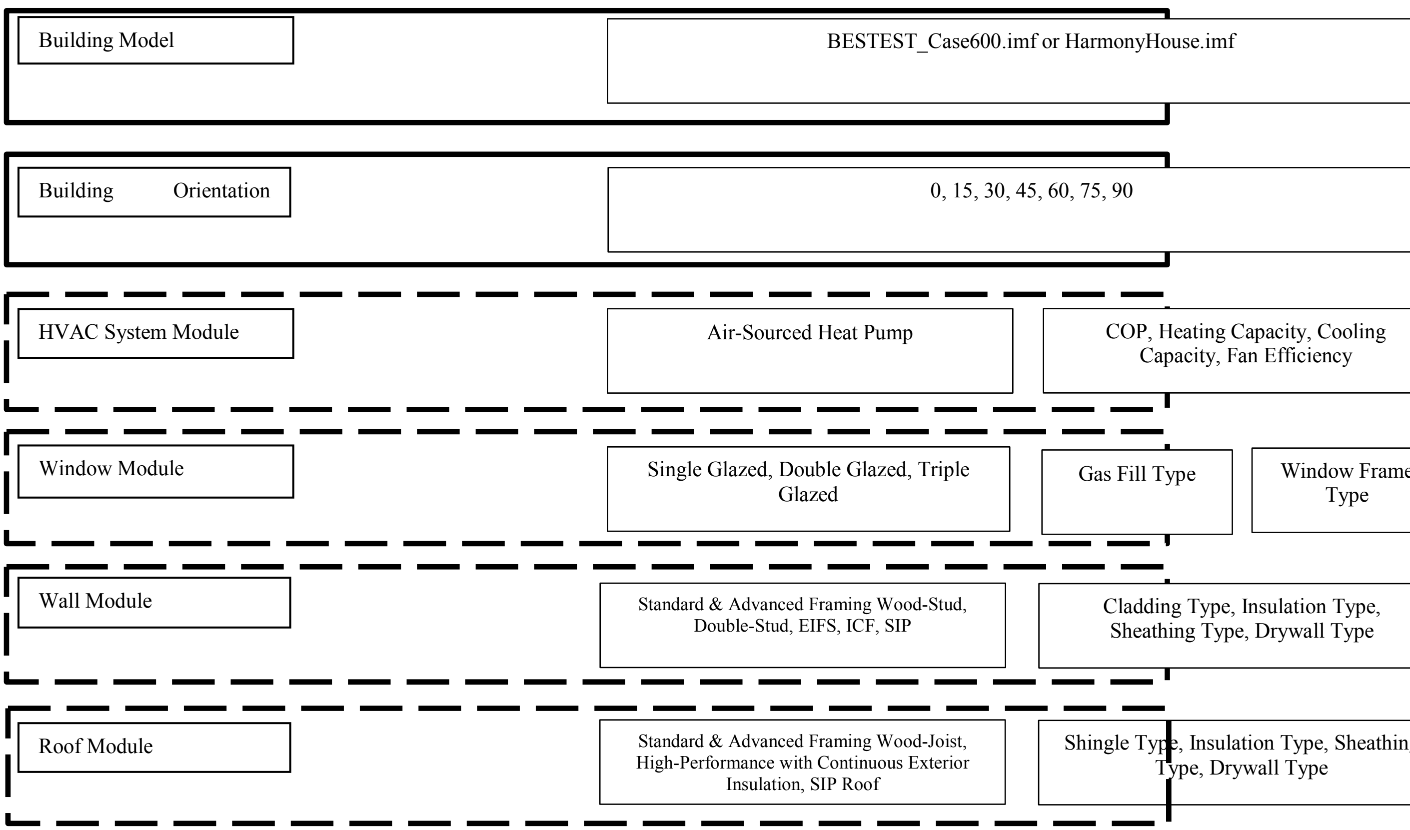



Figure 28: Flow chart showing how the modules fit into the optimization parameter hierarchy (dashed line denotes external module)

The input and output files associated with EnergyPlus and jEPlus+EA are explained in detail in this chapter as well. Each input file is essential to the success of the optimization study, and the method through which the user configures these input files can significantly impact the results of the study. For instance, by simply changing the weather data file can alter the results completely without altering the rest of the energy model.

Moreover, depending on which output results are extract using the (*rvi*) file, the direction and purpose of the optimization can change substantially.

Figure 28 shows the hierarchy process that jEPlus+EA considers when the genetic algorithm used to optimize each alternative. The hierarchy is configured according to the user's requirements and can incorporate as many or as few design alternatives as appropriate for the purpose of the optimization study. The main concept being shown in Figure 28 is the fact that design alternatives with multiple sub-level variables should be considered as an external module. Parameters with single level variables can be directly considered in the parameter tree without the need to create an external module. For instance, the parameter *Wall Type* must go through a structure level followed by material layer level while *Building Orientation* only has degrees relative to north as variables.

# Chapter 8 Validation and Case Study

## 8.1 Energy Model Configuration

The first step of any building optimization is to develop and configure the simulation model itself. The model consists of any information and data pertaining to a building design along with its environment. This includes simulation settings, weather data, geographical data, schedules, material properties, construction settings, HVAC settings, and building geometry. The geometry is the most important aspect of energy simulation because it defines the size, shape, and orientation of the building, all of which directly and significantly impact the simulation results. Defining the building geometry should be the first step taken by the user because all other data are automatically generated by EnergyPlus once the geometry is set.

OpenStudio is a Sketch-Up plug-in developed by the National Renewable Energy Laboratory (NREL) and is designed to make geometry creation suitable for EnergyPlus simulation easier (NREL 2013). OpenStudio gives the user full access to all of *Sketch-Up's* 3-D modeling tools with the ability to convert the 3-D model geometry to an EnergyPlus compatible model language. This program allows the user to define the coordinates and areas of different building related assemblies such as walls, floors, roofs, and windows. The program automatically converts the assemblies into the appropriate EnergyPlus construction objects. Once the geometry is created, the model can be represented with thermal zones. For example, a multi-room single-family residential building can be represented as one thermal zone covering the entire building, represented floor-by-floor, or represented room-by-room. Larger and more complex buildings have multiple HVAC systems which require the definition of multiple thermal zones. After the model geometry and thermal zones are defined and checked for any errors, the model can either be saved as an OpenStudio Model file with extension *.osm* for future editing or exported into an EnergyPlus Model (*.idf*) file for simulation.

The user must then configure the *idf* file exported from OpenStudio to suit the user's particular requirements. The default *idf* file contains only very basic information pertaining to the building such as geometry and standard materials and constructions depending on the OpenStudio template selected by the user during the geometry creation phase. For instance, the default model may use material and construction properties based on ASHRAE standards for energy modelling but it may not represent the exact specifications of the original building design. More often than not, the user must define his or her own material and construction database or acquire a particular database from third-party sources. Furthermore, model related data such as schedules and HVAC configurations can all be customized by the user during this phase.

## 8.2 Benchmark Model (BESTEST Case 600)

BESTEST Case 600 is a baseline benchmark model case from a series of validation cases within the ANSI/ASHRAE Standard 140-2001 validation method. The test building considered in BESTEST Case 600, shown in Figure 29, consists of a rectangular single zone (8 m x 6 m x 2.7 m) with no interior partitions and 12 $m^2$ of windows on the south facing wall. The building has lightweight construction, with more details provided Table 24, Table 25,Table 26, and Table 27.

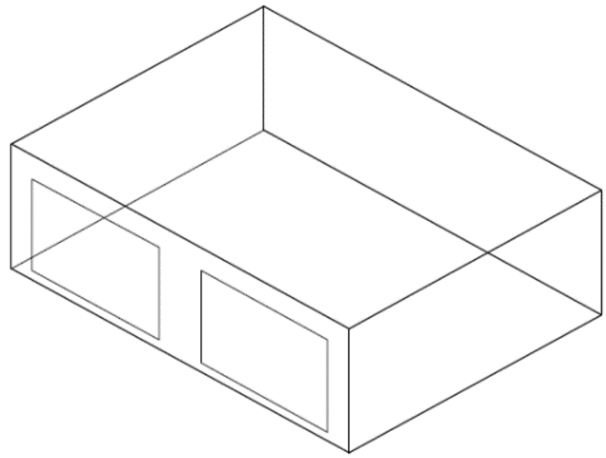


Figure 29: Base Building (BESTEST Case 600) – isometric view of southeast corner with windows on south wall (Orlando & Berkeley 2004).

Table 24: List of baseline wall construction materials and its material properties.

| Element | k (W/m-K) | Thickness (m) | U (W/m2-K) | R (m2-K/W) | Density (kg/m3) | Cp (J/kg-K) |
|---|---|---|---|---|---|---|
| **Interior Surface Coefficient** | | | 8.29 | 0.121 | | |
| **Plasterboard** | 0.16 | 0.012 | 13.333 | 0.075 | 950 | 840 |
| **Fiberglass Quilt** | 0.04 | 0.066 | 0.606 | 1.65 | 12 | 840 |
| **Wood Siding** | 0.14 | 0.009 | 15.556 | 0.064 | 530 | 900 |
| **Exterior Surface Coefficient** | | | 29.3 | 0.034 | | |
| **Overall, air-to-air** | | | 0.514 | 1.944 | | |

Table 25: List of baseline roof construction materials and its material properties.

| Element | k (W/m-K) | Thickness (m) | U (W/m2-K) | R (m2-K/W) | Density (kg/m3) | Cp (J/kg-K) |
|---|---|---|---|---|---|---|
| **Interior Surface Coefficient** | | | 8.29 | 0.121 | | |
| **Plasterboard** | 0.16 | 0.01 | 16 | 0.063 | 950 | 840 |
| **Fiberglass Quilt** | 0.04 | 0.1118 | 0.358 | 2.794 | 12 | 840 |
| **Roof Deck** | 0.14 | 0.019 | 7.368 | 0.136 | 530 | 900 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Exterior Surface Coefficient** | | | 29.3 | 0.034 | | |
| **Overall, air-to-air** | | | 0.318 | 3.147 | | |

Table 26: List of baseline floor construction materials and its material properties.

| Element | k (W/m-K) | Thickness (m) | U (W/m2-K) | R (m2-K/W) | Density (kg/m3) | Cp (J/kg-K) |
|---|---|---|---|---|---|---|
| **Interior Surface Coefficient** | | | 8.29 | 0.121 | | |
| **Timber Flooring** | 0.14 | 0.025 | 5.6 | 0.179 | 650 | 1200 |
| **Insulation** | 0.04 | 1.003 | 0.04 | 25.075 | | |
| **Overall, air-to-air** | | | 0.039 | 25.374 | | |

Table 27: List of baseline window properties used on the south facing wall.

| Window Parameter | Value |
|---|---|
| **Extinction coefficient** | 0.0196/mm |
| **Number of panes** | 2 |
| **Pane thickness** | 3.175 mm |
| **Air-gap thickness** | 13 mm |
| **Index of refraction** | 1.526 |
| **Normal direct-beam transmittance through one pane** | 0.86156 |
| **Thermal Conductivity of glass** | 1.06 W/m-K |
| **Conductance of each glass pane** | 333 W/m2-K |
| **Combined radiative and convective coefficient of air gap** | 6.297 W/m2-K |
| **Exterior combined surface coefficient** | 21.00 W/m2-K |
| **Interior combined surface coefficient** | 8.29 W/m2-K |
| **U-value from interior air to ambient air** | 3.0 W/m2-K |
| **Hemispherical infrared emittance of ordinary uncoated glass** | 0.9 |
| **Density of glass** | 2500 kg/m3 |
| **Specific heat of glass** | 750 K/kg-K |
| **Interior shade devices** | None |
| **Double-pane shading coefficient at normal incidence** | 0.907 |
| **Double-pane solar heat gain coefficient at normal incidence** | 0.789 |

### 8.2.1 Baseline Case 600 Model Calibration

The objective of this study is not to test the validity of the BESTEST validation method itself, but the purpose is to implement the baseline model for use in multi-objective optimization. In other words, this research modifies the baseline case model in order to use it in the multi-objective optimization environment discussed in the previous chapters. The augmented model can be called the *pseudo-model*.

The main validation involves running BESTEST Case 600 based on the original parameters and inputs described in the previous section. The results are then compared to the results provided by ANSI/ASHRAE Standard 140-2001. The second step is to substitute the input parameters with matching parameters from the developed material and component database. For example, if the original model calls for a 0.009 m wood siding material for the wall assembly, the pseudo model will also have a 0.009 m wood siding material but may have slightly different material properties based on the *ASHRAE Handbook of Fundamentals* (ASHRAE 2009).

#### 8.2.1.1 Calibration Results

To ensure that the results produced by the optimization process are accurate, the model itself must be validated by comparing default input parameters with customized input parameters. Table 28 shows the validation results by means of percentage difference between the results provided by the standard and the results generated by EnergyPlus using default and pseudo-model parameters. In this case, the model is simulated by using an Ideal Loads Air System (ILAS) which essentially meets all demand loads through heat balance method.

It is clear that the EnergyPlus model is functional and accurate. The model that uses custom parameters only show a difference in annual heating and annual cooling energy consumption of -1.91% and 2.79%, respectively.

Table 28: Comparative test results for Case 600 using default and custom parameters while using ILAS

| BESTEST Case 600 | Annual Heating (kWh) | Percentage Difference (%) | Annual Cooling (kWh) | Percentage Difference (%) |
|---|---|---|---|---|
| **BESTEST Standard 140-2011 Validation Results** | 4378 | n/a | 6740 | n/a |
| **THESIS BASELINE CASE (using default inputs)** | 4378.61 | 0.01 | 6763.42 | 0.35 |
| **THESIS BASELINE CASE (using pseudo-model inputs)** | 4295.17 | -1.91 | 6931.05 | 2.79 |

The next step in the calibration process is to test the accuracy of the model if a heat pump system is used as the main HVAC system rather than an ILAS. Table 29 shows the results in terms of percentage differences in annual electricity and annual gas consumption by comparing default input parameters with the custom input parameters. *PTHP-Gas* represents the use of a packaged terminal heat pump with gas fired supplemental heating. The results show that there is a difference in annual electricity and annual gas consumption of 0.61% and -6.51%, respectively, when design parameters from the material database developed during this research work are used.

Table 29: Comparative test results for Case 600 using default and custom parameters while using a heat pump as the primary HVAC system

| BESTEST Case 600 | Electricity Consumption (kWh) | Percentage Difference (%) | Gas Consumption (kWh) | Percentage Difference (%) |
|---|---|---|---|---|
| **THESIS BASELINE CASE (using default inputs and heat-pump)** | 4206.49 | n/a | 1091.41 | n/a |
| **THESIS BASELINE CASE (using pseudo-model inputs and heat-pump)** | 4232.19 | 0.61 | 1022.55 | -6.51 |

Now that the model is validated for accuracy, the multi-objective optimization environment can be implemented. The following sections will show the detailed results of the optimization environment when used on the pseudo-model of BESTEST Case 600.

### 8.2.2 Input Parameter Settings

In this case study, the simulation period is considered from January 1 to December 31 of any typical year. A TARP algorithm is used for inside surface convection calculations and the DOE-2 algorithm is used for outside surface convection. The simulation is divided into 4 time-steps per hour with each time-step being 15 minutes. The time-step dictates the frequency of results calculations so that the results resolution increases with an increase in the number of time-steps.

The interior design temperature threshold is set between 20°C and 27°C throughout the entire simulation period. In other words, if the indoor temperature drops below 20°C, the heating system will turn on and if the indoor reaches above 27°C, an internal air infiltration rate control algorithm will open the windows to allow for increased air infiltration rate to cool down the building. The EP-Macro input code for the internal EnergyPlus algorithm is shown in Figure 30. Additionally, the air infiltration rate of all building types is assumed to be constant at 1.5 ACH at 50 Pa. For the purpose of analyzing the effects of air infiltration rate on the building optimization, the ICF and SIP wall types are optimized twice, once with an air infiltration rate of 1.5 ACH at 50 Pa. and a second optimization at 0.5ACH at 50 Pa. Although this assumed infiltration rate is relatively low compared to current building standards, the maximum possible workmanship and material quality was assumed.

```
EnergyManagementSystem:Sensor,
 ZoneTemp , ! Name
 ZONE ONE, ! Output:Variable or Output:Meter Index Key Name
 Zone Mean Air Temperature; ! Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 InfiltrationRate, ! Name
 ZoneInfil, ! Component Name
 Zone Infiltration, ! Component Type
 Air Exchange Flow Rate; ! Control Type

EnergyManagementSystem:ProgramCallingManager,
 Zone Infiltration Control, ! Name
 BeginTimestepBeforePredictor , ! EnergyPlus Model Calling Point
 Infiltration_Controller ; ! Program Name 1

EnergyManagementSystem:Program,
 Infiltration_Controller , ! Name
 IF (ZoneTemp <= 20),
 SET InfiltrationRate = 0.054 , ! - Assume 1.5 ACH when windows closed
 ELSEIF (ZoneTemp > 20) && (ZoneTemp < 26),
 SET InfiltrationRate = 0.108 , ! - Assume 3 ACH when windows opened
 ELSEIF (ZoneTemp >= 27),
 SET InfiltrationRate = 0.108 , ! - Assume 3 ACH when windows opened
 ENDIF;

Output:EnergyManagementSystem,
 Verbose,
 Verbose,
 Verbose;
```

Figure 30: Sample of EP-Macro code that controls the air infiltration/ventilation rate depending on internal zone air temperature.

The utility rates used to calculate the life cycle operational cost of the model is based on BC Hydro rates. Electricity rate is based on a block charge system where utility rates can change based on the level of usage. In British Columbia, residential rates are \$0.0752/kWh for the first 1350 kWh of electricity used. If the particular building uses more than 1350 kWh of electricity, the rates will increase to \$0.1127/kWh (BC Hydro 2013). Moreover, the gas rate is based on the Fortis BC utility rate structure with a base monthly charge of \$11.67 and a unit consumption cost rate of \$0.03443/kWh.

To reiterate, the energy simulation models are separated by wall type and each wall type represents a separate optimization job. The wall types are split into: standard wall, double stud wall, EIFS (split insulation) wall, Structural Insulated Panels (SIPs), and Insulated Concrete Form (ICF) walls. In addition, the roofs are separated into a standard code compliant stud insulation roof design and a high performance roof (HPR) assembly. The HPR is essentially a standard code compliant roof design with additional layers of continuous insulation.

A weather file based in Vancouver, British Columbia, Canada is selected for the purpose of this research. The weather file is obtained from the *EnergyPlus* website and the files are in the form of *.epw* files that contain weather information such as hourly temperature, precipitation, relative humidity, etc. The sources of the weather files come from *Environment Canada*.

### 8.2.3 Optimization Results and Analysis

The following sections, including the sections for the Harmony House case study, show results gathered from the multi-objective optimization of the various wall and roof type combinations. The results are categorized in terms of exterior wall assembly type. For each category of results, a scatter plot is provided for visual inspection, which also have numbered labels to match with the corresponding tabular results presented either within the same section or within the corresponding appendices. In addition, the results are analyzed by comparing pairs of Pareto optimal solutions to spot any trends or trade-offs between design parameters. The extreme points for each set of Pareto optimal solutions related to standard roof cases are also analyzed to spot the differences in order realize the trade-offs between the design parameters.

#### *8.2.3.1 Standard Wall Solutions*

The complete set of optimized solutions for the standard wall cases presented in 6.1.1 is shown in Figure 31. There is a clear difference between standard roof solutions and high-performance roof solutions based on the Pareto front represented by the dashed lines. Based on the visible Pareto front, it is apparent that the standard wall with standard roof solutions generally perform better when compared to standard wall with high-performance roof solutions. However, the advantages of standard roof solutions diminish as the overall LCC increases and the LCGWP decreases. Once the LCGWP is decreased to approximately 57,000 kg-CO2-eq, the additional effects decreasing LCGWP by increasing LCC is relatively smaller. This trend is represented by the visible change in slope of the dashed lines shown in Figure 31.

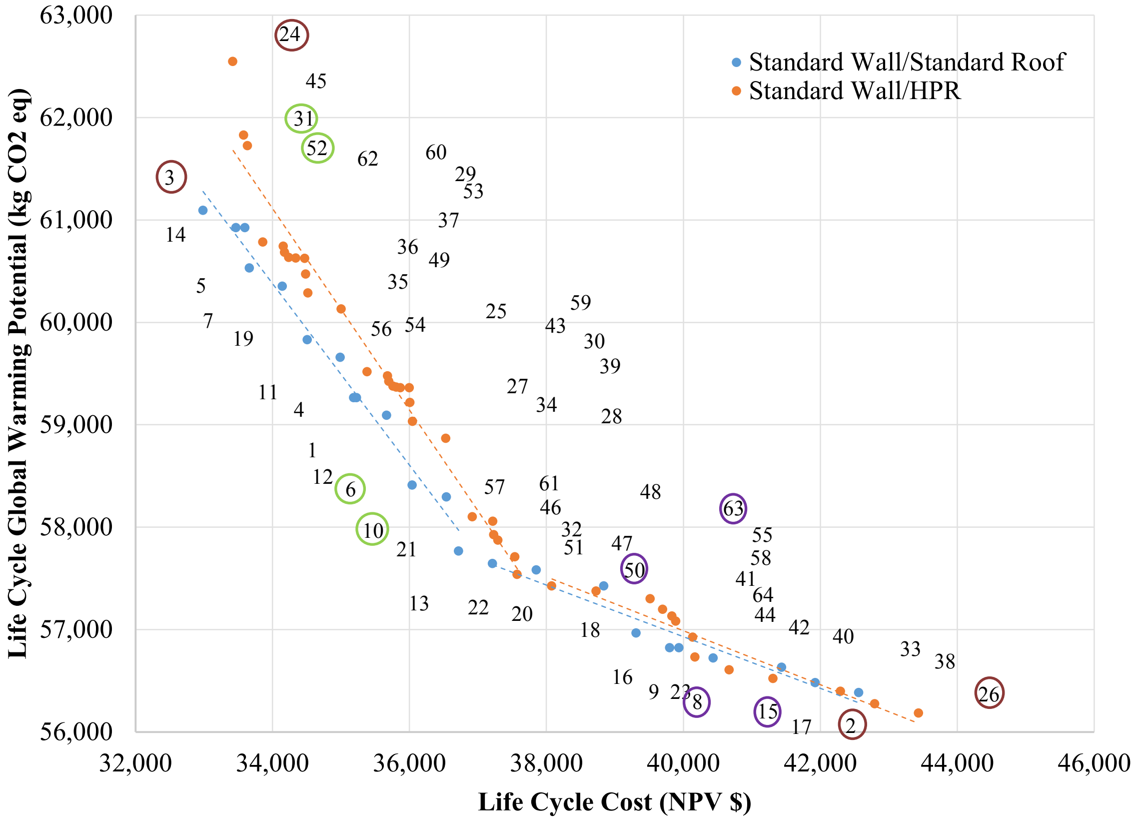



Figure 31: Scatter plot of Pareto solutions for the standard wall assemblies with numbered labels for input parameter reference.

Table 30: List of parameters for standard wall with standard roof Pareto solutions.

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Stud Insulation | Ceiling Drywall | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35190 | 59262 | 17 | 21002 | 10657 | 14187 | 48605 |
| **2** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 42563 | 56383 | 15 | 29320 | 11460 | 13243 | 44923 |
| **3** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 32989 | 61091 | 16 | 18486 | 10269 | 14503 | 50822 |
| **4** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 34994 | 59658 | 16 | 20684 | 9566 | 14310 | 50092 |
| **5** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33603 | 60922 | 16 | 19248 | 10476 | 14355 | 50446 |
| **6** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 35672 | 59090 | 17 | 21611 | 10820 | 14061 | 48270 |
| **7** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33666 | 60527 | 17 | 19413 | 11523 | 14253 | 49005 |
| **8** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40439 | 56719 | 15 | 27245 | 12104 | 13194 | 44615 |
| **9** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 39805 | 56819 | 15 | 26482 | 11897 | 13323 | 44922 |
| **10** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36046 | 58407 | 15 | 22129 | 9863 | 13917 | 48545 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **11** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34513 | 59829 | 16 | 20076 | 9404 | 14438 | 50425 |
| **12** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35232 | 59262 | 16 | 21466 | 11981 | 13766 | 47281 |
| **13** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36719 | 57765 | 16 | 23056 | 11116 | 13663 | 46649 |
| **14** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 33471 | 60924 | 16 | 19095 | 10431 | 14376 | 50493 |
| **15** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41439 | 56630 | 16 | 27948 | 11091 | 13492 | 45540 |
| **16** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39314 | 56965 | 16 | 25873 | 11735 | 13441 | 45230 |
| **17** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 41929 | 56479 | 15 | 28557 | 11253 | 13372 | 45226 |
| **18** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38842 | 57424 | 16 | 25130 | 10472 | 13711 | 46952 |
| **19** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 34148 | 60352 | 17 | 20022 | 11685 | 14126 | 48667 |
| **20** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 37855 | 57580 | 15 | 24430 | 11486 | 13425 | 46094 |
| **21** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 36543 | 58293 | 15 | 22739 | 10025 | 13804 | 48268 |
| **22** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 37217 | 57644 | 15 | 23667 | 11279 | 13550 | 46365 |
| **23** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39940 | 56819 | 15 | 26635 | 11942 | 13305 | 44877 |

Solutions 2 and 3, circled in red within Figure 31, represent the extreme points in the standard wall with standard roof solutions. These points present a trade-off between the solution with the highest LCGWP with the lowest LCC or the solution with the highest LCC but has the lowest LCGWP out of the Pareto optimal solution set. The results of the objective functions and the list of parameters used to achieve those solutions are shown in Table 30 and are highlighted in red. The breakdown of the initial and operating phases of the LCC and LCGWP of each solution is shown in Figure 32 (solutions 2 and 3 are enclosed in red circles). There are differences in the drywall type, stud-space insulation type, window frame type, glazing type, and roofing type. Assuming solution 3 is the baseline design case, solution 2 increases initial cost by 59.0 % and decreases operational cost by 9.0% over a 30-year period. Solution 2 also increases initial GWP by 12.0% but decreases operational GWP by 12.0%. Table 31 shows the differences in design parameters between solution 2 and 3, and the results of the initial cost and GWP breakdown show that window glazing and frames account for the majority of initial costs and GWP. It is interesting to see that the triple-glazed windows account for 14.9% of the total LCC while double-glazed windows account for 12.8%. The glazing appears to have the most significant impact on LCC while the window frames have the most impact on LCGWP.

Table 31: Comparison of differing design parameters between solutions 2 and 3 including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 2** | | | **Solution 3** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Gypsum Fiber Interior Drywall | 7.6 | 1.6 | Regular Gypsum Interior Drywall | 5.5 | 0.9 |
| Spray Polyurethane Foam Wall Insulation (5.5 in.) | 8.1 | 2.7 | Blown-Cellulose Wall Insulation (5.5 in.) | 1.2 | 1.0 |
| Vinyl-Clad Wood-Core Window Frames | 10.3 | 3.9 | Vinyl Window Frames | 2.4 | 6.0 |
| Triple-Glazed Non-Coated Windows (air-filled) | 14.9 | 2.5 | Double-Glazed Non-Coated Windows (air-filled) | 12.8 | 1.5 |
| Steel Roof Panels | 5.6 | 2.7 | Asphalt Shingle Roofing | 4.1 | 0.5 |

Solutions 6 and 10, enclosed in green circles, show a more significant decrease in LCGWP with relatively less increase in LCC compared to other adjacent pairs of solutions (i.e. solutions 8 and 15). Assuming solution 6 is the baseline design case, solution 10 increases LCC by 1.0% while decreasing LCGWP by 1.2%. These changes can be attributed to the upgrade from non-coated double-glazed windows to non-coated triple-glazed windows in addition to an asphalt roof as compared to a steel roof. Based on Table 32, the double-glazed and the triple-glazed windows account for 11.9% and 17.8% of LCC of their respective solutions.

Table 32: Comparison of differing design parameters between solutions 6 and 10 including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 6** | | | **Solution 10** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Double-Glazed Non-Coated Windows (air-filled) | 11.9 | 1.6 | Triple-Glazed Non-Coated Windows (air-filled) | 17.8 | 2.4 |
| Steel Roof Panels | 6.7 | 2.6 | Asphalt Shingle Roofing | 3.8 | 0.5 |

Taking solution 8 as the baseline case, solution 15 increases LCC by 2.5% while only decreasing LCGWP by 0.2%. The relatively large increase in LCC is because of the change from solid wood window frame (solution 8) to vinyl-clad wood-core window frames (solution 15). The interior drywall for solution 8 accounts for a higher portion of the total LCC when compared to window frames, but the window frame in solution 15 accounts for a higher percentage when compared to interior drywall. However, the percentage of LCGWP attributed to window frames is greater in both solutions when compared to the interior drywall.

Table 33: Comparison of differing design parameters between solutions 8 and 15 including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 8** | | | **Solution 15** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Gypsum Fiber Interior Drywall | 8.1 | 1.6 | Regular Gypsum Interior Drywall | 4.4 | 0.9 |
| Solid Wood Window Frames | 5.4 | 5.0 | Vinyl-Clad Wood-Core Window Frames | 10.5 | 3.8 |

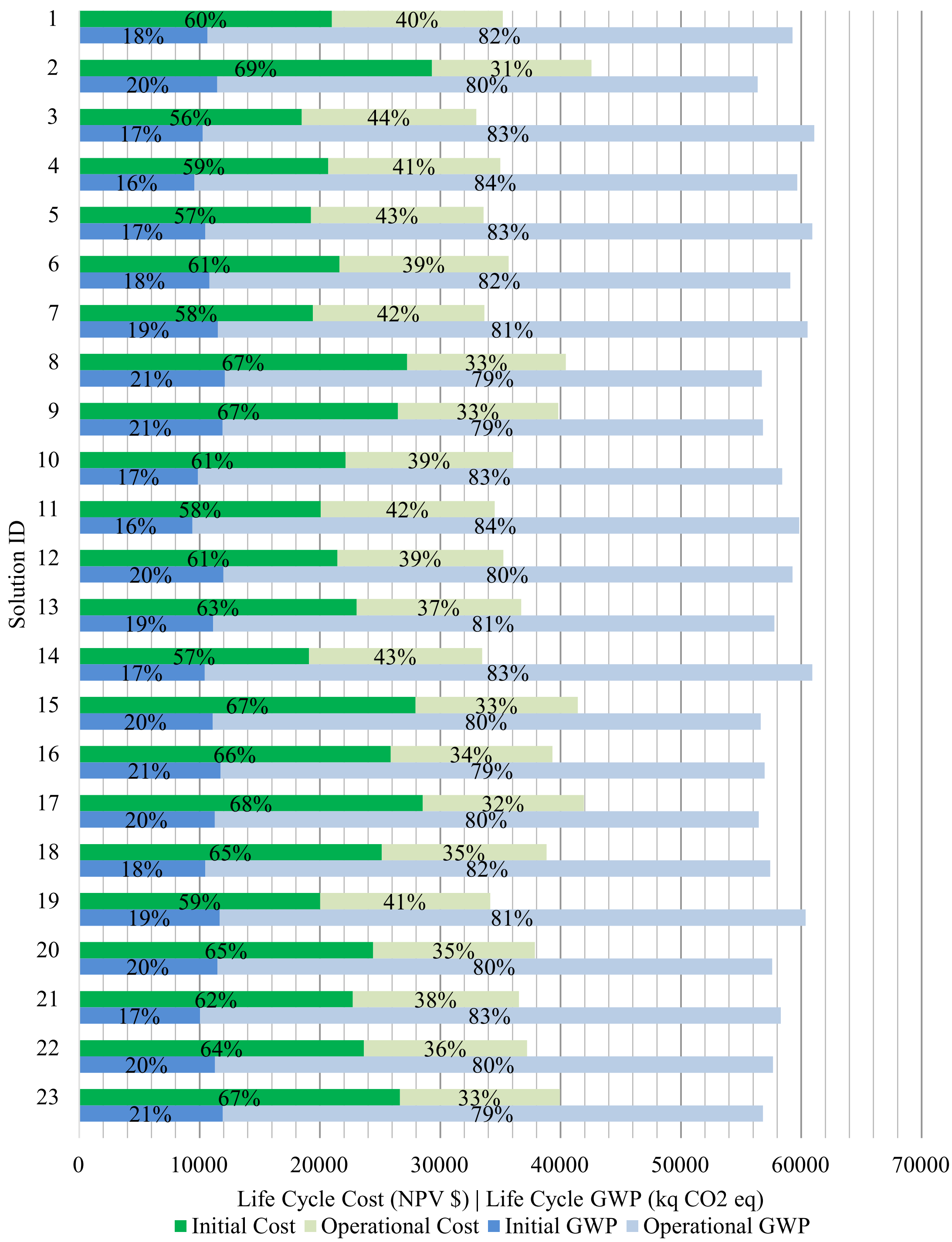



Figure 32: Comparison of LCC and LCGWP for each standard wall with standard roof Pareto solution.

For high-performance roofs in combination with standard wall assemblies, solutions 24 and 26 represent the extreme points (red circles in Figure 31). According to Table 34, the drywall type, stud-space insulation type, window frame type, glazing type, roofing type, and roof rafter framing type are different between solutions 24 and 26. Taking solution 24 as the baseline case, solution 26 increases LCC by 29.9% and decreases LCGWP by 10.2%. Furthermore, solution 26 increases initial cost by 63.2%, decreases operational cost by 11.6%, increases initial GWP by 20.9%, and decreases operational GWP by 16%. Table 34 also provides a list of the differences in design parameters between the two solutions and the relative impact on LCC and LCGWP.

Table 34: Comparison of differing design parameters between solutions 24 and 26 including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 24** | | | **Solution 26** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Regular Gypsum Interior Drywall | 5.4 | 0.9 | Gypsum Fiber Interior Drywall | 7.5 | 1.6 |
| Blown-Cellulose Wall Insulation (5.2 in.) | 1.6 | 1.4 | Spray Polyurethane Foam Wall Insulation (6.0 in.) | 8.7 | 2.9 |
| Vinyl Window Frames | 2.3 | 5.9 | Vinyl-Clad Wood-Core Window Frames | 10.1 | 3.9 |
| Double-Glazed Non-Coated Windows (air-filled) | 12.7 | 1.5 | Triple-Glazed Non-Coated Windows (air-filled) | 14.6 | 2.5 |
| Blown-Cellulose Roof Insulation (5.2 in.) | 1.2 | 1.0 | Blown-Cellulose Roof Insulation (10.4 in.) | 1.8 | 2.3 |
| Asphalt Shingle Roofing | 4.0 | 0.5 | Steel Roof Panels | 5.5 | 2.8 |

Compared to solution 31, solution 52 has a relatively lower LCGWP considering a relatively minimal increase in LCC. By upgrading the roof rafters to 2x12 advanced framing from 2x8 advanced framing, both with blown-cellulose insulation, LCC increases by 0.7% while LCGWP decreases by 1.5%. Moreover, initial construction cost increases by 2.6%, operational cost decreases by 1.8%, initial GWP increases by 5.7%, and operational GWP decreases by 2.9%. On the contrary, solutions 50 and 63 shows relatively large increases in LCC but the LCGWP has only relatively minimal decreases. Assuming solution 50 as the baseline case, solution 63 increases LCC by 2.0% while only decreasing LCGWP by 0.1%. In addition, both initial and operational cost increases by 2.0%, while initial GWP decreases by 8.5% and operational GWP increases by 2.0%. The main differences between solutions 50 and 63 are the drywall type, stud-space insulation type, and roofing type (refer to Table 35). The steel roof panels have the more significant impact on LCC and LCGWP for solution 50, while the spray polyurethane foam insulation has a greater impact on LCC and LCGWP for solution 63.

Table 35: Comparison of differing design parameters between solutions 50 and 63 including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 50** | | | **Solution 63** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Regular Gypsum Interior Drywall | 4.7 | 0.9 | Gypsum Fiber Interior Drywall | 8.2 | 1.6 |
| Blown-Cellulose Wall Insulation (5.2 in.) | 1.4 | 1.5 | Spray Polyurethane Foam Wall Insulation (6.0 in.) | 9.5 | 2.9 |
| Steel Roof Panels | 6.2 | 2.7 | Asphalt Shingle Roofing | 3.4 | 0.5 |

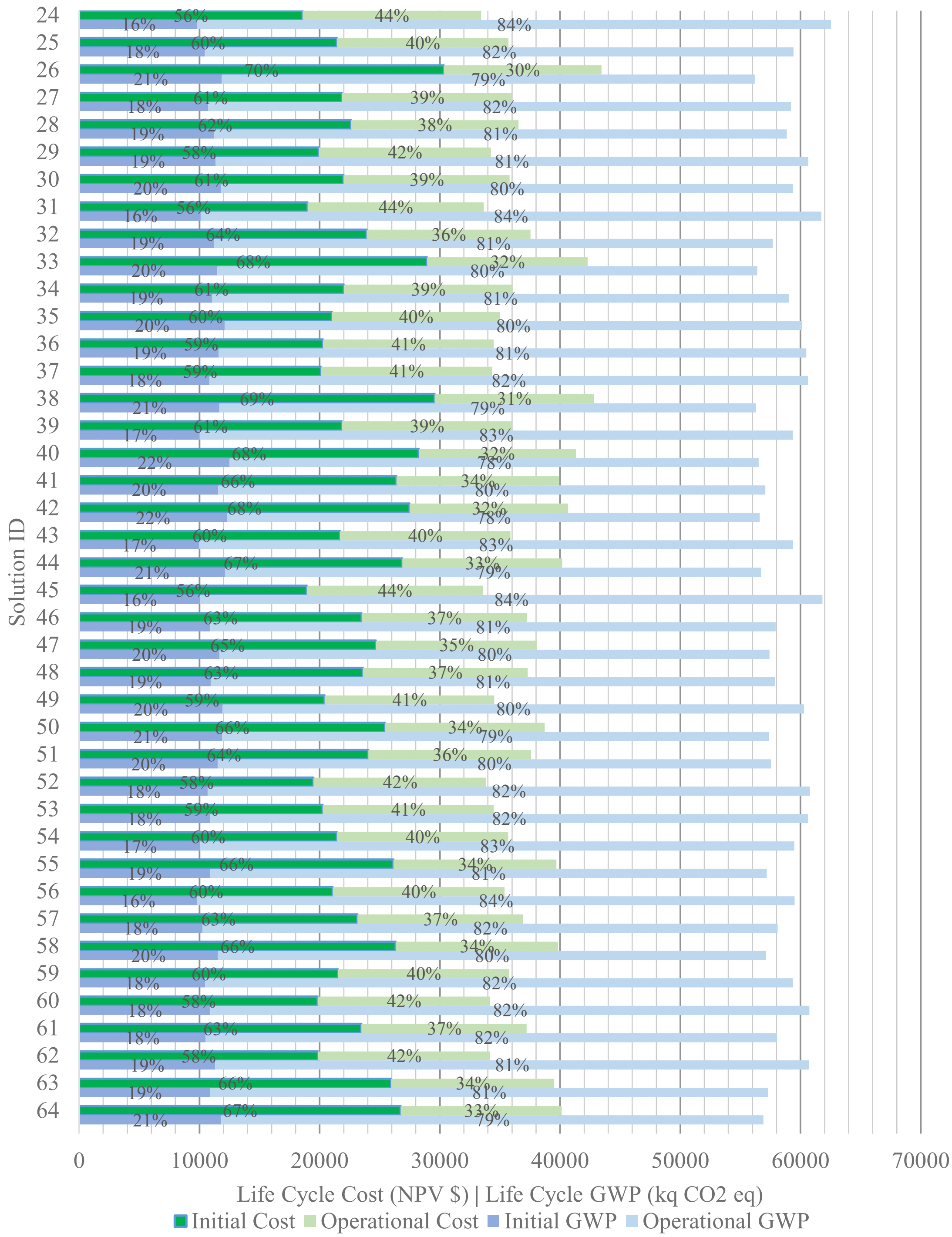



Figure 33: Comparison of LCC and LCGWP for each standard wall with high-performance roof Pareto solution.

#### 8.2.3.2 Double-Stud Wall Solutions

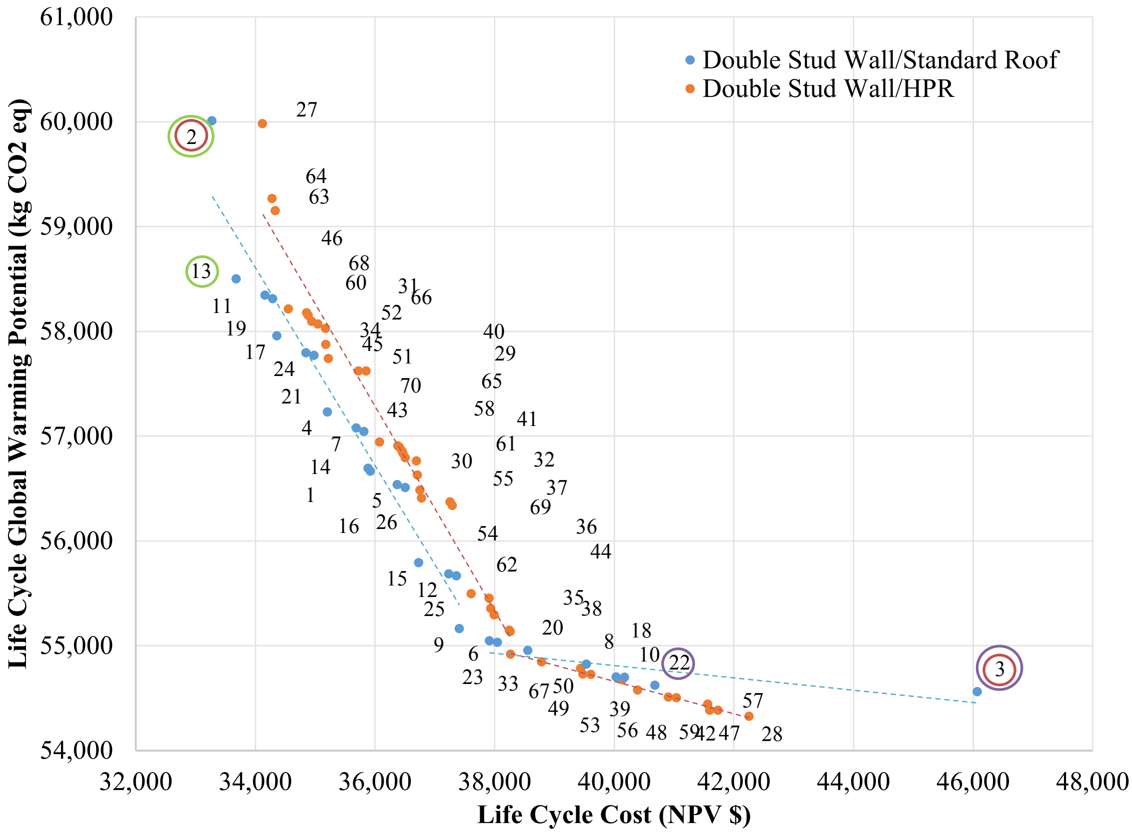



Figure 34: Scatter plot of Pareto solutions for double stud wall assemblies with numbered labels for input parameter reference.

The Pareto optimal solutions for double-stud wall assemblies with standard and high-performance roofs exhibits a similar trend as the standard wall solutions. As shown in Figure 34, the standard roof cases are closer to the global Pareto front for the majority of the solution set until the LCC begins to reach the high end of the spectrum. In other words, once the LCGWP is decreased to approximately 55,000 kg-CO2-eq, additional increases in LCC show relatively smaller decreases in LCGWP. It is also at this point where high-performance roof solutions begin to out-perform standard roof solutions in terms of LCC and LCGWP. The full set of solutions for the standard roof cases and the full set of solutions including the parameters for the high-performance roof cases are presented in Appendix M (refer to Table M2 and Table M3). Also, the Pareto optimal solutions for the high-performance roof in combination with double-stud wall assemblies are similar to the previous section so is not included in this section.

Solutions 2 and 3 (shown in red circles in Figure 34), are the extreme points for the double-stud wall with standard roof cases. Like the standard wall solutions, these points represent either the highest or lowest LCC or LCGWP within the solution space. With the exception of rafter-space insulation in the roof assembly, all other design parameters are different between solutions 2 and 3. Assuming solution 2 as the reference case, solution 3 increases LCC by 38.5%, and as a result, solution 3 decreases LCGWP by 9.1% over a 30 year period. To be more specific, using solution 3 results in an increase of 74.5% in initial costs as well as an increase of 9.0% in initial GWP. However, operational cost and operational GWP decreases by 9.7% and 13.0%, respectively. According to Table 36, the double-glazed windows have the greatest impact on LCC and the vinyl window frames have the greatest impact on the LCGWP for both solutions 2 and 3. However, the exterior cladding in both solutions also have a significant impact on LCC.

Table 36: Comparison of differing design parameters between solutions 2 and 3 including the breakdown of their corresponding impact on LCC and LCGWP.

| Solution 2 | | | Solution 3 | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Fiber-Cement Siding | 9.9 | 3.5 | Wood Siding | 12.3 | 2.9 |
| Regular Gypsum Interior Drywall | 5.5 | 0.9 | Gypsum Fiber Interior Drywall | 7.1 | 1.7 |
| Blown-Cellulose Wall Insulation (3.5 in.) | 1.1 | 1.0 | Blown-Cellulose Wall Insulation (5.2 in.) | 1.1 | 1.6 |
| Vinyl Window Frames | 2.3 | 6.1 | Vinyl-Clad Wood-Core Window Frames | 9.5 | 4.0 |
| Double-Glazed Non-Coated (air-filled) Windows | 12.7 | 1.6 | Triple-Glazed Non-Coated (air-filled) Windows | 13.8 | 2.6 |
| Asphalt Shingle Roofing | 4.1 | 0.5 | Steel Roof Panels | 5.2 | 2.8 |

Solutions 2 and 13 (shown in green circles) appear to show a relatively significant decrease in LCGWP with a relatively small increase in LCC. Taking solution 2 as the reference case, solution 13 increases LCC by 1.2% and decreases LCGWP by 2.5%. This results in a change in LCGWP to a change in LCC ($\Delta_{LCGWP/LCC}$) ratio of 2.1. In other words, for every 1% increase in LCC, there will be a 2.1% decrease in LCGWP. In comparison, the $\Delta_{LCGWP/LCC}$ ratio between solutions 2 and 3 is 0.24. Additionally, solution 13 increases the initial cost by 4.2% and increases initial GWP by 5.8% compared to solution 2. This also results in a decrease in operational cost by 2.8% and operational GWP by 4.3%. The only difference between solutions 2 and 13 is the wall framing thickness. Solution 2 uses blown-cellulose insulation in 2x4 double-stud configuration and advanced framing, while solution 13 uses 2x6 double-stud configuration and advanced framing. This trend emphasizes the importance of the thermal performance of wall assemblies compared to other design parameters.

Solutions 3 and 22 (shown in purple circles) appears to have a relatively significant increase in LCC but with relatively minimal decreases in LCGWP. Taking solution 22 as the reference solution, the LCC of solution 3 is increased by 13.3% while the LCGWP is only decreased by 0.1% over a 30-year period. This results in a $\Delta_{LCGWP/LCC}$ ratio of 0.0075, which is relatively inefficient. Furthermore, with an increase in initial cost by 19.2%, the operational cost and operational GWP is increased by 0.2% and 0.4%, respectively. However, using solution 3 decreases initial GWP by 2.0% relative to solution 22. The only difference between solutions 3 and 22 is the exterior cladding material. Solution 22 uses a fiber-cement board siding while solution 3 uses wood siding. This trend is most likely because the cost of wood siding is significantly more than the cost of fiber-cement board siding and with relatively small increases in thermal performance. This could also mean that exterior cladding has minimal impact on the optimization of a single-family residential building based on the three objective functions.

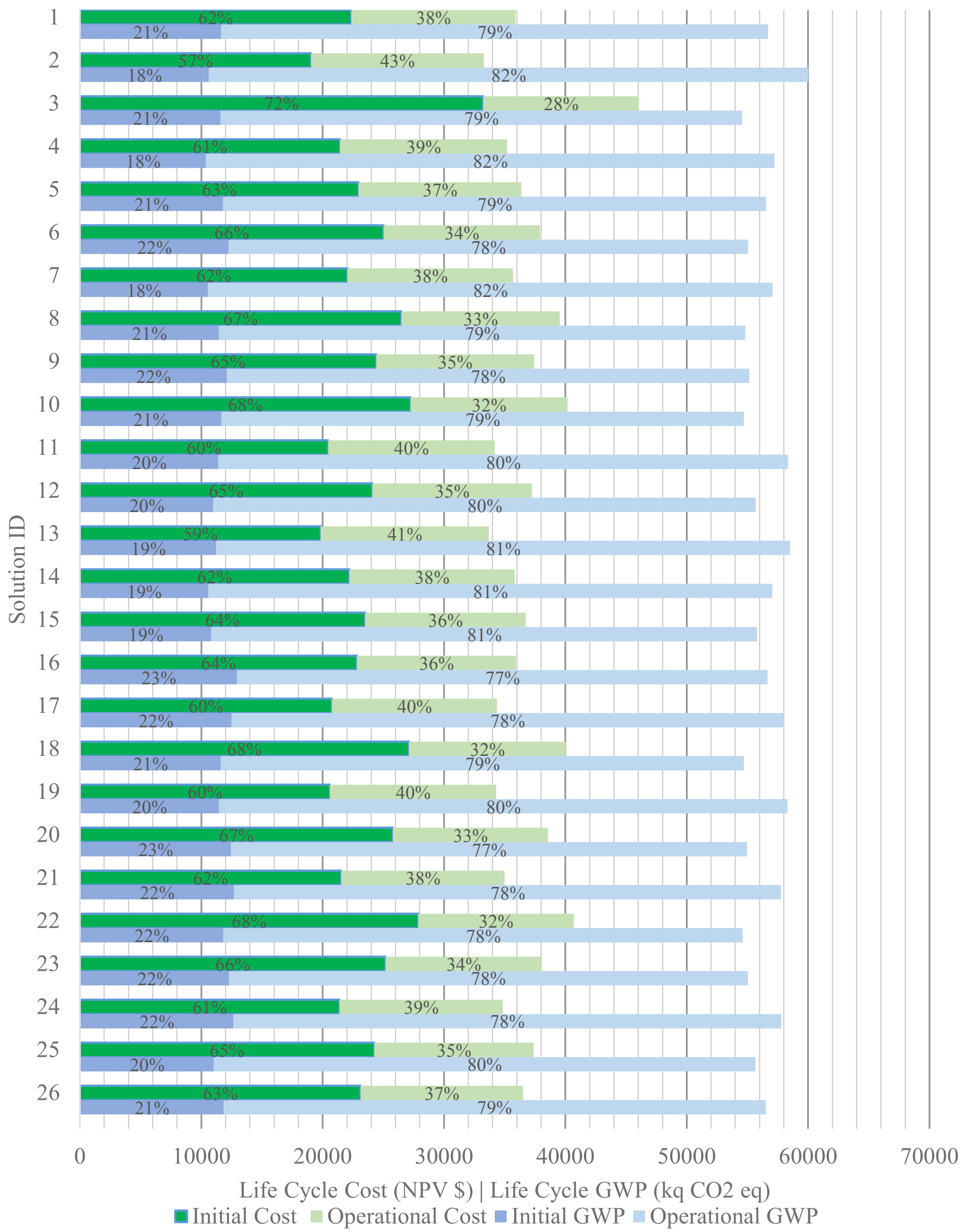



Figure 35: Comparison of LCC and LCGWP for each double-stud wall with standard roof Pareto solution.

### *8.2.3.3 EIFS Solutions*

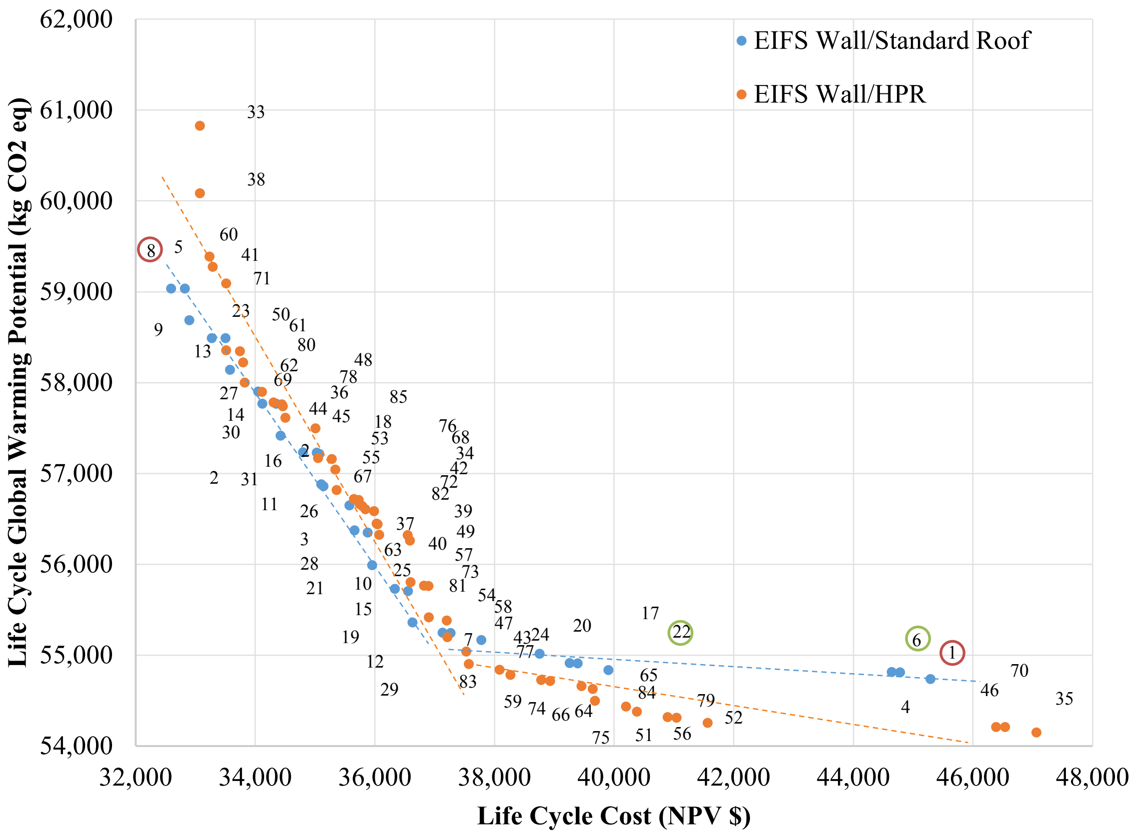



Figure 36: Scatter plot of Pareto solutions for EIFS wall assemblies with numbered labels for input parameter reference.

Based on Figure 36, there appears to be two distinct regions of the Pareto optimal solutions. For the majority of solutions up to a LCC of approximately $37,000, the solutions appear to follow a similar slope. After a LCC of $37,000, the magnitude of decrease in LCGWP per additional increase in LCC are less significant. The same trend exists for both the standard roof and high-performance roof cases. Since the trends are similar between the standard roof and high-performance roof, the high-performance roof solutions will not be discussed in this section. However, a full list of parameters and results for each EIFS wall with standard and high-performance roof solutions are shown in Appendix M (refer to Table M4 and Table M5).

Similar to the standard and double-stud wall Pareto solutions, there are extreme points representing the highest and lowest LCC and LCGWP cases. In this case, solutions 1 and 8 appear to be those extreme points (shown in red circles). Essentially, solution 1 has the least overall environmental impact but has the highest cost, while solution 8 has the highest environmental impact but has the lowest cost. Assuming solution 8 is the reference case, solution 1 results in a 39.3% increase in LCC but results in a 9.7% decrease in LCGWP. With exceptions to the wood sheathing type and the roof insulation/framing type, all other design parameters are different between solutions 1 and 2. According to the results presented in Table 37, the exterior cladding has the largest contributions to LCC in both solutions and the window frames have the greatest impact on LCGWP. Furthermore, by selection solution 1 over solution 8, the initial cost and initial GWP increases by 77.4% and 11.3%, respectively. The operating cost and operating GWP both decreases by 9.8% and 14.2%, respectively. Additional breakdown of initial and operating cost and GWP are shown in Figure 37.

Table 37: Comparison of differing design parameters between solutions 1 and 8 including the breakdown of their corresponding impact on LCC and LCGWP.

| Solution 1 | | | Solution 8 | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Wood Siding | 12.5 | 2.9 | Fiber Cement Siding | 10.1 | 3.4 |
| Vinyl-Clad Wood-Core Window Frames | 9.6 | 4.0 | Solid Wood Window Frames | 2.4 | 6.1 |

Solutions 6 and 22 represent a pair of solutions that has relatively low improvement in terms of decreasing LCGWP with a significant increase in LCC. Assuming solution 22 as the reference solution, solution 6 increases the initial cost, operational cost, and operational GWP by 17.0%, 1.1%, and 1.0%, respectively. The only objective function that decreases is the initial GWP, which decreases by 3.6%. For both solutions 6 and 22, the exterior cladding has the greatest impact on both LCC and LCGWP, as shown in Table 38. Also, the proportions of the initial and operating phases of both LCC and LCGWP are presented in Figure 37.

Table 38: Comparison of differing design parameters between solutions 6 and 22 including the breakdown of their corresponding impact on LCC and LCGWP.

| Solution 6 | | | Solution 22 | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Vinyl Window Frames | 12.6 | 2.9 | Solid Wood Window Frames | 8.3 | 3.8 |
| Double-Glazed Non-Coated (Air-Filled) Windows | 2.2 | 0.6 | Triple-Glazed Non-Coated (Air-Filled) Windows | 4.5 | 0.9 |

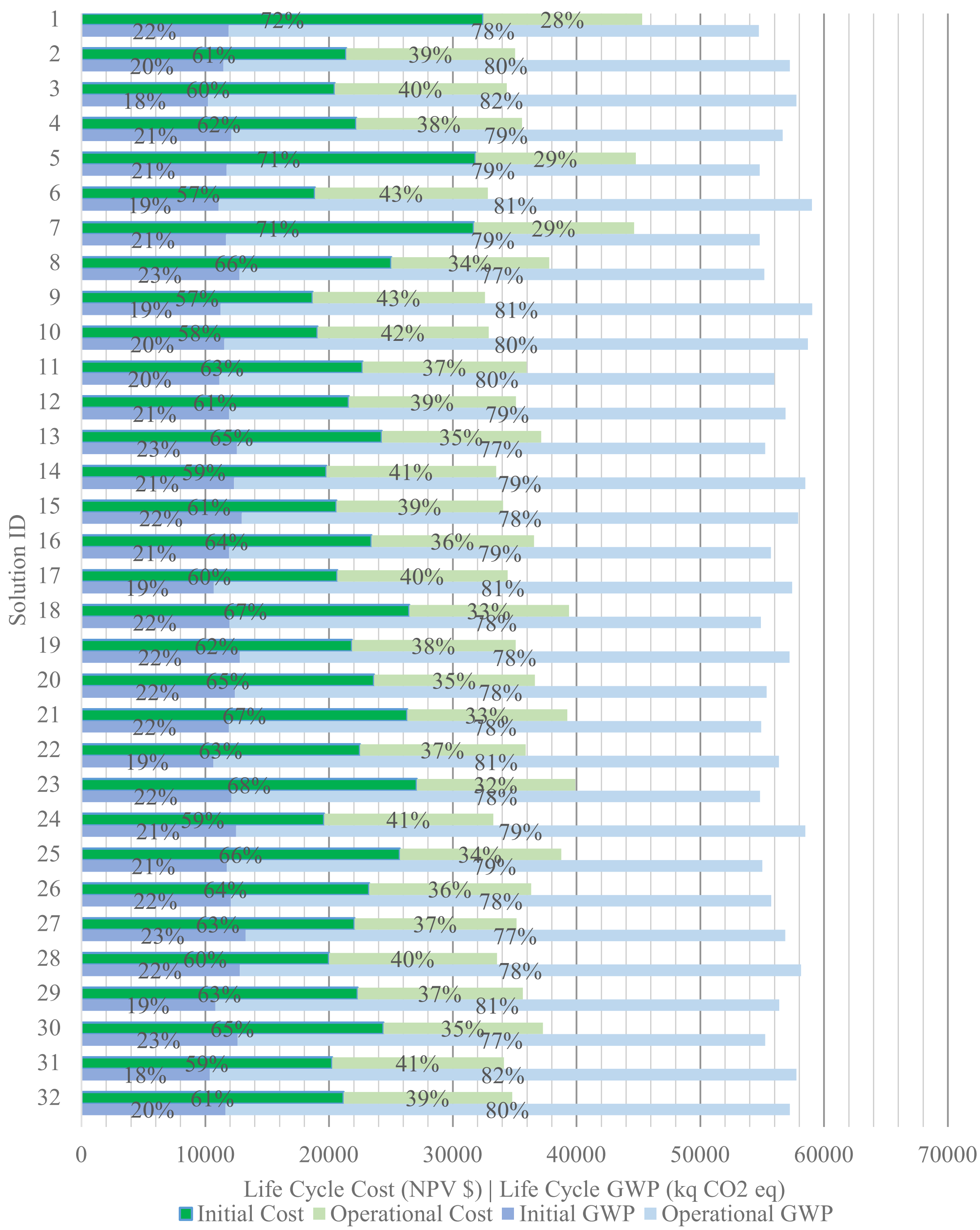



Figure 37: Comparison of LCC and LCGWP for each EIFS wall with standard roof Pareto solution.

#### 8.2.3.4 ICF Solutions

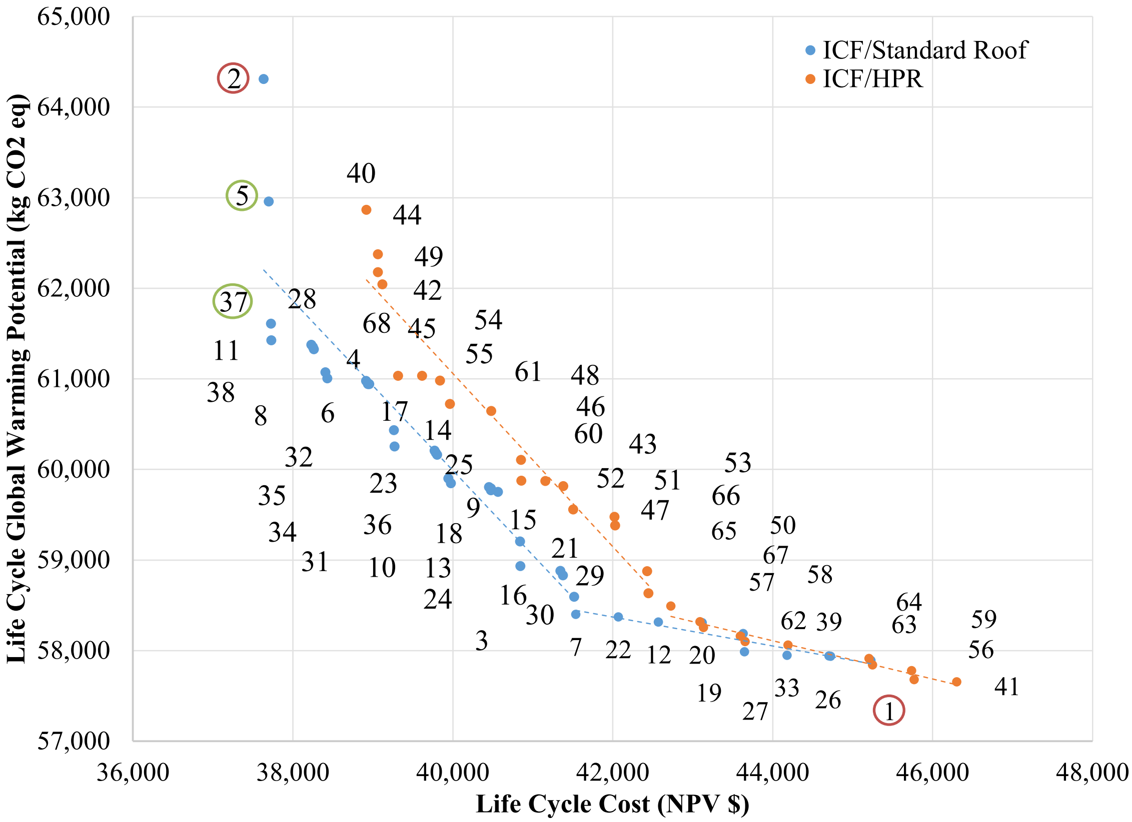



Figure 38: Scatter plot of Pareto solutions for ICF wall assemblies with numbered labels for input parameter reference.

Similar to the optimized solutions of all previous wall and roof assembly types, the ICF wall with standard and high-performance roof exhibits similar trends. The initial increase in LCC decreases the LCGWP of each solution with relatively high magnitude. Once the LCGWP of the solutions reach approximately 58,500 kg-CO2-eq, any solutions with incrementally greater LCC has a smaller impact on the decrease of the LCGWP. This trend is represented by the dashed lines shown in

Figure 38. The full list of input design parameters used to achieve each solution is shown in Appendix M (refer to Table M6 and Table M7).

Solutions 1 and 2 (red circles in Figure 38) represent the extreme points with the highest and lowest LCC and LCGWP out of all ICF wall Pareto optimal solutions. Taking solution 2 as the reference case, solution 1 results in a 20.2% increase in LCC and a 10.0% decrease in LCGWP. Compared to solution 2, solution 1 increases initial cost by 40.4% while decreasing operational costs by 10.7% over a 30-year period. In addition, the initial GWP of the materials and construction is increased by 9.9% while the operational phase GWP is decreased by 14.3% over the same optimization period. The parameters responsible for these differences are the thickness of the ICF concrete core, window and glazing types, roofing type, roof insulation thickness, and ceiling drywall type. According to the analysis conducted in Table 39, the ICF wall assembly has the most significant impact on both LCC and LCGWP in both solutions 1 and 2. However, the window glazing has a relatively large impact on LCC in both solutions as well. In addition, the breakdown of initial and operating phase costs and GWP are shown in Figure 39.

Table 39: Comparison of differing design parameters between solutions 1 and 2 for ICF cases including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 1** | | | **Solution 2** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| ICF (8 in. Core) | 14.6 | 10.7 | ICF (6 in. Core) | 16.0 | 7.8 |
| Vinyl-Clad Wood-Core Window Frames | 9.7 | 3.8 | Vinyl Window Frames | 2.1 | 5.7 |
| Triple-Glazed Non-Coated (air-filled) Windows | 14.1 | 2.4 | Double-Glazed Non-Coated (air-filled) Windows | 11.3 | 1.5 |
| Steel Roof Panels | 5.3 | 2.7 | Asphalt Shingle Roofing | 3.6 | 0.5 |
| Blown-Cellulose Roof Insulation (10.4 in.) | 1.8 | 2.2 | Blown-Cellulose Roof Insulation (5.2 in.) | 1.1 | 1.0 |
| Gypsum Fiber Ceiling Drywall | 3.3 | 0.7 | Regular Gypsum Ceiling Drywall | 2.3 | 0.4 |

Assuming solution 5 as the reference case, solution 37 appears to have significant decreases in LCGWP with relatively minimal increases in LCC. More specifically, by selecting solution 37 over solution 5, the LCGWP is decreased by 2.1% while the LCC is only increased by 0.1%. This results in a $\Delta_{LCGWP/LCC}$ ratio of 21.0, which is relatively significant compared to other solutions within the same Pareto optimal solution set as well as the optimal solution set of other wall and roof type combinations presented thus far. The only differences in design parameters between solution 5 and 37 are in the type of exterior cladding used (i.e. steel vs. fiber-cement siding) and roof thickness (i.e. 2x8 advanced framing vs. 2x12 advanced framing). It appears that the reason for the significant decrease in LCGWP is because the initial GWP of construction and materials for solution 37 decreases by 11.7% while the initial cost only increases by 0.7%. In this case, the exterior cladding type has a greater impact on both LCC and LCGWP in both solutions 5 and 37 (refer to Table 40). As a result, the use of fiber-cement siding has a significant effect on decreasing both LCC and LCGWP compared to steel panel siding.

Table 40: Comparison of differing design parameters between solutions 5 and 37 for ICF cases including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 5** | | | **Solution 37** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Steel Panel Siding | 8.5 | 9.6 | Fiber Cement Siding | 8.7 | 3.4 |
| Blown-Cellulose Roof Insulation (7.0 in.) | 1.5 | 1.4 | Blown-Cellulose Roof Insulation (10.4 in.) | 2.1 | 2.1 |

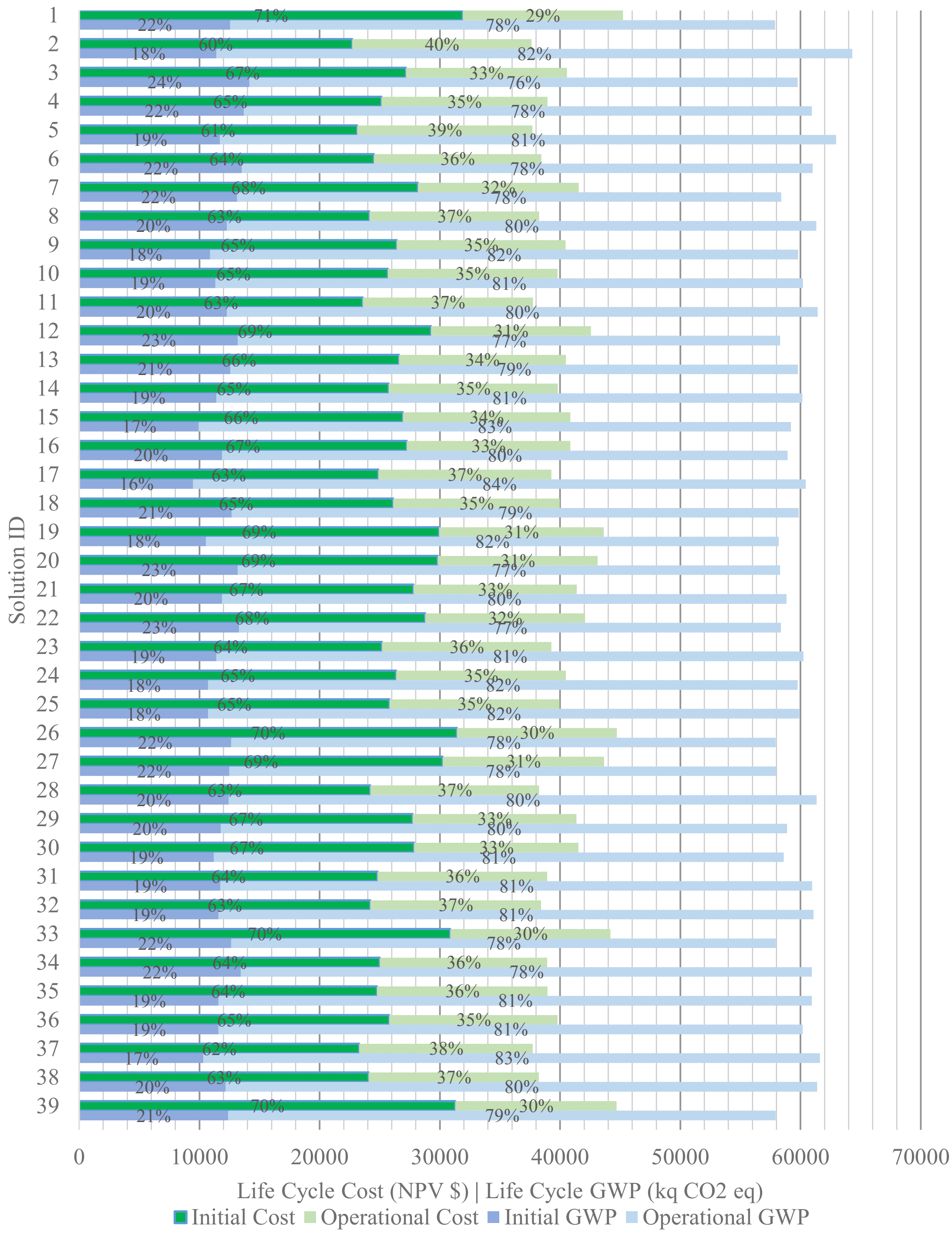



Figure 39: Comparison of LCC and LCGWP for each ICF wall with standard roof Pareto solution.

#### 8.2.3.5 SIP Solutions

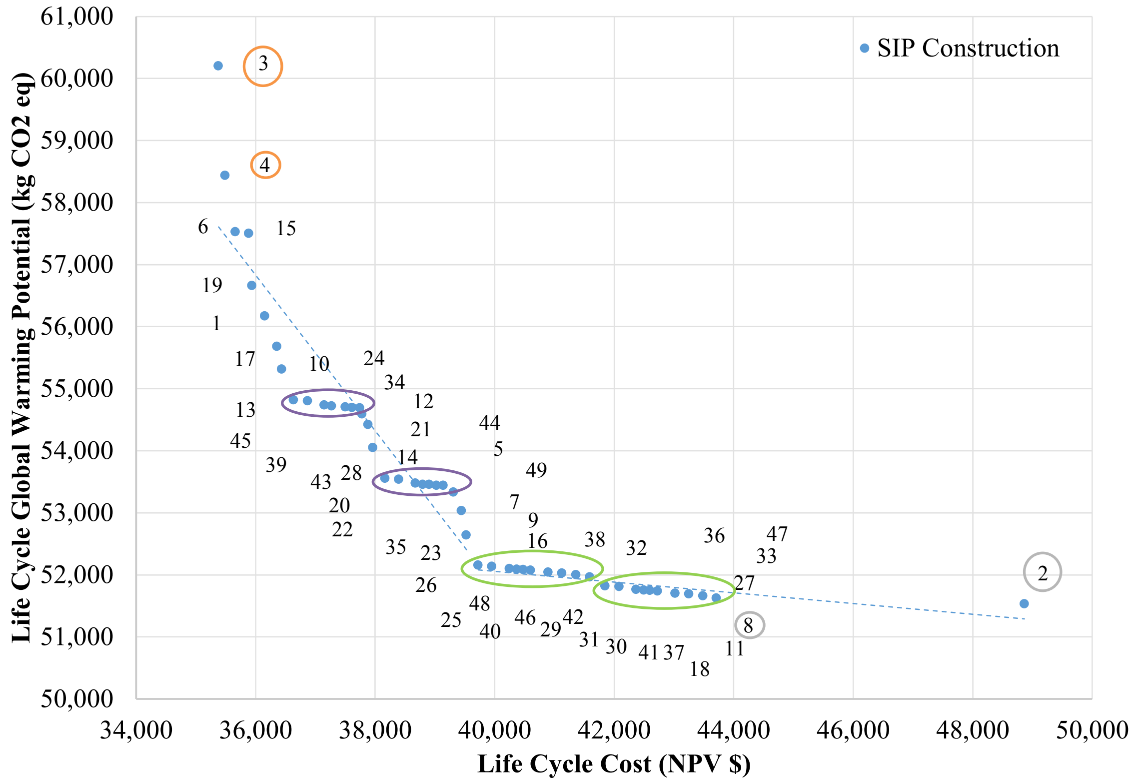



Figure 40: Scatter plot of Pareto solutions for SIP wall and SIP roof assembly with numbered labels for input parameter reference.

Unlike the other wall types previously mentioned, the SIP wall assembly does not require the use of a standard roof or a high-performance roof. Rather, the SIP wall assembly is combined with a SIP roof assembly, which is why Figure 40 only shows a single set of Pareto optimal solutions. There is a relatively large decrease in LCGWP for an additional increase in LCC until the LCGWP reaches approximately 52,000 kg-CO2-eq. After this point, any additional increases in LCC has relatively minimal impact on the decrease of LCGWP. This trend is represented by the dashed lines.

Based on the visual interpretation of Figure 40, there appears to be regions on the Pareto front where LCGWP remains relatively stagnant even with increases to LCC (enclosed in purple). By examining the design parameters used to achieve those solutions in the stagnant regions, it appears that the only design parameter being changed within each purple oval region is the interior drywall type, such as regular gypsum or gypsum-fiber. This trend points to the fact that interior drywall type has a relatively small impact on the LCGWP even with increases in LCC. The same trend can also be seen in the group of solutions enclosed in the green ovals. The only difference is that these solutions use triple-glazed windows rather than the double-glazed windows used in the purple oval region. Another design parameter that is changed between the two green oval regions is the window frame type (i.e. solid wood vs. vinyl-clad wood-core). This confirms the fact that interior drywall has minimal impact on LCGWP for any increases in overall LCC. Also, upgrading from solid wood to vinyl-clad wood-core window frames have minimal impact on decreasing LCGWP. Full list of design parameters used to achieve each solution is shown in Appendix M (refer to Table M8).

Assuming solution 3 as the reference design case, selecting solution 4 increases LCC by 0.3% while decreasing LCGWP by 2.9%. This results in a $\Delta_{LCGWP/LCC}$ ratio of 9.7, which is an improvement in terms of reducing LCGWP with minimal increases in LCC. The only difference in design parameters is in the SIP wall thickness. Solution 3 uses a 3.5 in. EPS core SIP wall while solution 4 uses a 5.5 in. EPS core SIP wall. Furthermore, selecting solution 4 over solution 3 increases initial cost and initial environmental impact by 2.2% and 2.5%, respectively. Selecting solution 4 rather than solution 3 also decreases operational cost and operational environmental impact by 2.5% and 3.9%, respectively.

Even though solution 2 represents an optimal solution with the highest LCC in the SIP Pareto optimal solution set, but it appears to show relatively minimal decreases in LCGWP compared to solution 8. Relative to solution 8, solution 2 increases LCC by 11.8% while only decreasing LCGWP by 0.2%. This results in a $\Delta_{LCGWP/LCC}$ ratio of 0.017 compared to the ratio of 9.7 between solutions 3 and 4. The only design parameter responsible for the increase in LCC is the exterior cladding type. Solution 8 uses fiber-cement siding as the primary exterior cladding material while solution 2 uses wood siding. Selecting wood siding as the exterior cladding has minimal effects on decreasing the environmental impact while increasing LCC. More specifically, selecting wood siding increases the initial cost of materials and construction by 16.5% while only decreasing initial GWP of materials and construction by 1.5%. The operational cost and GWP both have virtually no changes.

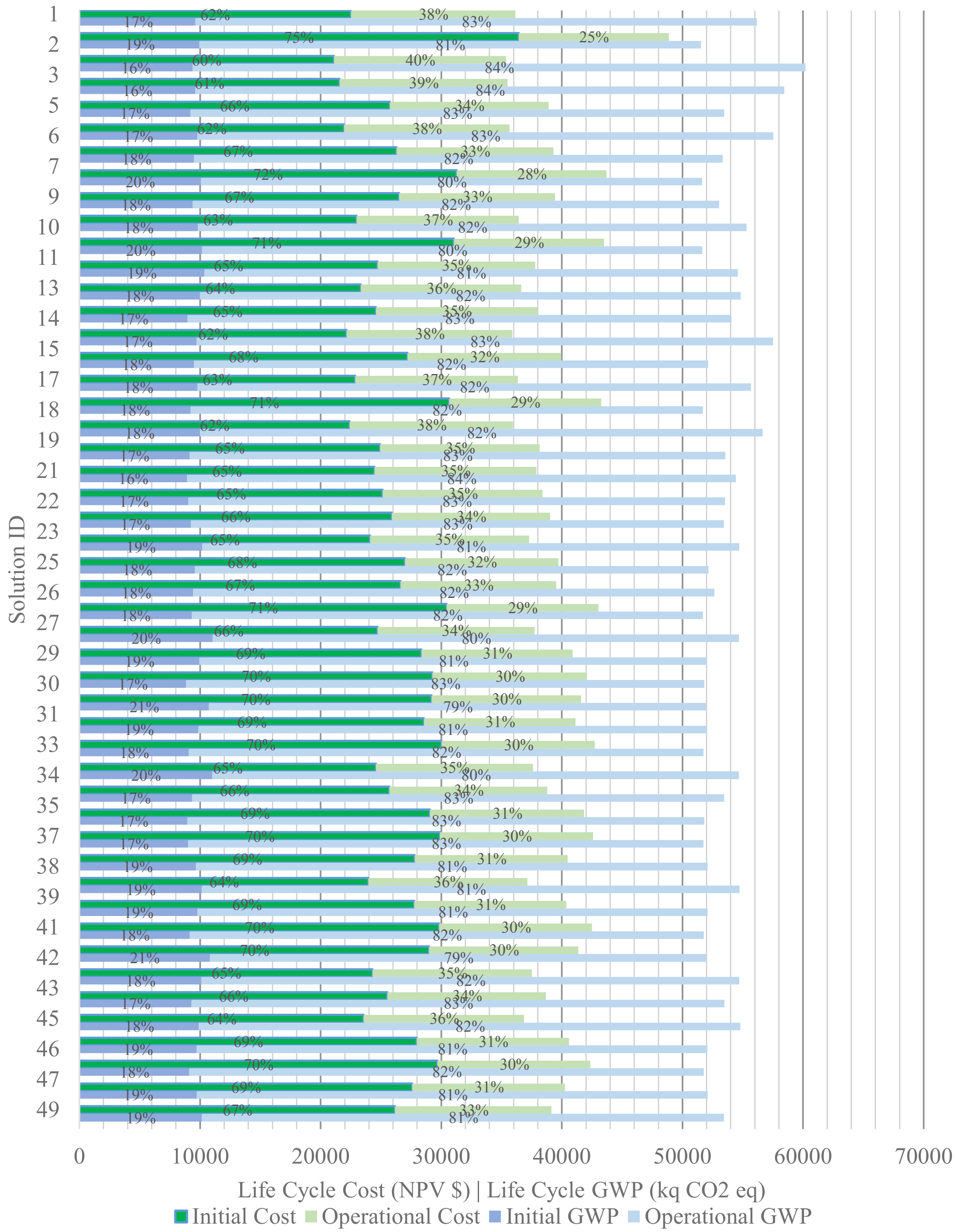



Figure 41: Comparison of LCC and LCGWP for each ICF wall with standard roof Pareto solution.

### 8.2.4 Summary

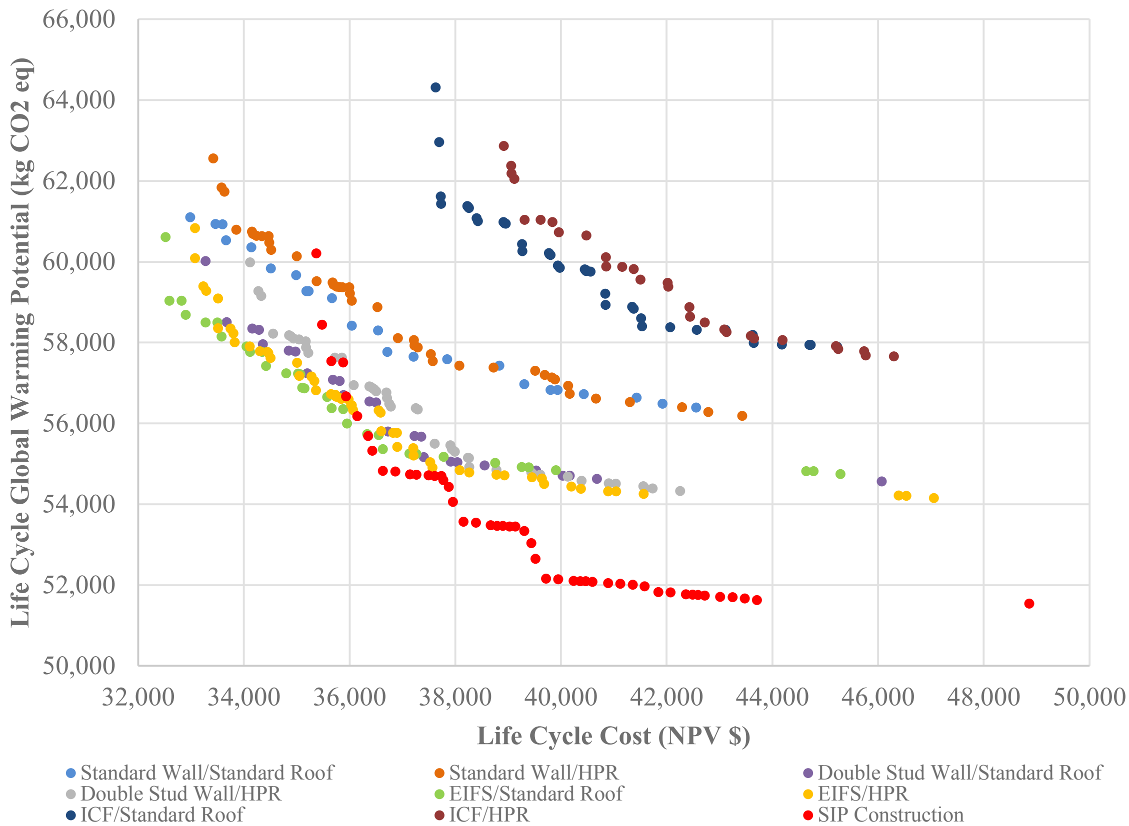



Figure 42: Scatter plot of BESTEST Case 600 Pareto results for all wall types in terms of LCC and LCGWP.

Figure 42 shows the Pareto solution sets for all wall and roof types based on the assumptions made in previous sections of this report. To reiterate, all the solutions on the Pareto front are equal in rank and any single solution is no better than another solution, assuming the same wall and roof type (same color points). Also, all solutions with a PPD greater than 20% are omitted from the Pareto Front. Based on the Pareto Front, there are various clusters of solutions that represent the solutions for different wall and roof types. Based on Figure 42, the best performing solutions appear to be the EIFS wall with standard roof in addition to a SIP wall and SIP roof system. There are also several EIFS wall with HPR assemblies that fall on the global Pareto Front considering all solutions.

Based on the comparison of all wall and roof types considered in this thesis, it appears that the ICF Wall with Standard Roof and ICF with HPR is the least advantageous enclosure system. In other words, the best solutions for ICF wall systems have the highest values in terms of LCC and LCGWP. Furthermore, it appears that the SIP wall and roof system has the lowest possible LCGWP and the EIFS wall with standard roof has the lowest possible LCC compared to all other solution.

It also appears that the solutions for each group of wall and roof type combinations display similar trends. The initial increase in LCC has relatively more significant improvements in terms of a decrease in LCGWP. As the LCC increases further, the LCGWP appears to show less decrease. Each wall and roof combination group shows a similar curve. Finally, a more detailed breakdown of each wall and roof type and their subsequent input parameters are provided in the subsequent sections of this Report.

Based on the results shown in the previous section, there are several noticeable trends that can be noted for each wall and roof type. Firstly, the optimal solutions for each wall and roof combination follow a similar trend. That is, considering the solution with the lowest LCC as the reference point for each group of results, the initial increase in LCC results in the greatest decrease in LCGWP. However, as the LCC continues to increase, the magnitude of decrease in LCGWP reduces. The SIP enclosure system is an example of this because solutions 3 and 4 shows minimal increase in LCC (0.3% increase) while decreasing the LCGWP by 2.9%. On the contrary, solution 2 increases the LCC by 11.8%

while only decreasing the LCGWP marginally by 0.2%, when compared to solution 8. This trend can be found within each wall and roof type combinations.

Another noticeable trend with regards to wall and roof combinations is the impact of HPRs on LCC and LCGWP, when compared to a standard roof. To be more specific, a HPR is no better than a standard roof unless the thermal performance of the HPR in question is significantly higher than a comparable standard roof. This results in a relatively higher LCC when compared to the reference point with the lowest LCC and LCGWP. However, as mentioned in the previous paragraph, the higher the LCC, the less impact the solution has on decreasing the LCGWP. The effects of using a HPR compared to a standard roof is more noticeable with ICF walls and has more significant differences in LCC with similar LCGWP when compared to other wall types such as a standard wall or an EIFS wall.

In terms of the materials and components used to achieve each solution, there are also tendencies to use certain materials over others. For most wall assembly types, the Fiber Cement siding is the most prevalent exterior cladding material and the OSB is the most dominant sheathing material. For example, all solutions for the standard wall and standard roof type combination incorporates the use of Fiber Cement siding and OSB sheathing.

Not all input parameters are significantly more prevalent than others in the same category. For instance, the glazing type used for solutions in the standard wall and standard roof combinations is not uniform. Figure 43 shows that triple-glazed, air-filled, non-coated windows are selected 14 times, while double-glazed, air-filled, non-coated windows are only selected 9 times. The same can be said for wall stud space insulation for the same wall and roof type combinations. Figure 44 shows that blown cellulose insulation in 2x6 advanced framing is selected 9 more times when compared to spray foam insulation in 2x6 advanced framing. However, these results do not necessarily mean one material or component type is significantly better than another, it simply indicates that a particular material or component produces a better overall result in combination with all other considered input parameters such as window frame type, roofing type, etc.

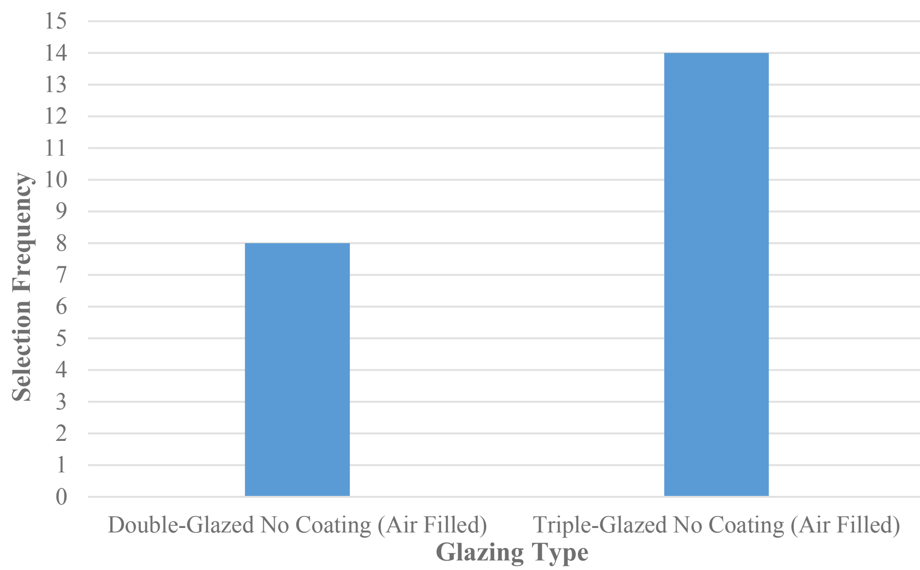



Figure 43: Column chart showing the number of times each glazing type is selected to achieve solutions for standard wall and standard roof type combinations.

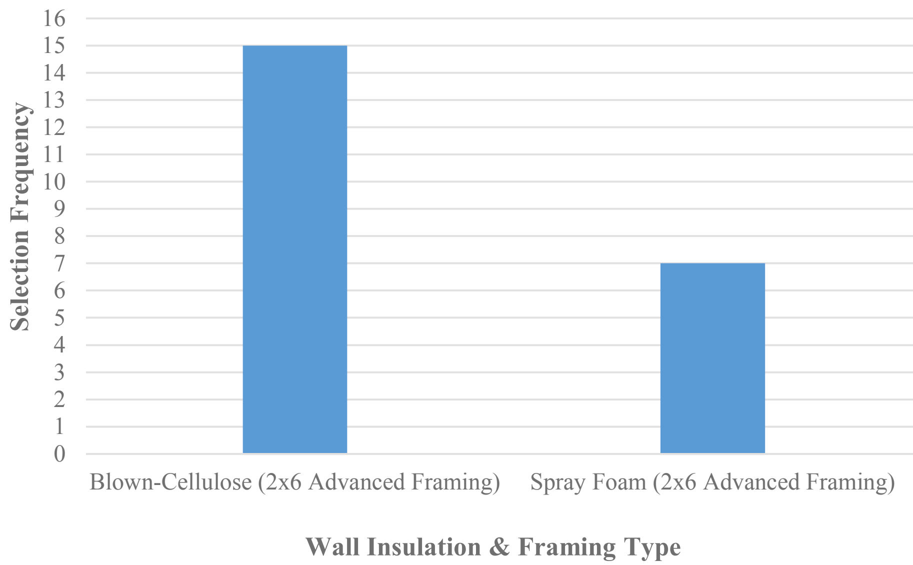



Figure 44: Column chart showing the number of times each stud space insulation type is used to achieve solutions for standard wall and standard roof type combinations.

Air infiltration has a significant impact on the overall performance of the building. Air infiltration (denoted by ACH), when set at different levels, can significantly affect the overall LCC and LCGWP solutions. Figure 45 shows distinct differences in terms of LCC and LCGWP for both ICF and SIP construction. The solutions enclosed in the red oval represent ICF and SIP construction solutions with a pre-defined air infiltration rate of 1.5 ACH at 50 Pa. while the blue oval represents the same wall and roof type combinations with a pre-define air infiltration rate of 0.5 ACH at 50 Pa. It is evident that SIP construction performs better than ICF wall construction with standard roof, but the main difference is in the air infiltration rate of the building.

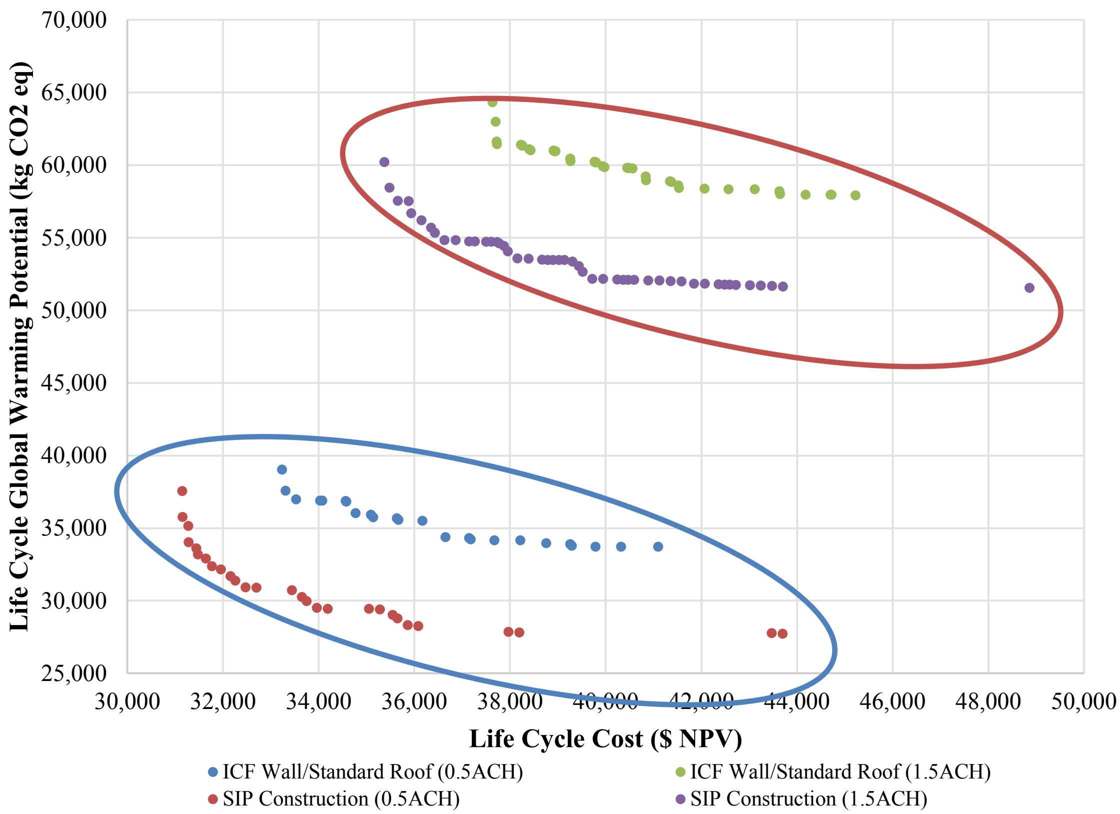



Figure 45: Scatter plot showing the effect of air infiltration (ACH) on overall building performance.

When comparing all wall and roof type combinations, as shown in Figure 46, there are distinct ranks in terms of LCC and LCGWP that make certain solutions better than others. The three ovals with different colors (orange, green, and red), presents a visual distinction between groups of solutions. More specifically, the orange oval encircles EIFS wall with Standard Roof, EIFS wall with HPR, Double Stud Wall with Standard Roof, Double Stud Wall with HPR, and SIP Construction. The green oval encircles the Standard Wall with Standard roof and Standard Wall with HPR. Lastly, the red oval encircles solutions generated by ICF wall with Standard Roof and ICF wall with HPR. It is apparent that solutions in the orange oval perform better than solutions in the green oval, and that solutions in the green oval perform better than solutions in the red oval.

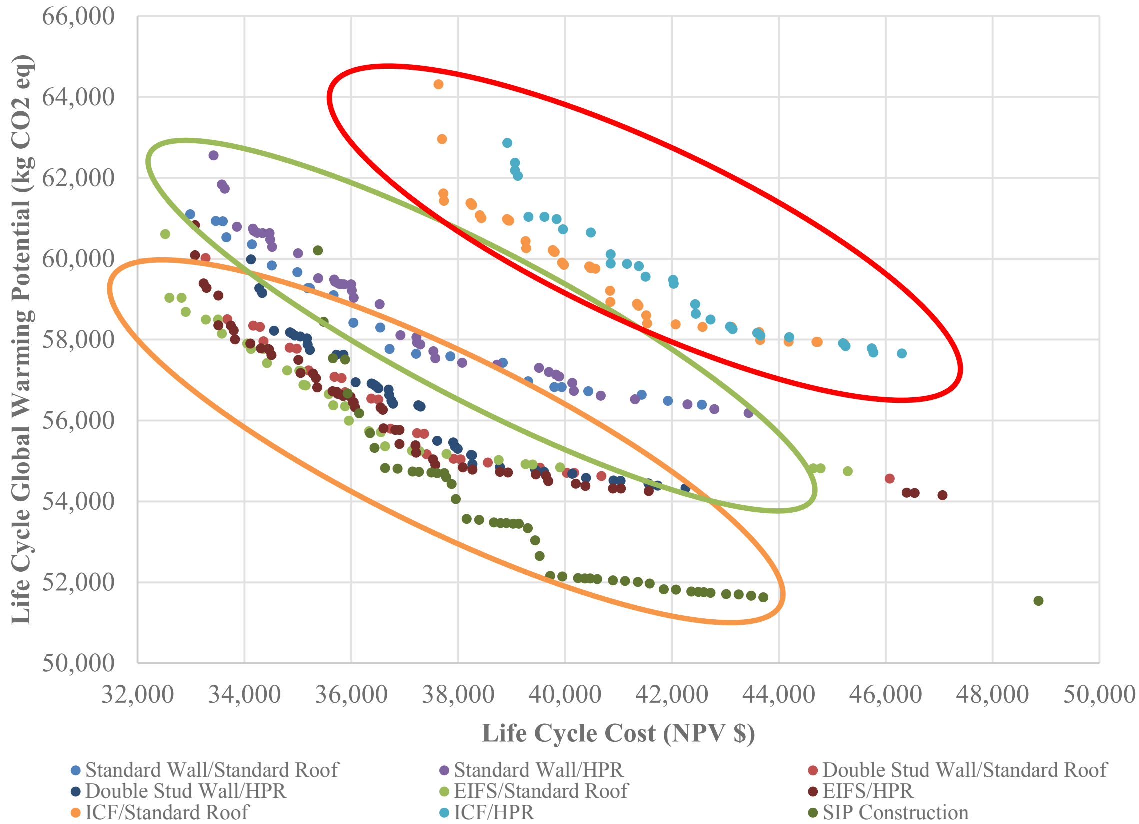



Figure 46: Scatter plot showing results for all wall and roof type combinations with additional annotations.

In conclusion, the best overall solutions appear to be generated by a combination of EIFS Wall with Standard Roof in addition to SIP Construction, which contains both SIP walls and roofs. However, this is considering a standardized air infiltration rate of 1.5 ACH across all construction types, so an ICF wall construction with an air infiltration rate of 0.5 ACH can potentially perform better than all solutions. Figure 47 shows the significant impact of air infiltration rate on the overall building performance. The orange oval represents solutions from ICF wall constructions with standard roof assemblies while the green oval encloses all other solutions.

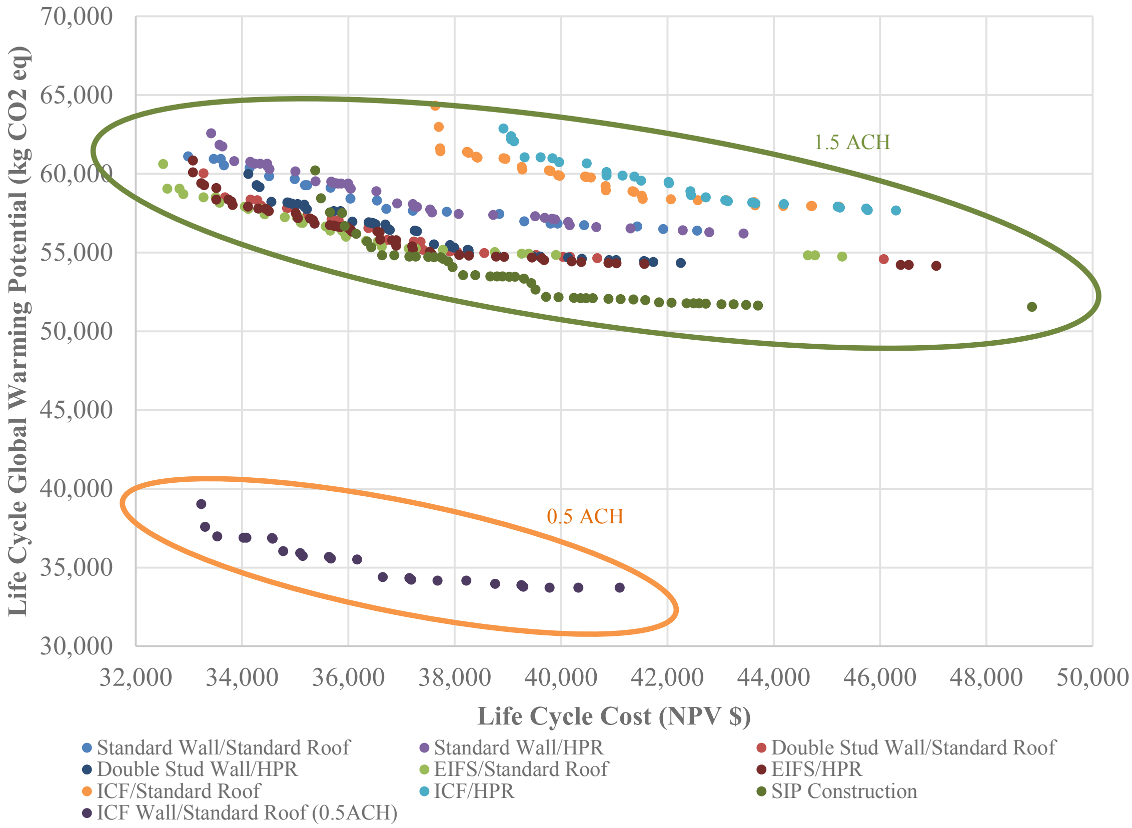



Figure 47: Scatter plot showing the impact of air infiltration on overall building performance regardless of building enclosure type.

## 8.3 Case Study Model (Harmony House)

For the purpose of validating the optimization methodology beyond a hypothetical or pseudo model, a real-life single-family residential home is taken as a case study. More specifically, the Harmony House, located in Burnaby, British Columbia, is a product of the CMHC EQuilibrium™ Sustainable Housing Demonstration Initiative. The Harmony House project is a two storey home with a basement which includes a self-contained secondary suite, and an attached 2-vehicle garage (CMHC 2011). Moreover, this project is chosen as the case study for this research thesis because of convenient access to building specifications and design information. The Harmony House project is also built with advanced building technology in mind and incorporates high performance enclosures, which is the main focus of this research project. Further Harmony House related details and specifications are provided in the following section of this report.

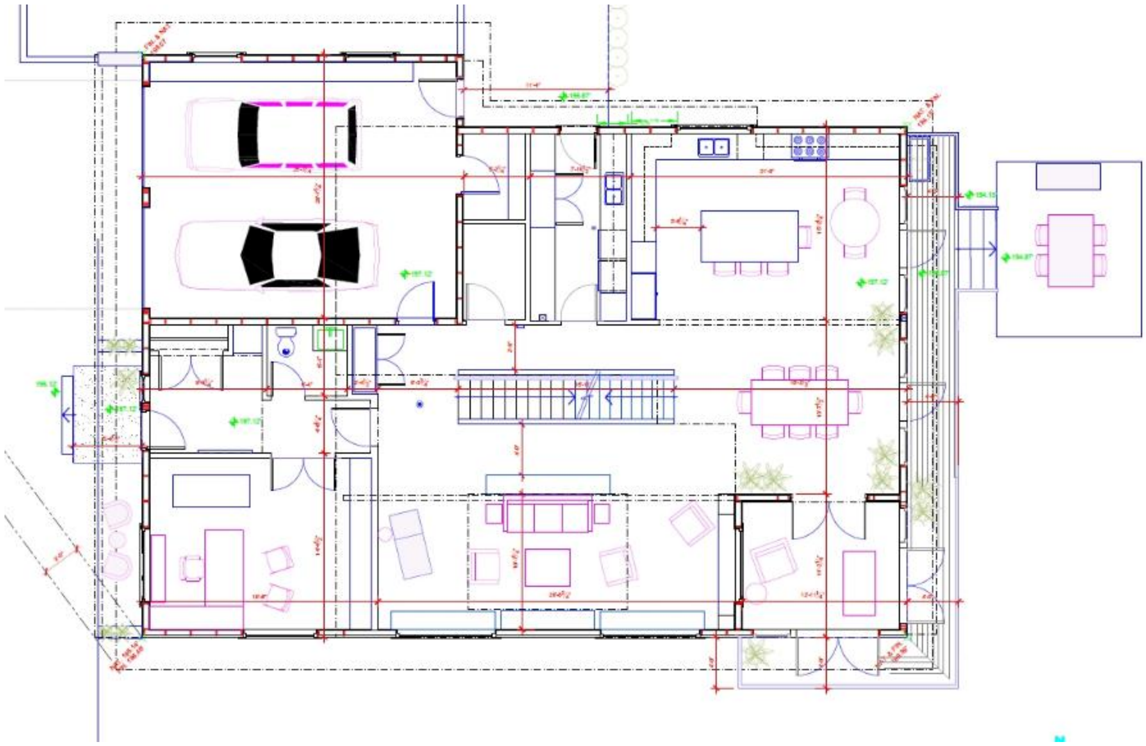


Figure 48: Diagram showing the main-level floor plan of the Harmony House with dimensions and specifications (Habitat Design+Consulting Ltd.).

There is a 194 m$^2$ main floor living area, shown in Figure 25, with an open-concept design with a combined living and dining area, solarium, kitchen, two-piece powder room, office, bedroom, and laundry room. There is also a 113 m$^2$ second floor that includes the master bedroom with four-piece ensuite and walk-in closet, two other bedrooms, a three-piece bathroom, and a spacious hallway open to the living and dining room on the floor below. Additionally, there is a 131 m$^2$ basement suite that has its own entrance from a below-grade patio on the south-east corner of the building. The basement suite consists of a combined kitchen, dining and living area, a three-piece bath, two bedrooms, a laundry room and a storage/mechanical room. There are also two crawl spaces attached to the basement which have approximately half the height the main basement areas (CMHC 2011).

For the purpose of this research project, only the enclosure assemblies/components and mechanical systems are discussed in detail. Even though the Harmony House contains numerous features such as solar hot-water heating, solar PV panels, etc., those components are not included in the case study model because they do not directly impact the thermal performance of the building. Now, the exterior enclosure assemblies is highly insulated and well-sealed. The foundation consists of a 127 mm concrete floor slab that rests on 100 mm panels of extruded polystyrene (EPS) Type II rigid insulation, yielding an RSI value of approximately 3.5. The foundation wall is primarily built with an insulated concrete form (ICF) system which comprises of 57 mm EPS on the exterior face with 200 mm of reinforced concrete and 210 mm of EPS insulation covered with 12.5 mm drywall on the interior face. Overall, this below-grade ICF systems results in an RSI value of approximately 7.9 (CMHC 2011).

The above-grade exterior wall systems consists of 38 mm x 140 mm studs at 610 mm on center, which results in an advanced framing configuration that reduce the amount of lumber in the wall by approximately 15%, while keeping code required structural integrity. The exterior sheathing is primarily 12.5 mm plywood with wood fiber reinforced cement lapped siding attached to 10 mm x 50 mm vertical strapping. In terms of the wall insulation, it consists of several layers made up of 50 mm thick foil faced isocyanurate foam board placed in the study cavity along the inside face of the exterior sheathing, 15 mm thick vacuum insulated panels (VIPs), and 76 mm castor bean oil based open cell spray foam insulation applied over the inside face of the VIPs. The resulting wall insulation effective RSI value is 6.6. The roof, represented as the red areas in Figure 49, consists of 50 mm foil faced isocyanurate foam board insulation, a vapor permeable water proof membrane, 16 mm plywood sheathing, and 400 mm deep I-joists (610 mm on center and filled with low density castor bean-oil cased spray foam insulation). The overall effective roof RSI value is approximately 10.6 (CMHC 2011).

The Harmony House uses high-performance fiberglass frame, argon filled, low-emissivity triple glazed windows. These windows can be visualized in Figure 49 as opaque blue areas. The windows have a center of glass RSI value of 1.4 and an overall U-value of 0.125. These high-performance windows, walls, and roof assemblies in conjunction with proper sealing results in an air-leakage rate of 0.75 ACH at 50 Pa, which is determined by a blower door test. In addition, the building uses a high-efficiency air source heat pump (ASHP) that provides the majority of heating throughout. The ASHP (rated at 40,000 btu/h) has a Heating Seasonal Performance Factor (HSPF) of 9.4 and its Coefficient of Performance (COP) ranges from 1.4 to 3.19, depending on exterior temperatures (CMHC 2011).

Figure 49 provides a visualization of the Harmony House model that is used for energy simulations and optimization. EnergyPlus converts the geometric model into text-based data that is then used to size the mechanical systems prior to a full energy simulation.

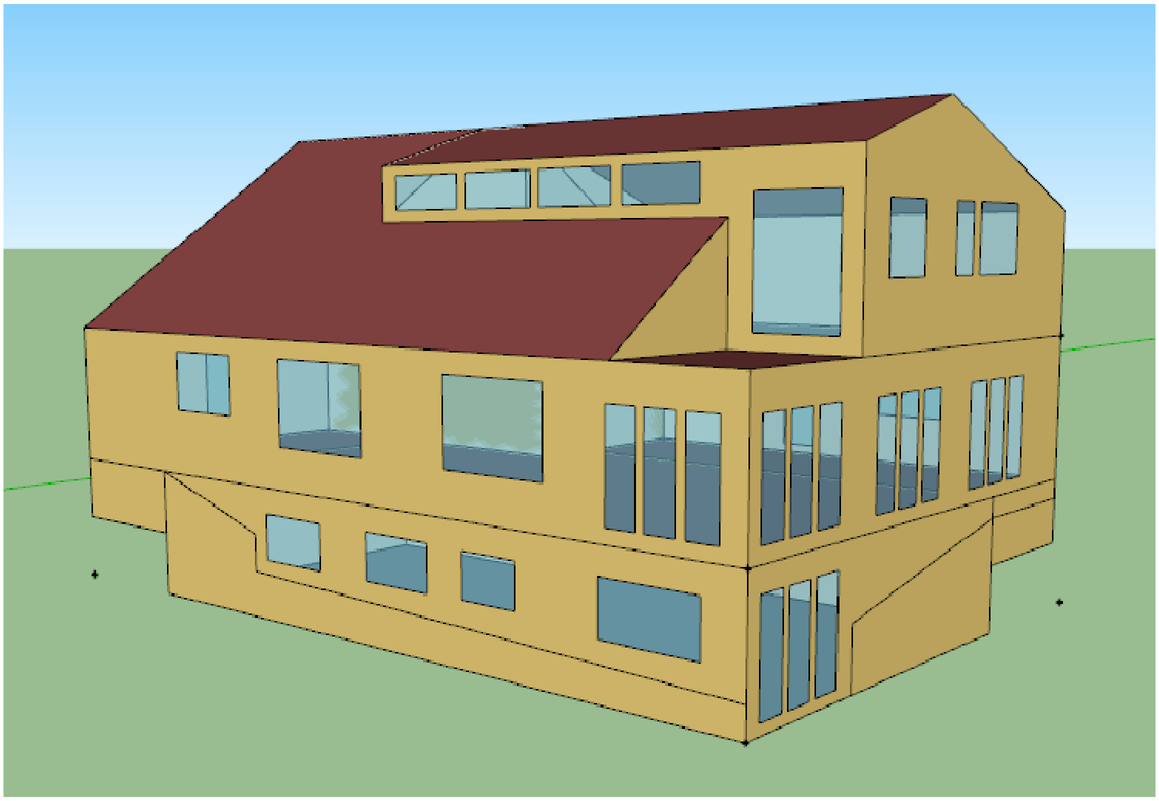


Figure 49: South-east view of the Harmony House geometric model developed in Google Sketchup with an OpenStudio plugin.

### 8.3.1 Harmony House Model Calibration

As mentioned in previous sections, the BESTEST validation model is used as a benchmark in order to test the validity and accuracy of the energy model. It is also used to test the energy model in terms of input parameters, material properties, and various optimization related variables. Now, the purpose of modelling a real building, such as the Harmony House, is to further validate the energy model and to understand how the optimization will work when applied to a full-sized residential building. It is also used to compare the optimization results between the Harmony House model and the BESTEST model.

In order to calibrate the Harmony House to match the actual collected energy consumption data provided by BC Hydro, an EnergyPlus model is created with geometry that matches available floor plans, elevations, and various design specification. Furthermore, weather data collected from BCIT Burnaby campus is used as the main weather data for calibration because the weather data provided by BC Hydro does not contain adequate solar radiation data. All other parameters are calibrated using the same method discussed in section 8.2.1 of this report.

The calibration results shown in Table 41 presents the comparison between actual monthly energy consumption data collected by BC Hydro and the monthly energy consumption data generated as a result of the Harmony House energy simulation model. The Harmony House energy simulation model uses the input design parameters shown in section 8.3.2. Table 41 shows that the Harmony House model developed as part of this research is in relatively close agreement with real-world collected energy consumption data.

Table 41: Difference in monthly and annual energy consumption between BC Hydro data and EnergyPlus model results in kilowatt-hours (kWh).

| Harmony House | BC Hydro Collected Energy Consumption Data (kWh) | Benchmark Model Energy Consumption Data (kWh) | Percentage Difference |
|---|---|---|---|
| January | 2001 | 2023 | 1.12% |
| February | 1484 | 1457 | -1.79% |
| March | 1170 | 1159 | -0.92% |
| April | 739 | 745 | 0.78% |
| May | 515 | 508 | -1.29% |
| June | 462 | 440 | -4.88% |
| July | 402 | 431 | 7.29% |
| August | 470 | 431 | -8.12% |
| September | 610 | 581 | -4.83% |
| October | 762 | 753 | -1.19% |
| November | 1295 | 1236 | -4.57% |
| December | 1766 | 1759 | -0.42% |
| Annual | 11677 | 11525 | -1.30% |

### 8.3.2 Input Parameter Settings

In the Harmony House case study, the simulation period runs between January 1 and December 31 of 2013. A TARP algorithm is used for inside surface convection calculations and the DOE-2 algorithm is used for outside surface convection. The simulation is divided into 2 time-steps per hour with each time-step being 30 minutes.

The interior design temperature threshold is set between 20°C and 27°C throughout the entire simulation period. In other words, if the indoor temperature drops below 20°C, the heating system will turn on. Additionally, the air infiltration rate of each building type is assumed to be constant at 1.5 ACH with exceptions. However, the building types with

ICF and SIP wall assemblies will be optimized in separate cases of both 1.5 and 0.5 ACH at 50 Pa. These air infiltration rates are used instead of the stated air infiltration rate of 0.75 ACH at 50 Pa because the optimization model is based on the BESTEST Case 600 model, which does not provide a baseline air infiltration rate

The weather file "*weather_vancouver.epw*" based in Burnaby, British Columbia, Canada is used for the energy simulation model for the Harmony House. The weather data is custom collected by BCIT at the Burnaby campus. There are also numerous other typical EnergyPlus input parameters that can be found in Appendix F of this Report (i.e. *HarmonyHouse.imf*). In addition, the Harmony House model will use the same electricity rates to calculate the LCC based on the operational phase of the building.

The simulations are separated by wall type and each wall type represents a separate optimization job. More specifically, the wall types are split into: standard wall, double stud wall, EIFS (split insulation) wall, Structural Insulated Panels (SIPs), and Insulated Concrete Form (ICF) walls. In addition, the roofs are separated into a standard code compliant stud insulation roof design and a high performance roof (HPR) assembly. The HPR is essentially a standard code compliant roof design with additional layers of continuous insulation.

### 8.3.3 Optimization Results

Once the input parameters are prepared and setup for optimization, the Harmony House model can then be optimized using the same optimization parameters as the BESTEST 600 benchmark study. The population size is 50 and the maximum number of generations is 500, resulting in a maximum of 25000 simulations for optimization purposes. Based on the optimization parameters used by other studies and research, a crossover rate of 80%, mutation rate of 20%, and a tournament selection size of 2 is used. All solutions with a PDD greater than 20% is rejected from the list of possible optimal solutions since they do not meet the ASHRAE 55 comfort requirements. PPD is not shown as an axis in the final results because any solution with a PPD below 20% is assumed to be optimal and differentiating solutions based on PPD is less meaningful. For instance, a percentage difference of 1% in PPD between two solutions is less significant compared to a 1% difference in LCC or LCGWP.

#### *8.3.3.1 Standard Wall Solutions*

On average, the standard wall with HPR Pareto solution set appears to have a more significant impact on reducing GWP compared to the standard wall with standard roof Pareto solutions, and this is shown by the dashed lines in Figure 50. Also, compared to the standard wall Pareto solution set for BESTEST Case 600, there are fewer optimal solutions to select within the Harmony House solution space. The Harmony House standard wall solution set has 24 standard roof solutions and 9 HPR solutions. In comparison, the BESTEST Case 600 standard wall solution set has 23 standard roof solutions and 41 HPR solutions. The fewer number of Pareto optimal solutions is likely because of the larger size of the Harmony House, in terms of geometry, as compared to the Case 600 model. The larger dimensions of the Harmony House model increases the amount of materials used as well as the interior volume that needs to be heated. As a result, the initial and operating costs and GWP will increase significantly in comparison.

The differences in terms of the objective functions, which are directly affected by the design parameters, will also be greater. Another possible reason for the fewer number of Pareto optimal solutions for the Harmony House case is because the larger interior space is more difficult to satisfy the occupant thermal comfort level of 20% PPD and below. More specifically, since the Harmony House model is only heated and not cooled, it is likely that fewer combinations of design parameters can prevent the building from being over-heated during summer months.

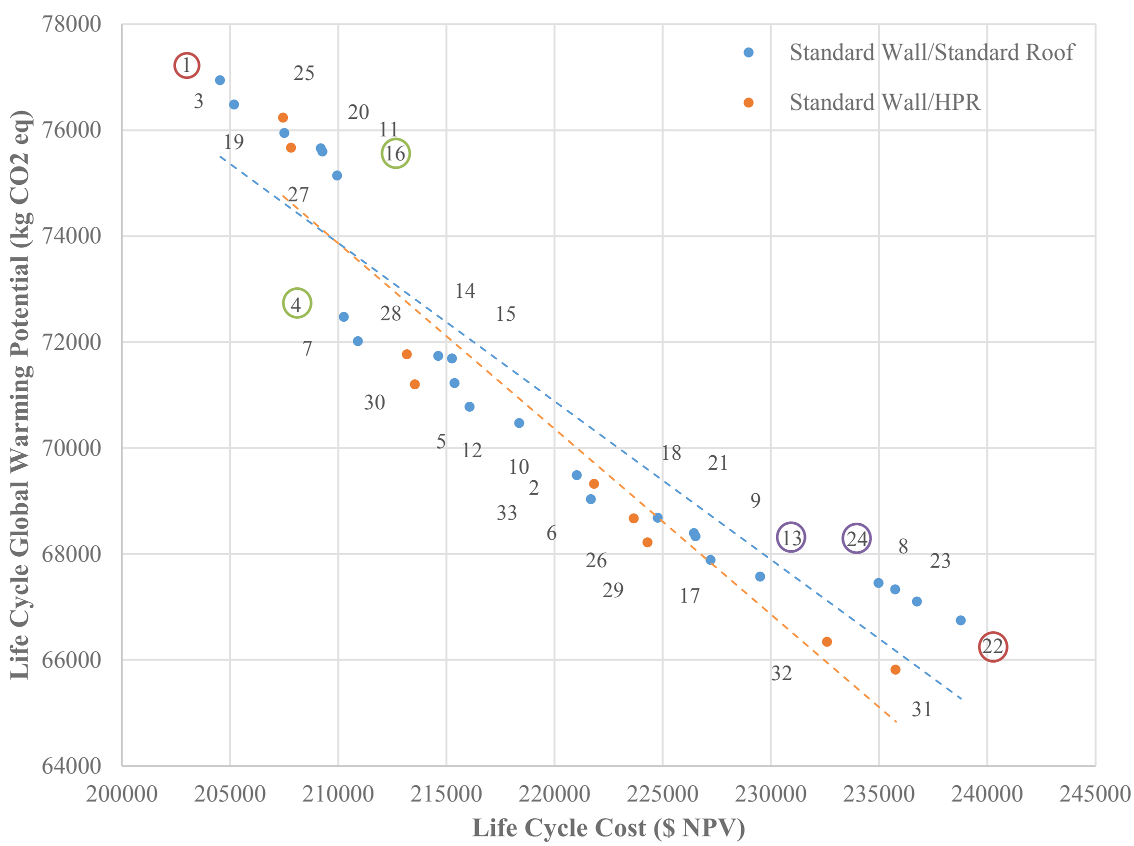



Figure 50: Scatter plot of Pareto solutions for the standard wall assemblies with numbered labels for input parameter reference.

Assuming solution 1 (red circle) has the reference design case with the lowest LCC and highest LCGWP, solution 22 (red circle) has the highest LCC and lowest LCGWP for the standard roof cases. Selecting solution 22 over solution 1 increases LCC by 16.7% and decreases LCGWP by 13.3%. Solution 22 has a $\Delta_{LCGWP/LCC}$ ratio of 0.80 over solution 1. With exceptions to the roofing type and interior ceiling drywall type, all other design parameters are different between solutions 1 and 22, as shown in Table 42 (refer to Appendix O for a full list of parameters and results for the standard roof and HPR solution sets). As a result, selecting solution 22 increases initial cost and initial GWP by 31.8% and 7.6%, respectively. Compared to solution 1, solution 22 also decreases operational cost by 28.9%, but increases operational GWP by 7.4%. Table 42 compares the relative impacts of each design parameter that is different between solutions 1 and 22 on the LCC and LCGWP. In the case for solution 1, the double-glazed Low-E coated (argon-filled) windows represent the highest proportion of LCC and the vinyl window frames have the most impact on LCC. For solution 22, the vinyl-clad wood-core windows affect the overall LCC and LCGWP most significantly.

Table 42: Comparison of differing design parameters between solutions 1 and 22 for standard wall cases including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 1** | | | **Solution 22** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Fiber Cement Siding | 5.4 | 9.0 | Stucco Siding | 6.3 | 5.6 |
| OSB Sheathing | 2.2 | 3.2 | Plywood Sheathing | 2.7 | 3.1 |
| Regular Gypsum Wall Drywall | 1.6 | 1.3 | Gypsum-Fiber Wall Drywall | 1.6 | 1.5 |
| Vinyl Window Frames | 1.8 | 23.0 | Vinyl-Clad Wood-Core Window Frames | 8.8 | 15.6 |
| Double-Glazed Low-E Coated (argon-filled) Windows | 11.1 | 6.0 | Double-Glazed Non-Coated (air-filled) Windows | 8.5 | 6.8 |
| Blown-Cellulose Roof Insulation (10.4 in.) | 1.8 | 7.9 | Blown-Cellulose Roof Insulation (5.2 in.) | 0.8 | 4.6 |

Solutions 4 and 16 (green circles) represent two optimal solutions where a small increase in LCC results in a relatively large decrease in LCGWP. Taking solution 16 as the reference case, solution 4 increases LCC by 0.1% while decreasing LCGWP by 3.6%. This results in a $\Delta_{LCGWP/LCC}$ ratio of 36, which is a relatively significant improvement compared to the ratio between solutions 1 and 22. Based on Table 43, the differences are in the exterior cladding, wall assembly interior drywall, window frame type, window glazing type, and roof insulation thickness. Window glazing has the greatest impact on LCC and window frames have the highest impact on LCGWP. Moreover, selecting solution 4 over solution 16 also results in a 13.8% increase in initial cost while the operational cost, initial GWP, and operational GWP all decreases by 0.4%, 7.3%, and 7.1%, respectively. Additional breakdowns of LCC and LCGWP in terms of initial and operating phases are presented in Figure 51.

Table 43: Comparison of differing design parameters between solutions 4 and 16 for standard wall cases including the breakdown of their corresponding impact on LCC and LCGWP.

| Solution 4 | | | Solution 16 | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Fiber Cement Siding | 5.2 | 9.6 | Vinyl | 4.6 | 7.6 |
| Regular Gypsum Wall Drywall | 1.5 | 1.4 | Gypsum-Fiber Wall Drywall | 2.8 | 2.3 |
| Solid Wood Window Frames | 5.0 | 18.7 | Vinyl Window Frames | 1.8 | 23.5 |
| Double-Glazed Low-E Coated (argon-filled) Windows | 10.8 | 6.4 | Double-Glazed Non-Coated (air-filled) Windows | 9.7 | 6.1 |
| Blown-Cellulose Roof Insulation (10.4 in.) | 1.8 | 8.4 | Blown-Cellulose Roof Insulation (5.2 in.) | 0.9 | 4.1 |

Assuming solution 13 (purple circle) as the reference case, solution 24 (purple circle) shows relative significant increases in LCC with minimal decreases in LCGWP. For a 2.4% increase in LCC, the LCGWP of solution 24 only decreases by 0.2%, which results in a $\Delta_{LCGWP/LCC}$ ratio of 0.083. The differences in design parameters are in the exterior cladding, wood sheathing, and roof insulation thickness (refer to Table 44). Out of the three pairs of different design parameters, the exterior cladding impacts the LCC most significantly for both solutions 13 and 24. The exterior cladding impacts the LCGWP for solution 13, but the roof insulation has a greater effect on LCGWP for solution 24. As a result, initial construction and material costs of solution 24 increase by 6.1% over the initial cost of solution 13. The initial and operational GWP both decreases by an almost negligible 0.2%, which is approximately 50 kg-CO2-eq and 69 kg-CO2-eq, respectively. Figure 51 also shows that the proportions of initial and operating phases of LCC and LCGWP are similar between solutions 13 and 24, with exception to the larger initial cost of solution 24.

Table 44: Comparison of differing design parameters between solutions 13 and 24 for standard wall cases including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 13** | | | **Solution 24** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Vinyl Siding | 4.2 | 8.5 | Stucco Siding | 6.4 | 5.5 |
| Plywood Sheathing | 2.8 | 3.1 | OSB Sheathing | 1.9 | 3.7 |
| Blown-Cellulose Roof Insulation (5.2 in.) | 0.8 | 4.5 | Blown-Cellulose Roof Insulation (7.0 in.) | 1.1 | 6.1 |

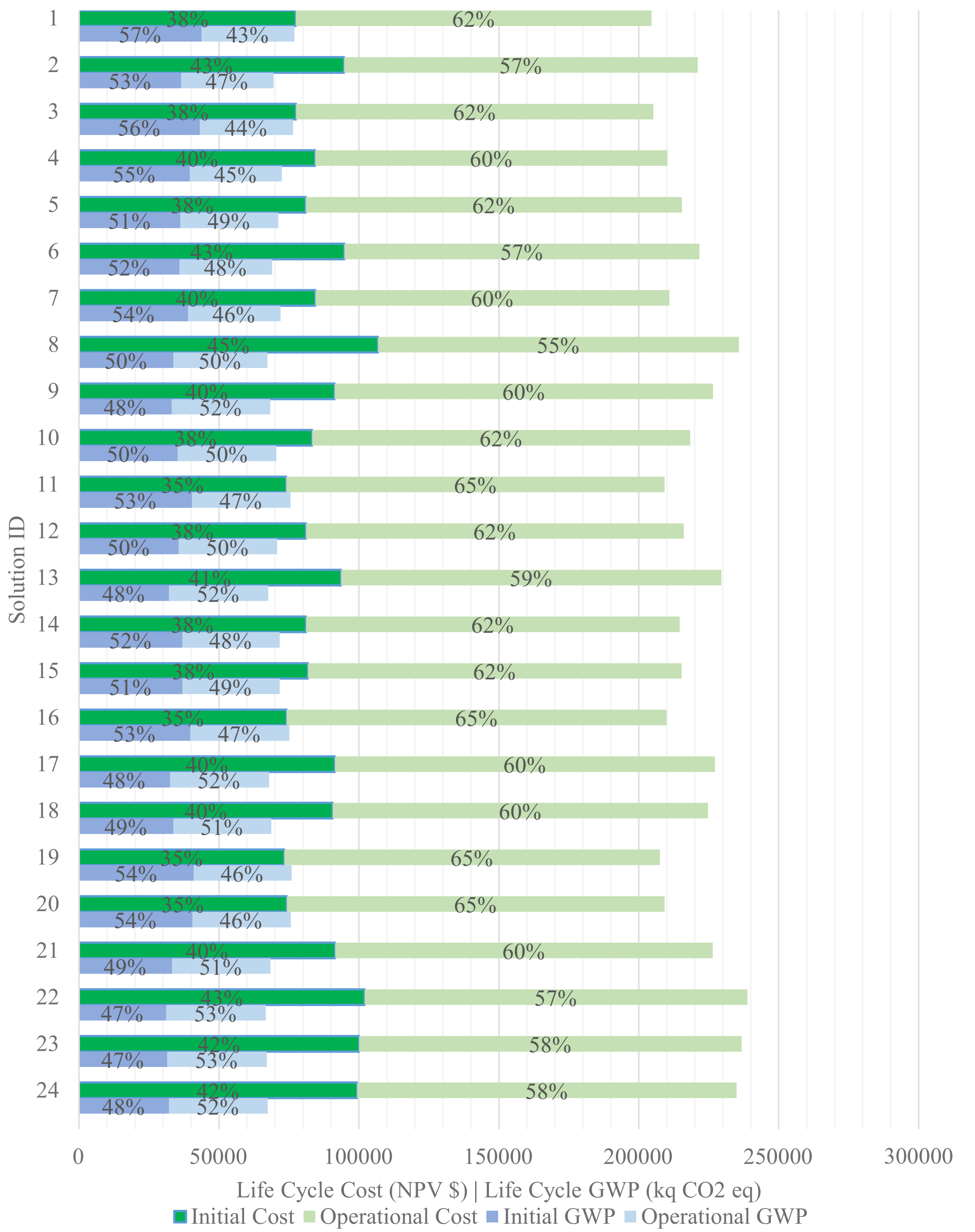



Figure 51: Comparison of LCC and LCGWP for each standard wall with standard roof Pareto solution.

#### 8.3.3.2 Double-Stud Wall Solutions

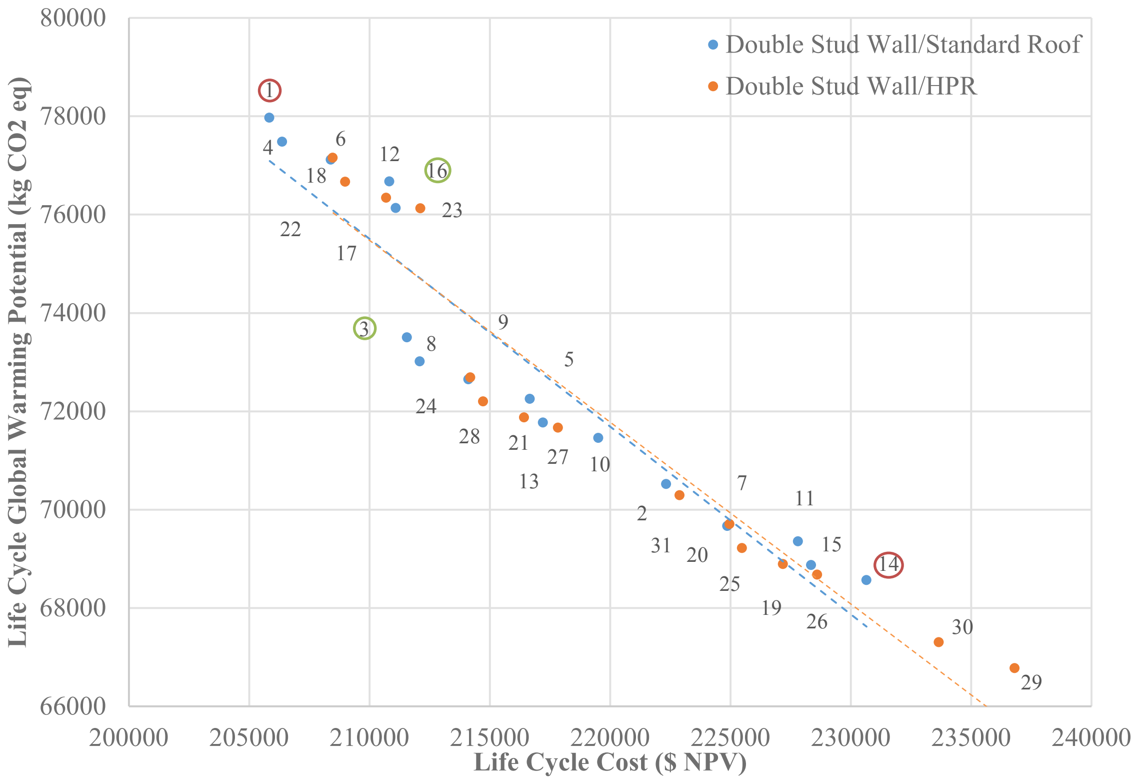



Figure 52: Scatter plot of Pareto solutions for the double-stud wall assemblies with numbered labels for input parameter reference.

The Pareto optimal solution set for the double-stud wall with standard roof cases are much more similar to the double-stud wall with HPR cases in terms of overall LCC and LCGWP when compared to the same results for the BESTEST Case 600. The dashed lines shown in Figure 52 have a very similar slope indicating that HPR solutions have a similar rate of improvement as the standard roof solutions with respect to differences in LCGWP and LCC. The full list of double-stud wall with standard roof and HPR solution sets are provided in Appendix O (refer to Table O3 and Table O4).

Assuming solution 1 as the reference solution, selecting solution 14 results in an increase in LCC by 12.1% and a decrease in LCGWP by 12.1% over the course of 30 years. In more detail, solution 14 increases the initial cost by 20.4% while decreasing initial GWP by 25.8%. However, both the operational costs and operational GWP increases by 6.8% and 6.7, respectively, as a result of selecting solution 14 over solution 1. With exceptions to the wall drywall type, stud-space insulation type, and roofing type, all other design parameters are different between solutions 1 and 14. According to Table 45, the window glazing for solution 1 has the great contribution to the LCC and the window frames for the same solution have the greatest impact on LCGWP when compared to the other design parameters. For solution 14, the vinyl-clad wood-core window frames have the greatest contributions to both the LCC and LCGWP as compared to other design parameters.

Table 45: Comparison of design parameters between solutions 1 and 14 for double-stud wall cases including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 1** | | | **Solution 14** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Fiber Cement Siding | 5.3 | 8.9 | Vinyl Siding | 4.2 | 8.3 |
| OSB Sheathing | 2.2 | 3.2 | Plywood Sheathing | 2.8 | 3.0 |
| Vinyl Window Frames | 1.8 | 22.7 | Vinyl-Clad Wood-Core Window Frames | 9.1 | 15.2 |
| Double-Glazed Low-E Coated (argon-filled) Windows | 11.1 | 6.0 | Double-Glazed Non-Coated (air-filled) Windows | 8.8 | 6.6 |
| Blown-Cellulose Roof Insulation (10.4 in.) | 1.8 | 7.8 | Blown-Cellulose Roof Insulation (5.2 in.) | 0.8 | 4.4 |

| | | | | | |
|---|---|---|---|---|---|
| Regular Gypsum Ceiling Drywall | 1.9 | 1.4 | Gypsum-Fiber Ceiling Drywall | 3.0 | 2.7 |

Solutions 3 and 16 represents two Pareto optimal solutions where one solution has a relatively lower LCGWP with minimal increases in LCC. Assuming solution 16 as the references solution, selecting solution 3 results in a decrease in LCGWP by 3.5% but increases LCC by only 0.2%. Moreover, the initial cost increases by 13.4% as a result of selecting solution 3 over solution 16, but the initial GWP, operational GWP, and operational cost decreases by 0.4%, 7.1% and 7.2%, respectively. Table 46 shows that the differences are in the exterior cladding, interior drywall, window frame type, glazing type, and roof insulation thickness. In both solutions 3 and 16, the glazing type has the greatest impact on LCC and the window frame type provides the greatest contributions to the LCGWP over a 30-year period. Figure 53 provides a more detailed and visual breakdown of the initial and operational cost and environmental impact on the overall LCC and LCGWP of solutions 1 to 22.

Table 46: Comparison of design parameters between solutions 3 and 16 for double-stud wall cases including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 3** | | | **Solution 16** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Fiber Cement Siding | 5.2 | 7.2 | Vinyl Siding | 4.6 | 7.5 |
| Regular Gypsum Wall Drywall | 1.5 | 1.4 | Gypsum-Fiber Wall Drywall | 2.8 | 2.3 |
| Solid Wood Window Frames | 5.0 | 18.4 | Vinyl Window Frames | 1.8 | 23.2 |
| Double-Glazed Low-E Coated (argon-filled) Windows | 10.8 | 6.3 | Double-Glazed Non-Coated (air-filled) Windows | 9.6 | 6.0 |
| Blown-Cellulose Roof | 1.8 | 7.8 | Blown-Cellulose Roof Insulation (5.2 | 0.9 | 3.8 |

| | | | | | |
|---|---|---|---|---|---|
| Insulation (10.4 in.) | | | in.) | | |

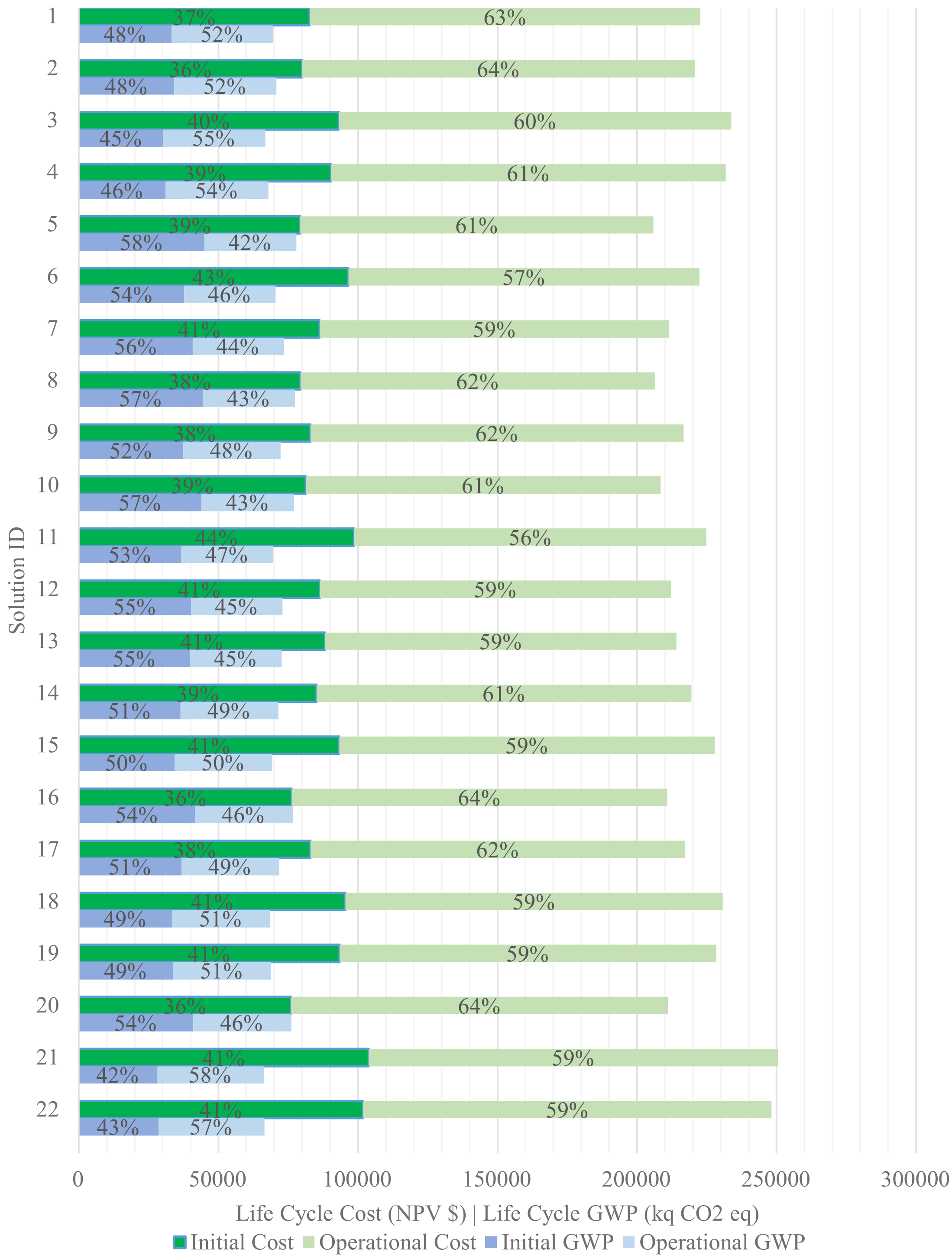



Figure 53: Comparison of LCC and LCGWP for each double-stud wall with standard roof Pareto solution.

#### *8.3.3.3 EIFS Solutions*

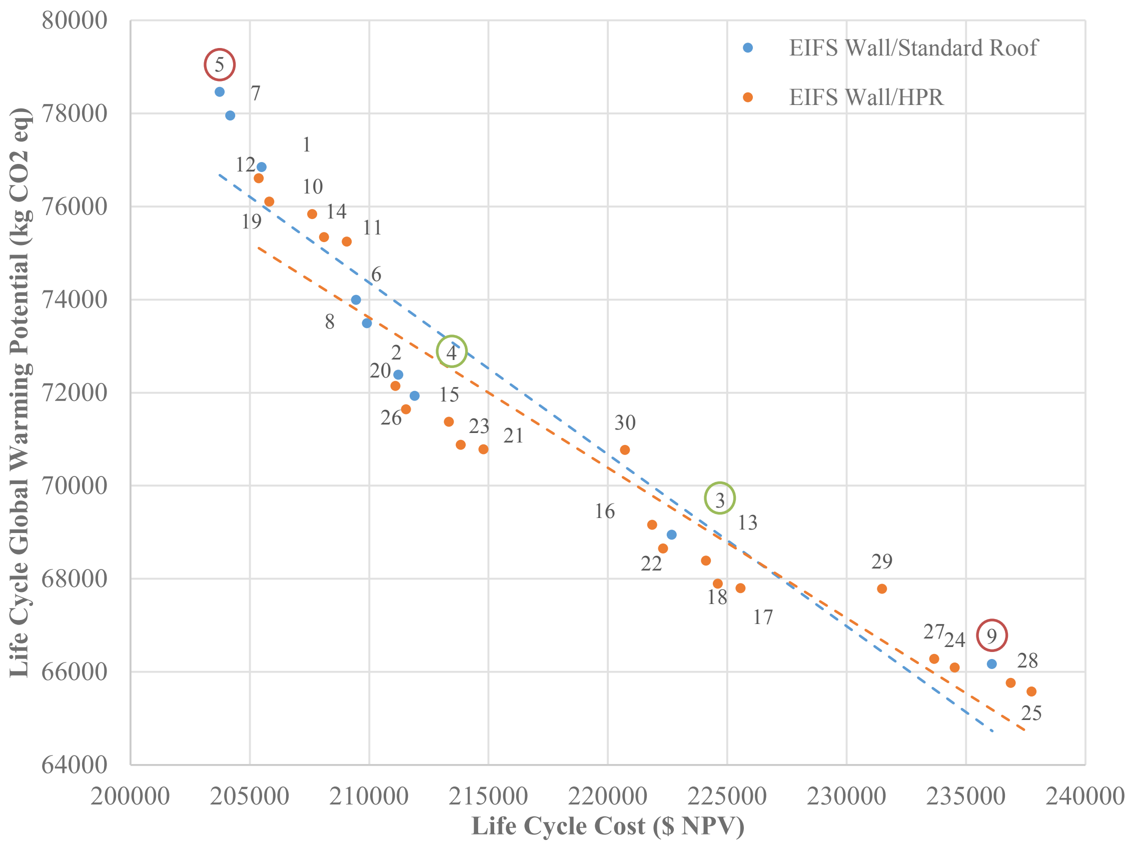



Figure 54: Scatter plot of Pareto solutions for the EIFS wall assemblies with numbered labels for input parameter reference.

Figure 54 shows the full set of Pareto solutions for both the EIFS wall assembly in combination with standard roof assemblies as well as HPR assemblies. In general, both the standard roof solutions and the HPR solutions appear to be very similar in overall optimality in terms of LCC and LCGWP. In other words, unlike many solutions presented in the BESTEST Case 600 solutions, both the standard roof and HPR solutions are close to the Pareto Front. The dashed lines also show that the two sets of solutions are similar in terms of the trade-off relationship as represented by the slope of the dashed lines. In addition, there are more HPR solution than there are standard roof solutions. In fact, there is a total of 9 Pareto optimal solutions for the standard roof cases and a total of 21 Pareto optimal solutions for the HPR cases. One possible reason for the difference in number of Pareto optimal solutions is the fact that HPR solutions have more design parameter combinations to consider compared to the fewer number of EIFS wall with standard roof parameter combinations. The full set of EIFS wall with standard roof and HPR solutions is presented in Appendix O (refer to Table O5 and Table O6).

Solutions 5 and 9 represent the extreme points in terms of LCC and LCGWP that exists on the Pareto Front. Taking solution 5 as the reference solution, solution 9 results in an increase in LCC by 15.9% and a decrease in LCGWP by 15.7%. Further analysis of the results also shows that the initial cost is increased by 27.1%, initial GWP is decreased by 33.4%, operational cost is increased by 9.0%, and the operational GWP is also increased by 8.8%. It appears that solution 9 does not necessary improve the thermal performance of the building when compared to solution 5, but the initial GWP of the selected design parameters is significantly reduced as a result of the higher initial cost. Additionally, Table 47 indicates that the window frames and window glazing have the most significant contributions to the overall LCC and LCGWP of both solutions. For instance, the window glazing selected for solution 5 accounts for 11.2% of the total LCC considering all initial and operational costs over a 30-year period.

Table 47: Comparison of differing design parameters between solutions 5 and 9 for EIFS wall cases including the breakdown of their corresponding impact on LCC and LCGWP.

| Solution 5 | | | Solution 9 | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| Fiber Cement Siding | 5.4 | 8.8 | Stucco Siding | 6.4 | 5.6 |
| Mineral Wool Continuous Exterior Wall Insulation (3.5 in.) | 0.7 | 3.5 | Isocyanurate Foam Exterior Wall Insulation (0.5 in.) | 1.0 | 0.8 |
| Vinyl Window Frames | 1.8 | 22.5 | Vinyl-Clad Wood-Core Window Frames | 8.9 | 15.8 |
| Double-Glazed Low-E Coated (argon-filled) Windows | 11.2 | 5.9 | Double-Glazed Non-Coated (air-filled) Windows | 8.6 | 6.9 |
| Blown-Cellulose Roof Insulation (10.4 in.) | 1.8 | 7.8 | Blown-Cellulose Roof Insulation (5.2 in.) | 0.8 | 4.6 |

By visual inspection of Figure 54, a significant gap exists between solutions 3 and 4 for the EIFS wall with standard roof cases. There are 5 EIFS wall with HPR solutions in between solutions 3 and 4 in terms of the Pareto Front. Assuming solution 4 as the reference solution, solution 3 decreases LCGWP by 4.2% as a result of an increase in LCC of 5.1%. Additional breakdown of the LCC and LCGWP indicates that by selecting solution 3 over solution 4, the initial cost increases by 12.1% and decreases initial GWP by 8.0% at a cost of an increase in both operational cost and GWP by 0.3%. The differences between solutions 3 and 4 appears to show the relationship between initial cost and initial GWP, whereas more expensive design parameters inherit a lower initial environmental impact. Furthermore, the only difference in design parameter between solution 3 and 4 is the window frame type. Solution 3 uses vinyl-clad wood-core window frames while solution 4 uses solid wood window frames. Therefore, the trade-off between the two solutions is either to use the lower initial environmental impact of the vinyl-clad wood-core window frames at a higher initial cost or to use a the lower costing solid-wood window frames with a higher initial environmental impact. In addition, Figure 55 shows the contributions of the initial and operational cost and environmental impact on the overall LCC and LCGWP of solutions 1 to 9.

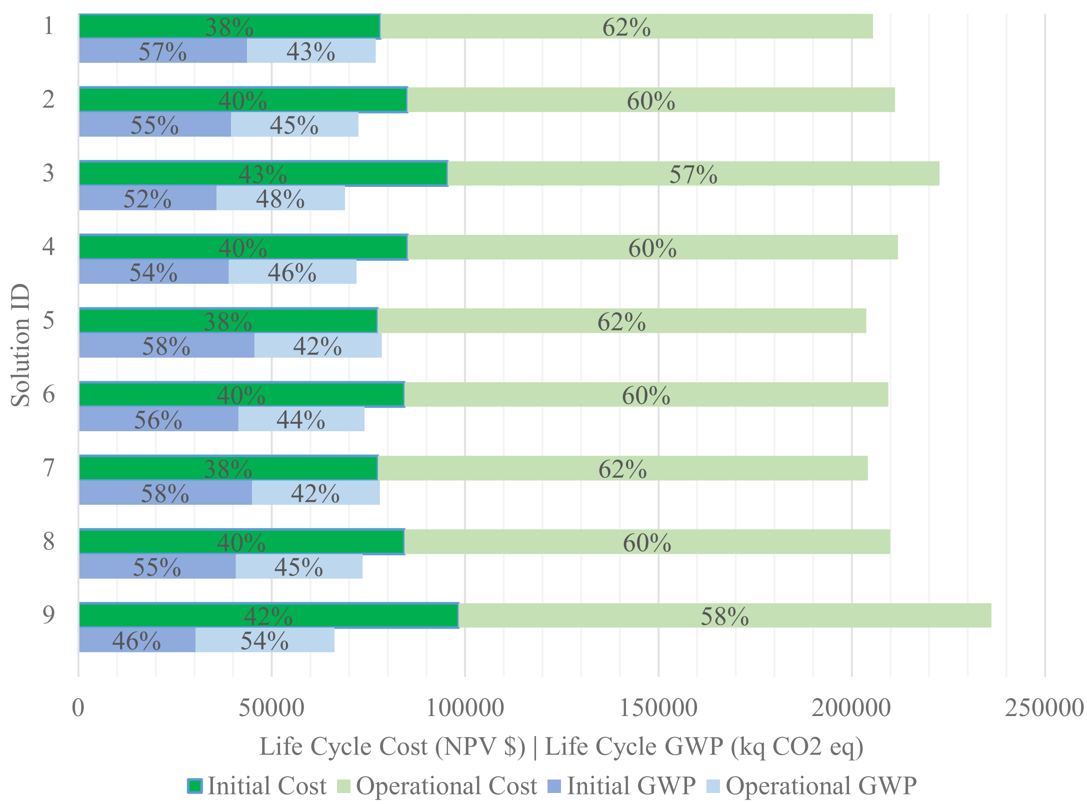



Figure 55: Comparison of LCC and LCGWP for each EIFS wall with standard roof Pareto solution.

#### 8.3.3.4 ICF Solutions

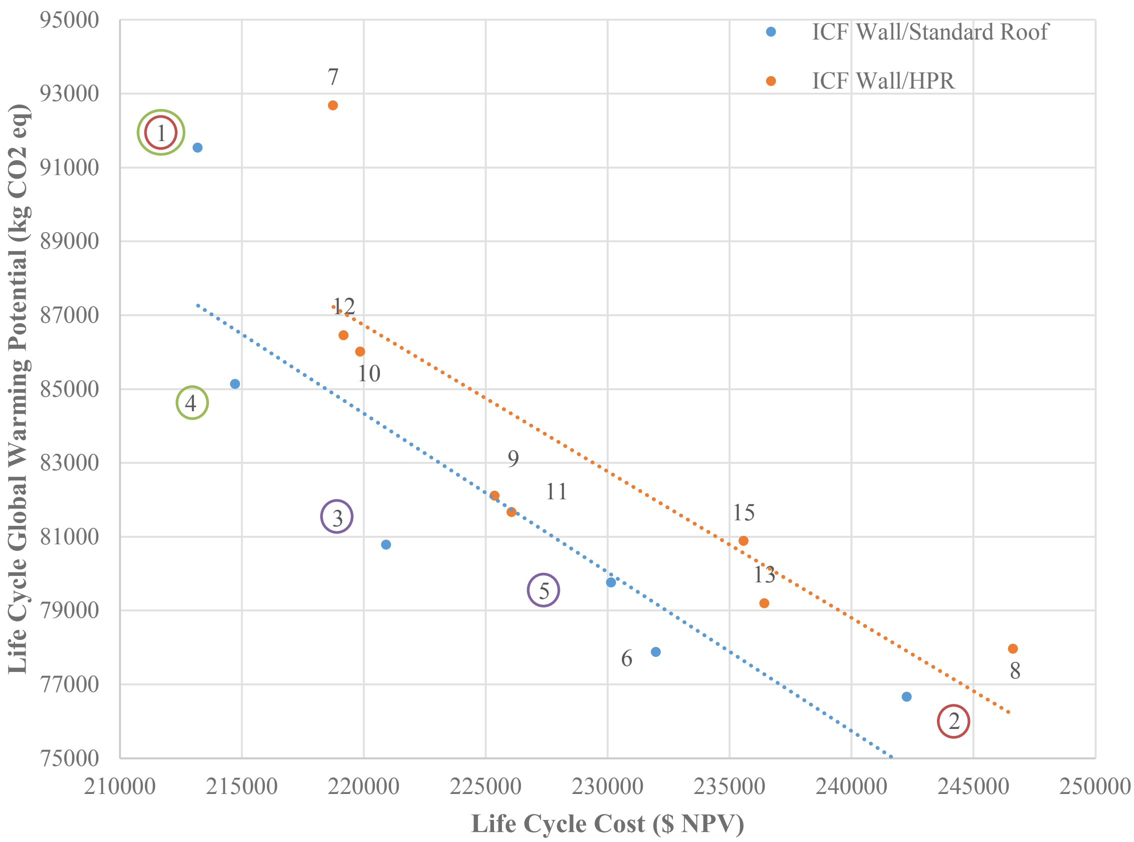



Figure 56: Scatter plot of Pareto solutions for the ICF wall assemblies with numbered labels for input parameter reference.

Figure 56 shows the entire set of Pareto optimal solutions for both the standard roof and HPR cases. By comparing LCC and LCGWP only, it is clear that the ICF wall with standard roof solutions have the better options, as shown by the dashed lines. However, by considering occupant thermal comfort as an objective function, all of these Pareto solutions have comparable results. On average, the occupant thermal comfort for the HPR cases have a PPD of 19.5% while the standard roof cases average 19.6%. Even by considering occupant thermal comfort, the majority ICF wall with standard roof cases are still closer to the global Pareto front compared to HPR cases. The full set of Pareto optimal results for the ICF wall with standard roof cases are shown in Table 49 and the ICF wall with HPR cases are shown in Appendix O (refer to Table O7)

Solutions 1 and 2 (red circles) represent the extreme points for the ICF wall with standard roof cases, where assuming solution 1 is the reference solution, solution 2 increases LCC by 13.6% and decreases LCGWP by 16.2%. Furthermore, the initial and operational cost increases by 30.5% and 2.3%, respectively. The initial GWP decreases by 26.8% as a result, but the operational GWP increases by 2.3%. With exceptions to the exterior cladding and window frame type, all other design parameters are the same between the two solutions (refer to Table 48). Both the steel panel exterior cladding and vinyl window frames have a significant impact on the LCGWP of solution 1, which combines to a total of 41.2% of the LCGWP. For solution 2, it appears that the vinyl-clad wood-core window frames have the most significant impact on LCC and LCGWP. In this case, the differences are not in the operational phases but rather from the initial cost and initial environmental impact of materials and construction. Further breakdown of LCC and LCGWP in terms of the proportions of initial and operational phases is shown in Figure 57.

Table 48: Comparison of differing design parameters between solutions 1 and 2 for ICF wall cases including the breakdown of their corresponding impact on LCC and LCGWP.

| Solution 1 | | | Solution 2 | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| **Steel Panel Siding** | 5.0 | 21.9 | Stucco Siding | 6.2 | 4.8 |
| **Vinyl Window Frames** | 1.8 | 19.3 | Vinyl-Clad Wood-Core Window Frames | 8.7 | 13.6 |

Compared to solution 1, solution 4 (green circle) has a 0.7% higher LCC but selecting it will decrease the LCGWP by 7.0% over a 30-year period. This results in a relatively higher $\Delta_{LCGWP/LCC}$ ratio of 10.0 compared to a $\Delta_{LCGWP/LCC}$ ratio of approximately 1.2 between solutions 1 and 2. The only difference in design parameter between solutions 1 and 4 is in the exterior cladding type. Solution 1 uses steel siding while solution 4 uses fiber-cement siding. Selecting solution 4 over solution 1 results in an increase in initial cost, operational cost and operational GWP of 0.1%, 1.1%, and 1.1%, respectively, while the initial GWP of materials and construction decreases by 11.6%. In this case, the LCGWP is improved by focusing on reducing the initial environmental impact of construction and materials rather than the operational phases. By comparing these two solutions, it is apparent that fiber-cement siding has significant benefits over steel siding if environmental impact is the user's primary concern.

Solutions 3 and 5 (purple circles) show significant differences in LCC while LCGWP has relatively small differences. More specifically, the LCC of selecting solution 5 over solution 3 increases by 4.2% while LCGWP decreases by 1.3%. The main difference between solutions 3 and 5 is in the exterior cladding as well. Solution 3 uses fiber-cement siding while solution 5 uses stucco siding, which results in an increase in initial cost by 8.3% while initial GWP decreases by 3.0%. Moreover, both operational cost and operational GWP increases by 1.2% and 1.1%, respectively. Again, this shows that selecting different exterior cladding does not necessarily improve the thermal performance of the building, but rather it decreases initial GWP of the different materials, which also affects the initial costs to a certain extent.

Table 49: List of parameters for ICF wall with standard roof Pareto solutions.

| ID | Exterior Cladding | Wall Drywall | ICF Type | Window Frame | Glazing Type | Roofing Type | Roof Stud Insulation | Ceiling Drywall | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 213201 | 91530 | 19.6 | 85651 | 58275 | 127550 | 33255 |
| **2** | Stucco on Mesh (White), 1 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 242266 | 76659 | 19.6 | 111742 | 42646 | 130525 | 34013 |
| **3** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 220925 | 80781 | 19.6 | 92680 | 47349 | 128245 | 33432 |
| **4** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 214731 | 85128 | 19.6 | 85728 | 51503 | 129003 | 33625 |
| **5** | Stucco on Mesh (White), 1 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 230146 | 79755 | 19.6 | 100398 | 45939 | 129748 | 33815 |
| **6** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 231989 | 77869 | 19.6 | 103032 | 44255 | 128957 | 33613 |

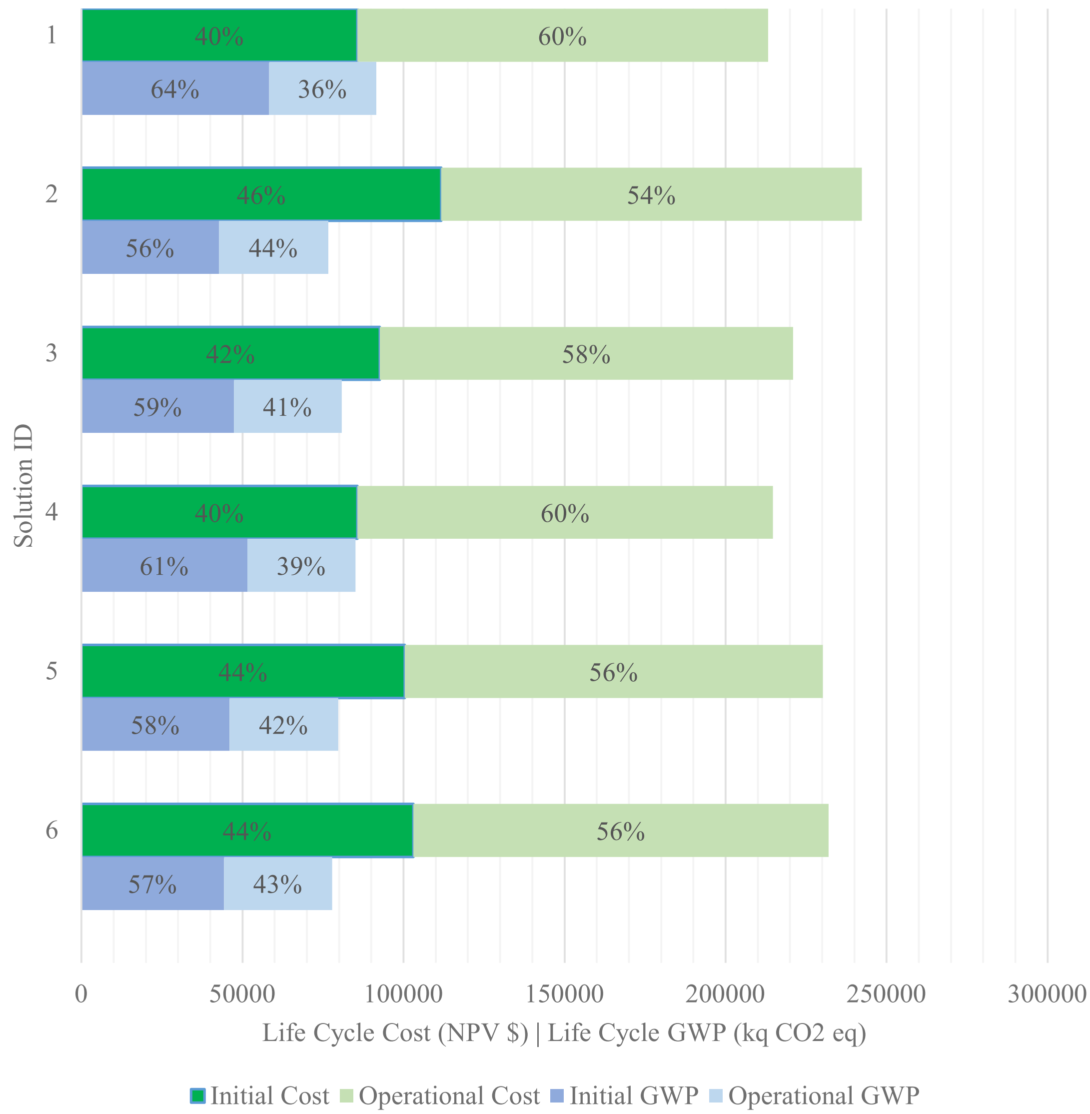



Figure 57: Comparison of LCC and LCGWP for each ICF wall with standard roof Pareto solution.

#### *8.3.3.5 SIP Solutions*

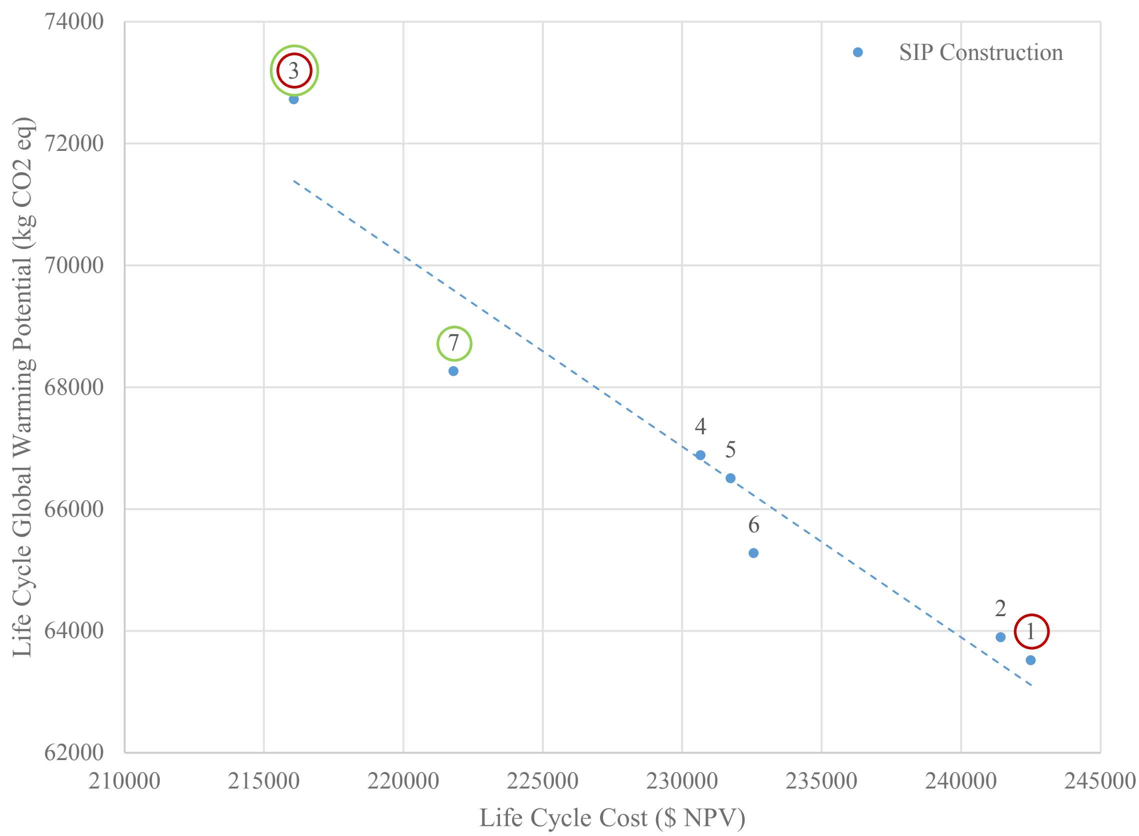



Figure 58: Scatter plot of Pareto solutions for the SIP wall assemblies with numbered labels for input parameter reference.

Out of all the wall types being optimized for the Harmony House case study, the SIP wall with SIP roof system has the fewest total number of Pareto optimal solutions. Even compared to the BESTEST Case 600, the Harmony House case has fewer total number of Pareto solutions in the optimal solution set. Figure 58 shows that there is a total of 7 optimal solutions making use of the SIP enclosure system where as the BESTEST Case 600 has 49 solutions making use of the SIP enclosure system. The full set of Pareto optimal results for the SIP wall with SIP roof system for the Harmony House model is shown in Table 51.

Solutions 1 and 3 (red circles) are the extreme points in terms of highest and lowest LCC and LCGWP within the solution set and the input design parameters are shown in Table 50. Taking solution 3 as the reference solution, selecting solution 1 results in an increase in LCC by 12.2% and a decrease in LCGWP by 12.7%. With exceptions to the exterior cladding, wood sheathing type, window frame type, and SIP roof type, the remaining design parameters remain the same between both solutions. Solution 3 uses vinyl siding, OSB sheathing, vinyl window frames, and 5.5 in. EPS core SIP roof, while solution 1 uses stucco siding, softwood plywood sheathing, vinyl-clad wood-core window frames, and 3.5 in. EPS core SIP roof. The main trade-off between solutions 1 and 3 is between the initial cost and initial GWP of materials and construction. More specifically, selecting solution 1 over solution 3 increases the initial cost by 28.7% while decreasing initial GWP by 24.2%. Moreover, the operational cost and operational GWP of solution 1 have the same increase of 0.9% over solution 3. This means that thermal performance gains by increasing the EPS core of the SIP roof from 3.5 in. to 5.5 in. are relatively small.

Table 50: Comparison of differing design parameters between solutions 1 and 3 for SIP wall cases including the breakdown of their corresponding impact on LCC and LCGWP.

| **Solution 1** | | | **Solution 3** | | |
|---|---|---|---|---|---|
| **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** | **Design Parameter** | **Percent of LCC (%)** | **Percent of LCGWP (%)** |
| **Steel Panel Siding** | 5.0 | 21.9 | Stucco Siding | 6.2 | 4.8 |
| **Vinyl Window Frames** | 1.8 | 19.3 | Vinyl-Clad Wood-Core Window | 8.7 | 13.6 |

| | | | | | |
|---|---|---|---|---|---|
| | | | Frames | | |

Assuming solution 3 as the baseline case, solution 7 increases LCC by 2.6% and decreases LCGWP by 6.1%. The only difference in design parameters between solutions 3 and 7 is the window frame type (i.e. vinyl vs. solid-wood). By using a solid-wood window frame rather than vinyl, the initial cost of materials increases by 7.9% but the initial environmental impact also decreases by 10.6%. However, both operational cost and operational GWP decrease by a relatively small 0.9% compared to solution 3.

Table 51: List of parameters for SIP wall with SIP roof Pareto solutions.

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall SIP Type | Window Frame | Glazing Type | Roofing Type | Ceiling Drywall | Roof SIP Type | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Stucco on Mesh (White), 1 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | 242507 | 63513 | 20 | 113046 | 29771 | 129461 | 33742 |
| **2** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | 241431 | 63892 | 20 | 112053 | 30171 | 129378 | 33721 |
| **3** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 216085 | 72719 | 20 | 87833 | 39286 | 128252 | 33434 |
| **4** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | 230669 | 66879 | 20 | 101708 | 33265 | 128960 | 33614 |
| **5** | Stucco on Mesh (White), 1 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | 231745 | 66500 | 20 | 102702 | 32865 | 129043 | 33635 |
| **6** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 232575 | 65270 | 20 | 105115 | 32038 | 127460 | 33232 |
| **7** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 221809 | 68256 | 20 | 94770 | 35132 | 127039 | 33124 |

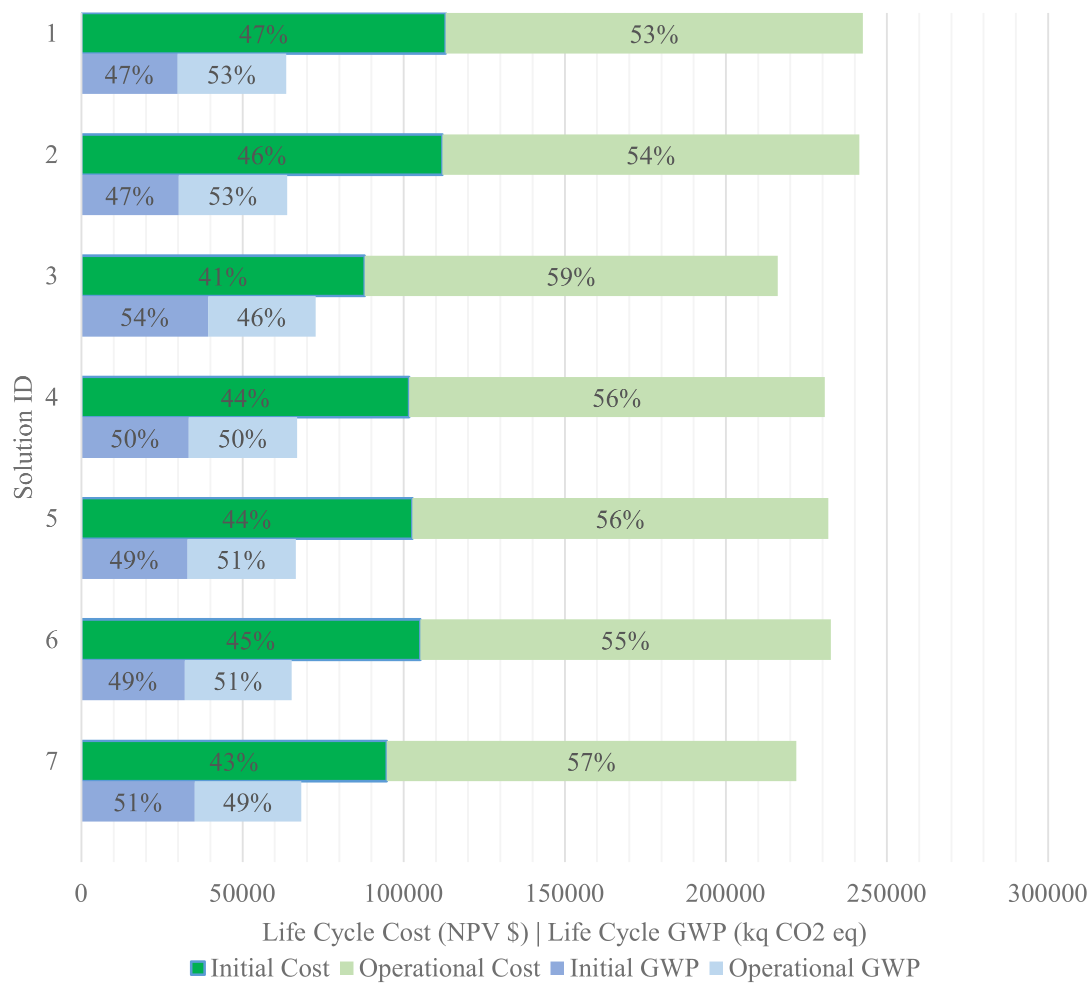



Figure 59: Comparison of LCC and LCGWP for each SIP wall with SIP roof Pareto solution.

### 8.3.4 Summary

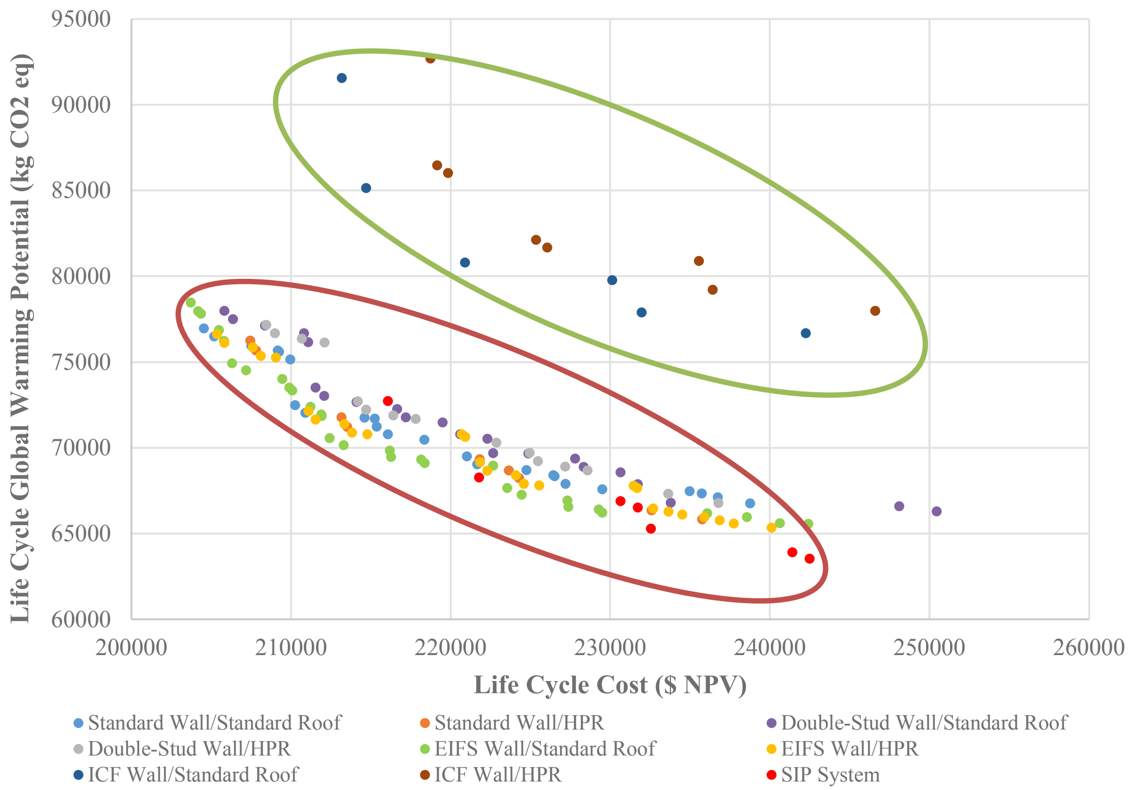



Figure 60: Scatter plot of Harmony House Pareto results for all wall types in terms of LCC and LCGWP.

Although the BESTEST Case 600 and the Harmony House case study are not directly comparable, the results for both cases show slightly different characteristics. For example, by comparing the combined solutions for both cases, the global solution set for the BESTEST 600 cases has several different clusters based on the wall and roof type combinations. In other words, certain wall types are clearly separated in terms of LCC and LCGWP and thus showing a clear representation of the best global solutions (refer to Figure 42). The differences between wall types are also amplified as the LCC increases and LCGWP decreases. On the contrary, the global solution set for the Harmony House case does not have such distinct clusters separated by wall and roof assembly type. Figure 60 shows one main cluster of solutions that have all wall and roof type combinations (red oval) which have been considered for optimization. However, there is a small outlier cluster of solutions from ICF wall assemblies encircled in the green oval. The order in which each wall and roof type combinations are ranked in terms of distance from the global Pareto front is similar compared to the BESTEST Case 600 global Pareto set as well. This confirms that the optimization model does in fact function appropriately in both cases without any errors.

A possible explanation for this trend is the difference in the size of the building being optimized. A larger building requires a larger area of walls, roofs, and windows in addition to a larger mechanical system. Therefore, the difference in initial cost between different wall and roof types of a larger building is less significant compared to smaller buildings. By comparing different wall and roof combinations for both the Harmony House and BESTEST Case 600, the differences in initial cost are apparent. Comparing solutions with the lowest LCC from the standard wall and EIFS wall from both the BESTEST Case 600 and the Harmony House case study, the difference in initial cost between the wall types and between the two case studies is apparent. For instance, the percentage difference in initial cost of BESTEST Case 600 standard wall solution 3 and the BESTEST Case 600 EIFS wall solution 2 is 1.1%. The percentage difference in initial cost of Harmony House standard wall solution 1 and Harmony House EIFS wall solution 17 is 0.12%.

Even though the design parameters used for solution with the lowest LCC in each case is different, it still shows the fact that the effects of using different high performance building solutions are more significant for smaller buildings than they are for larger buildings. However, this does not mean that the differences in building performance in terms of LCC and LCGWP are insignificant between solutions of the same building size.

Similar to BESTEST Case 600, there are certain components that are chosen more frequently than others in order to achieve the optimal solutions. For instance, there is a total of 6 different glazing types considered for optimization (refer to Appendix G for additional information), but only a select few may be selected during the optimization process. Figure 61 indicates that out of the 6 possible window glazing types, only two glazing types are selected in order to achieve the most optimal solutions for the EIFS wall and standard roof type cases. The double-glazed no low-e coating air-filled system is selected twice as often as the double-glazed low-e coated argon-filled system in combination with EIFS wall and standard roof assemblies. However, this may not always be the case for all wall and roof type combinations. For instance, out of the 6 possible window glazing assemblies for optimization, only the double-glazed low-e coated argon-filled system is selected for the standard wall with HPR cases.

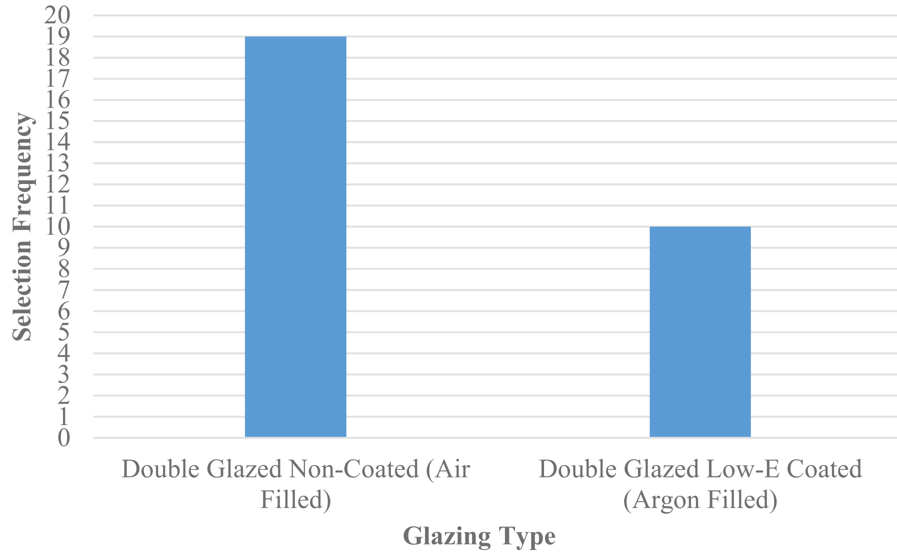



Figure 61: Frequency of window glazing types selected during the optimization process for Harmony House EIFS wall with standard roof cases.

Frequency characteristics do not only apply to glazing systems, but to all input design parameters used for optimization such as exterior cladding type, window frame type, stud space insulation, etc. Figure 62 shows that the optimization process does not only select one or two parameters, but can select more than three parameters in one category. Out of the four possible window frame types for optimization, three window frame types were selected multiple times. By examining the frequency of window frame type selections, it is evident that a vinyl-clad wood-core window frame is selected more often than other selected window frame types. Figure 63 shows that the vinyl-clad wood-core window frame is selected 14 times while the vinyl and solid wood window frames are selected 4 and 7 times, respectively. This trend is exists in both the double-stud wall with HPR and EIFS wall with HPR cases.

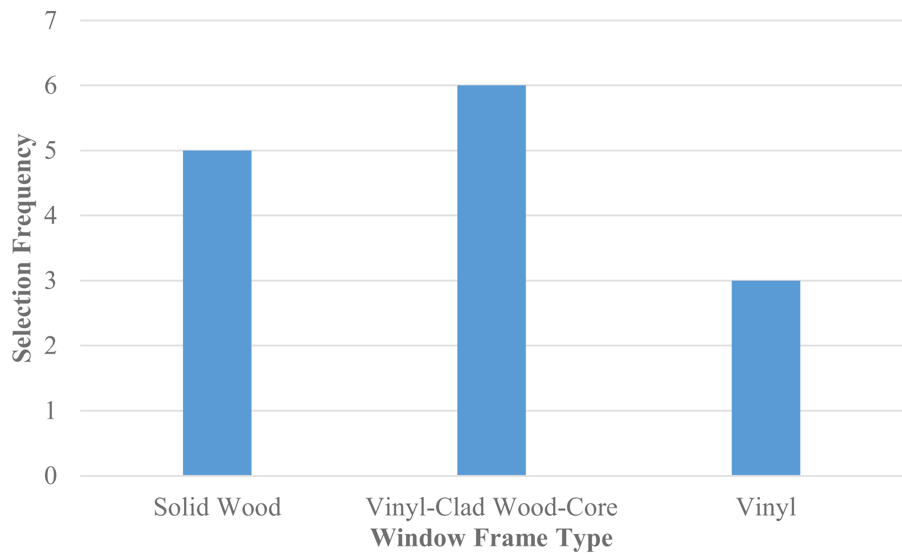



Figure 62: Frequency of window frame types selected during the optimization process for double stud wall with HPR cases.

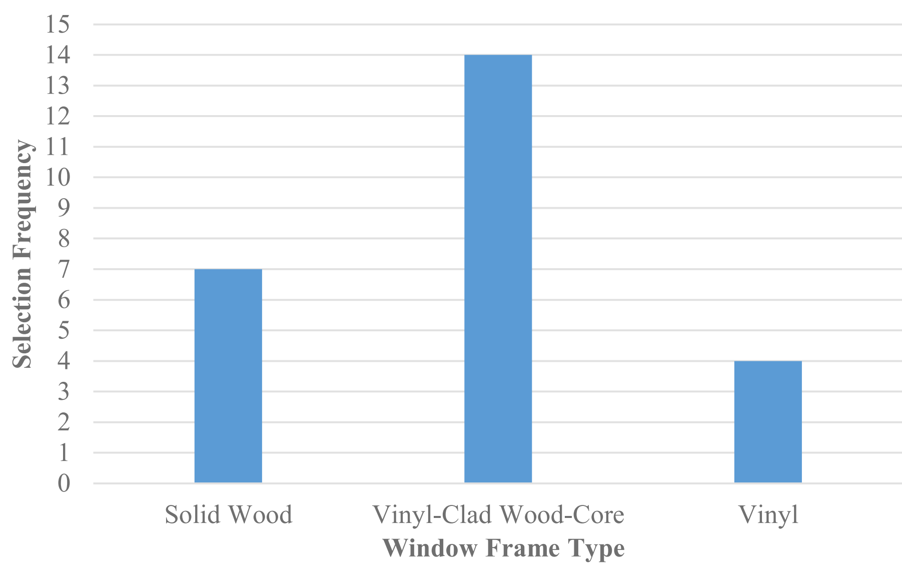



Figure 63: Frequency of window frame types selected during the optimization process for EIFS wall with HPR cases.

Air infiltration has a significant impact on the overall thermal performance of a building, as discussed in the BESTEST 600 case. For the Harmony House case study, the ICF wall with standard roof cases were optimized with an infiltration rate of 0.5 ACH at 50 Pa and optimization a second time with an infiltration rate of 1.5 ACH at 50 Pa. The results for both these optimization runs are shown in Figure 64 below. Assuming solution 1a as the reference case, solution 1b decreases LCC and LCGWP by 33.2% and 26.3%, respectively. The initial cost of solution 1b increases by 0.7% in comparison to solution 1a while initial GWP, operational cost, and operational GWP decreases by 10.1%, 56.0%, and 54.9%, respectively. There are also fewer number of solutions as the air infiltration rate is decreased to 0.5 ACH compared to 1.5 ACH. For instance, the ICF wall optimized with an air infiltration rate of 0.5ACH at 50 Pa. results in a total of 5 optimal solutions, while the same wall and roof combination with 1.5 ACH at 50 Pa. has a total of 6 optimal solutions.

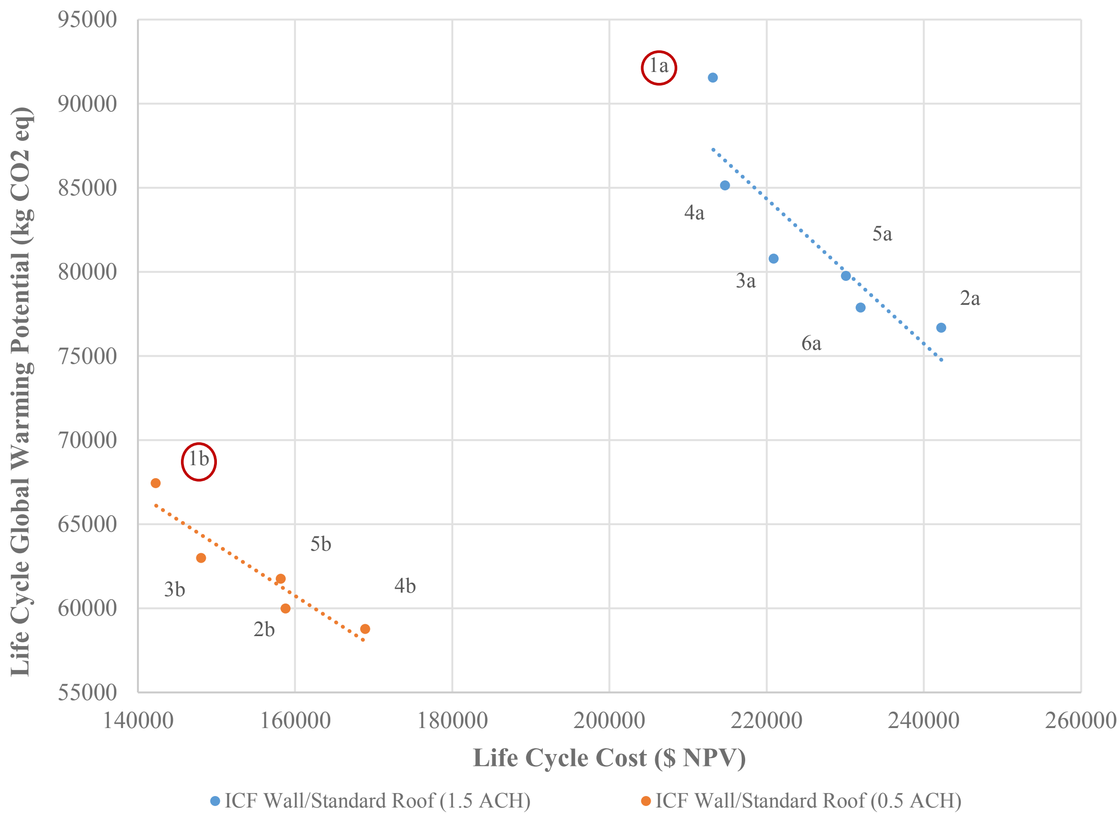



Figure 64: Scatter plot showing the impact of air infiltration on the LCC and LCGWP for the Harmony House ICF wall with standard roof cases.

Table 52: List of design parameters for ICF wall with standard roof Pareto solutions optimized with an air infiltration rate of 0.5 ACH.

| ID | Exterior Cladding | Wall Drywall | ICF Type | Window Frame | Glazing Type | Roofing Type | Roof Stud Insulation | Ceiling Drywall | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1b** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Fiberglass 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 142324 | 67427 | 19 | 86246 | 52413 | 56078 | 15014 |
| **2b** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Fiberglass 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 158824 | 59973 | 18 | 103527 | 45165 | 55297 | 14809 |
| **3b** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Fiberglass 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 148105 | 62968 | 18 | 93184 | 48259 | 54921 | 14709 |
| **4b** | Stucco on Mesh (White), 1 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Fiberglass 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 168966 | 58749 | 18 | 112232 | 43555 | 56734 | 15194 |
| **5b** | Stucco on Mesh (White), 1 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Fiberglass 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 158209 | 61738 | 18 | 101888 | 46649 | 56322 | 15089 |

A possible reason for the lower number of optimal solutions with a lower air infiltration rate is due to the fact that a lower air infiltration rate will improve the energy performance of the building significantly, thus reducing the operational phase costs and operational phase environmental impacts. The savings in operational cost and operational environmental impact can allow for a higher budget for more expensive construction materials. The majority of input design parameters between solution 1a and 1b are the same, with exception to the exterior cladding and roof-stud insulation. For instance, Table 53 indicates that for solution 1b, fiber-cement siding is selected rather than steel siding and fiberglass batt insulation is selected rather than blown-cellulose. The LCC cost of the steel panel siding is slightly lower than the fiber cement siding because this research assumes a replacement cost for fiber-cement siding (refer to Appendix A).

Table 53: Solution 1a and 1b input parameters for wall with standard roof cases.

| **Design Parameter** | **Solution 1a (1.5 ACH@50 Pa.)** | **Solution 1b (0.5 ACH@50 Pa.)** |
|---|---|---|
| **Exterior Cladding** | Residential 30 ga. Steel Siding, 0.016 in. | Fiber Cement Siding, 0.3125 in. |
| **Wall Drywall** | Regular Gypsum Board (Wall), 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. |
| **ICF Type** | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core |
| **Window Frame** | Vinyl | Vinyl |
| **Glazing Type** | Double Glazed No Coating (Air Filled) | Double Glazed Low-E Coating (Argon Filled) |
| **Roofing Type** | Asphalt Roof Shingles, 0.125 in. | Asphalt Roof Shingles, 0.125 in. |
| **Roof Stud Insulation** | Blown Cell 2x6 24 in. o.c. Framing | Fiberglass 2x6 24 in. o.c. Framing |
| **Ceiling Drywall** | Regular Gypsum Board (Ceiling), 0.5 in. | Regular Gypsum Board (Ceiling), 0.5 in. |

To reiterate, the Harmony House case study confirms the results produced by the BESTEST 600 benchmark study, and vice versa. To be specific, the EIFS wall with standard roof and the SIP wall and roof system appears to have the most optimal solutions overall. However, the optimal solutions for the Harmony House case appear to be more clustered when compared to the optimal solutions for the BESTEST Case 600 benchmark study. This difference in optimal solutions can be attributed to the size of the building being optimized. The observation can be confirmed by breaking down the LCC and LCGWP into its initial and operating phases for both cost and environmental impact. Additionally, different wall and roof type combinations results in different frequencies of selected parameters. Depending on the type of wall or roof, the frequency of selecting certain parameters may differ. However, certain wall and roof combinations may result in a similar trend in terms of the level of frequency in selecting multiple parameters. Lastly, air infiltration rate has a significant impact on the thermal performance of the building as well as the characteristics of the genetic algorithm optimized solution sets. In other words, the overall air infiltration rate defines how the optimization process selects each parameter, and will combine the most optimal parameters based on the default performance of the building based on the air infiltration rate.

# Chapter 9 Conclusions and Future Work

## 9.1 Executive Summary

To address the problem of global warming and to combat the problem with degrading environmental conditions throughout the world, the building sector has created a trend and path towards "green" or "sustainable" buildings and building technologies. Now, the problem with this trend lies in the inconsistencies in the current building design process. There are numerous organizations and government entities that have tried to produce a solution for this problem by implementing different certifications or qualification programs that make buildings "green." However, the problem is that every organization or entity has its own criteria and sometimes have very different concepts of what a "green" or "sustainable" building is. This research project aims to address this issue by creating a new methodology for determining the most optimal building design given a set of pre-determined rules or criterion.

In order to create a new design methodology to tackle the problem mentioned above, a literature review and background research must be conducted. The literature review provides a brief overview of what other's in the research or building design industry have done to address the same or similar problem. The majority of research conducted have pointed to the direction of design optimization by means of objective functions. In other words, the designer determines the basic criteria or objectives to which the building design must satisfy. However, the method of which this is done varies depending on the researcher's goals and intentions. For instance, the weighted sum method uses the concept of multiplying each objective function by a relative weight which then sums up to a single value which gives the designer an idea of the best solutions. However, the problem with this method is that different users can assign different weights to each objective function, which will vary the optimal solution depending on the users. This leads to the method of Genetic Algorithm optimization, which considers all objective functions as equals.

For the purpose of this research project, the optimization environment discussed in Chapter 7 includes the following aspects:

- The optimization of three major objective functions including life-cycle cost (LCC), life-cycle global warming potential (LCGWP), and occupant thermal comfort (PPD). The LCC considers both initial construction cost as well as operating and replacement costs of certain components. The LCGWP includes the total global warming potential (GWP) measured in kilograms of CO2-equivalent. The GWP considers the complete life-cycle of a building with exception to the demolition phase because of the 30 year scope of this project. Lastly, the occupant thermal comfort is measured based on the Fanger Percent People Dissatisfied (PPD) model and is used as a constraint objective.
- This research project considers building enclosure related variables such as the wall, roof, windows, and foundations. More specifically, the structure of the wall and roofs as well as the type of window frame and glazing assemblies can be set as variables or input parameters. It is important to note that all input parameters are discrete variables with pre-determined LCC and LCGWP. Furthermore, the

wall and roof types are separated in terms of typical and advanced building technologies such as a typical stud wall assembly and an EIFS wall assembly. The concept of structured input parameters is employed to help understand the relationship between each input parameter such as wall type, wall layers, window glazing, etc.

Various combinations of input parameters can result in a large number of optimization problems, which is then defined and solved with the optimization system discussed in Chapter 7. The simulation-based optimization system consists of several components including:

- A text-based input and output environment that can be used to customize a particular model and to setup the optimization problem.
- A building energy simulation program, such as EnergyPlus, used to simulate a pre-defined model building in order to determine the objection functions and functional constraints.
- Modules used to replace entire sections of simulation input that represent different input parameters of variables.
- An optimization program, such as jEPlus+EA, which implements the Genetic Algorithm used to find the optimal solutions based on the design space.
- The data files used to store the data generated by the optimization program, which allows the user to analyze the optimized results in further detail.

The problem with most optimization methodology discussed in Chapter 2, is the inability to adjust the model to optimize different aspects of a building or building type. For instance, many of the previously developed optimization systems are designed specifically for a particular problem or building. During the optimization process, if the user decides to add or remove parameters, the developed model will not be able to optimize the building design. The concept of using modules and sections of input parameter code, which can be easily pre-developed to cover a wide range of possible optimization parameters, allows the optimization system to adapt to future reuse and expansion (or simplification). For example, if the user decides to ignore the optimization of walls and only focus on roof assemblies, the wall modules can be default to a fixed input in order to see the effects of only optimizing the roof assemblies.

Chapter 8 shows the use of the optimization system in both a benchmark study (i.e. BESTEST Case 600) as well as a real-life green building design (i.e. Harmony House). The BESTEST Case 600 model is used as the benchmark analysis in order to test the accuracy and functionality of the optimization system. The benchmark validation clearly shows that the default inputs and modified inputs agree with each other. This is done by running a single simulation with default BESTEST Case 600 input provided by the ASHRAE 140 benchmarking protocol followed by running the same model using input parameters such as material properties and schedules developed specifically for this research project.

A benchmark study for the Harmony House model is designed to match the actual design specifications as closely as possible. The geometry of the model is based on floor plans and elevations provided by the original architect who designed the building. Other design specifications, such as HVAC type or wall components, are based on CMHC parameters in addition to specifications provided by the original architect. The benchmark validation shows variations in monthly energy consumption when compared to BC Hydro measured data, but the aggregate annual energy consumption rate is relatively close with a percentage difference of approximately 7.0%. The monthly variations when compared to measured data is most likely due to inaccuracies of the schedules used for the model. Occupant, lighting, mechanical, and plug-load schedules have not been measured, so assumptions have to be made.

The results of the optimization process show that the best performing wall types are the EIFS wall with standard roof and the SIP construction system. The results also indicate that as the LCC increases, the LCGWP decreases, but the occupant comfort level does not necessarily follow the same trend. Also, the initial increases in LCC decreases the LCGWP significantly, but as the LCC increases further, the effects of the changes do not make a significant impact on the LCGWP. When comparing the results from the BESTEST 600 case and the Harmony House case, the BESTEST 600 case has apparent clusters of solutions separated by wall and roof type combinations. However, the Harmony House case does not have separate clusters, but rather one main cluster of solutions with the results being relatively close to one another in terms of LCC and LCGWP.

Through further analysis of the results, the frequency of selecting certain input parameters follow similar trends depending on the wall or roof type combination. For instance, certain wall types may select a triple-glazed window system with a higher frequency rather than a double-glazed window system, while another wall and roof type combination may select the double-glazed argon-filled system more frequently than a double-glazed air-filled system. To be more specific, the frequency refers to the number of times the optimization algorithm selects a certain input parameter considering all variables within the same input parameters.

The research also shows that air infiltration rate of the building significantly impacts the results of the optimization. Since air infiltration rate cannot be variable input parameter for optimization, the infiltration rate must be pre-determined by the user. Now, the air infiltration rate depends on several factors including wall and roof type, window type, building size, workmanship, quality of materials, etc. The results show that decreasing the allowable air infiltration rate improves the overall building energy performance for any wall or roof type combination. For example, an ICF wall with standard roof with 1.5 ACH exhibits the poorest performance in terms of LCC and LCGWP; however, decreasing the allowable infiltration rate to 0.5 ACH for the same wall and roof type combination makes the results significantly better than all other solutions with an infiltration rate of 1.5 ACH.

## 9.2 Recommendations for Future Work

Even though this research project attempts to improve upon the implementation of an optimization algorithm for building design, there are still numerous ways to improve the system overall including:

- A local search method running in conjunction with the genetic algorithms to find the most optimal solution with reduced overall simulation time. Although genetic algorithms are good at generating random solutions and selecting optimal solutions based on these generations, the process consumes significant time at later generations. Therefore, a local search method can be implemented in the later stages of the optimization process to speed up the optimization process.
- The incorporation of various mechanical system types such as gas furnace, heat pump, hydronic, solar hot water, etc., because this research project focuses mainly on the building enclosure, even though a dynamic mechanical system is used. In other words, the mechanical system cost and environmental impact is dependent on the energy requirements of the building, but the type of mechanical system remains the same for all solutions. As a result, various types of mechanical systems can be incorporated into the optimization scope. This could help user further understand the effects of mechanical systems on the overall building optimization process and how respond to building enclosures.
- Daylighting and moisture that could also be additional factors the simulation program can consider. The current methodology only considers constant lighting schedules pre-determined by the user, and moisture is not a factor considered for the energy simulation. Daylighting sensors can be added to the energy model to reflect actual occupant lighting usage schedules, which is dependent on the weather file solar data. Moisture can also be included by adding a heat and moisture interaction model, which better reflects the effects of relative humidity

and moisture on the energy performance of building enclosure components or mechanical systems.

- The accuracy of the simulation output largely depends on the accuracy of the database contents so a comprehensive database of building materials, components, and mechanical system that include their material properties, cost data, and environmental impact data is required. As with all optimization processes, the optimization solutions are only meaningful if the input variables are accurate and representative of real-life scenarios. This database can be constantly updated with real-time costs and environmental impact data, and the data can also be uploaded globally to allow for its use throughout the world.
- A graphical user interface that allows users to easily adjust input variables and parameters related to the model without having to edit a text file. Even though the geometry can be developed with relative ease with a graphical user interface such as Google Sketchup and OpenStudio, the process to adjust input variables and parameters is still relatively complicated. Also, a program can be developed to automatically analyze the optimization results as new solutions or simulations are run in order to visualize the effects of changing certain parameters or modules.

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# Appendices

## Appendix A jEPlus+EA Optimization Parameters

```
##########################################################################
# GA engine settings file
##########################################################################
# Default GA settings
        GAengine.PMutation = 0.2
        GAengine.PCrossover =0.8
        # Percent of population to be updated in each generation.
        # This parameter is ignored if elitism is used
        GAengine.PPopReplace = 0.95
        GAengine.PopSize = 50
        GAengine.MaxPops = 500

# More GA settings
# Population allows duplicated individuals or not
        GAengine.PopAllowDuplication = false
        # Choice of population initialization methods, from:
          # 0 - Default (create a random population)
          # 1 - Reserved
          # 2 - Reserved
          # 3 - N/A
          # 4 - N/A
          # 5 - N/A
        GAengine.PopInitialization = 0

# Snapshot file name of the seeds population
        GAengine.PopSeedsFN = PopSeeds.rec

# Assign the seeds population to the generation number
        GAengine.StartGenerationNumber = 0
        # Preferred Population ranking:
        # 0 - No ranking
        # 1 - OVLRanking from Zyyz
        # 2 - SORanking from J. Wright and R. Famani
        # 3 - Stochastic ranking from Yao
        # 4 - Deb's?
        # 5 - Powell and Skolnick's
        # 6 - (** not in use **)SORanking with sharing
        # 7 - (** not in use **)Stochastic ranking with sharing
        GAengine.PopRanking = 0

# Option for Population ranking method. Depends on the choise of ranking method, the option represents:
        # 0 - Not defined
        # 1 - Prominence of feasible solutions [0, 1.0] (The proportion of feasible solutions that the best infeasible solution ranks
behind)
        # 2 - Not defined
        # 3 - Probability for bubbling on objective only [0, 0.5)
        # 4 - Not defined
        # 5 - Not defined

GAengine.PopRankingOption = 0.1
        # Choice of selection option, from:
```

```
        # 0 - Roulette Wheel selector
        # 1 - Uniform Random selector
        # 2 - 1/2 Tournament selector
        # 3 - 1/3 Tournament selector
        # 4 - 1/4 Tournament selector
        GAengine.PreferredSelector = 2
        # Choice of termination criteria for evolution, from:
        # 0 - Number of generations
        # 1 - N/A
        # 2 - N/A
        # 3 - N/A
        # 4 - N/A
        GAengine.PreferredTerminator = 0

# Output and Log Files
        GAengine.OutputFolder = K:\Output
        GAengine.WriteLogFile = false
        GAengine.LogFileName = GAcore.log
        GAengine.SaveSnapShots = false
        GAengine.SnapShotsGap = 1
        GAengine.SaveProgress = false
        GAengine.ProgressFile = GA_Progress.sco
        GAengine.SaveFamilyStat = false
        GAengine.FamilyStatDumpDir = dump
        GAengine.SaveOpStat = false
        GAengine.OpStatFile = OpStat.sco
        GAengine.SavePopStat = false
        GAengine.PopStatFile = GA_PopStat.sta
        GAengine.SaveEliteList = false
        GAengine.EliteListFile = EliteList.sco
# End of settings
```

# Appendix B Roof Module EP-Macro Input Code

```
##if #[ewalltype[] eqs SIP]

        ##set1 rooftype SIP_Roof

        Construction,
        SIP_Roof,
        SHINGLES[],
        SHEATHING[],
        RIGID_INS[],
        WS3,
        ROOF_SIP[],
        WS3,
        ROOF_DRYWALL[];

        ComponentCost:LineItem,
        Total Cost of Roof,
        ,
        Construction,
        SIP_Roof,
        ,
        ,
        #[#[#[#[SHINGLES_COST[] + ROOF_SIP_COST[]] + ROOF_DRYWALL_COST[]] + SHEATHING_COST[]] + RIGID_INS_COST[]];

        ComponentCost:LineItem,
        Total GWP of Roof,
        ,
        Construction,
        SIP_Roof,
        ,
        ,
        #[#[#[#[SHEATHING_GWP[] + ROOF_SIP_GWP[]] + ROOF_DRYWALL_GWP[]] + SHEATHING_GWP[]] + RIGID_INS_GWP[]];

##else

        ##if #[rooftype[] eqs HPR]

                Construction,
                rooftype[],
                SHINGLES[],
                SHEATHING[],
                RIGID_INS[],
                RIGID_INS[],
                SHEATHING[],
                RAFTER_INS[],
                ROOF_DRYWALL[];

                ComponentCost:LineItem,
                Total Cost of Roof,
                ,
                Construction,
                rooftype[],
                ,
                ,
                #[#[#[#[#[#[SHINGLES_COST[] + SHEATHING_COST[]] + SHEATHING_COST[]] + RIGID_INS_COST[]] + RIGID_INS_COST[]] +
ROOF_DRYWALL_COST[]] + RAFTER_INS_COST[]];

                ComponentCost:LineItem,
                Total GWP of Roof,
                ,
                Construction,
                rooftype[],
                ,
                ,
                #[#[#[#[#[#[SHINGLES_GWP[] + SHEATHING_GWP[]] + SHEATHING_GWP[]] + RIGID_INS_GWP[]] + RIGID_INS_GWP[]] +
ROOF_DRYWALL_GWP[]] + RAFTER_INS_GWP[]];


        ##elseif #[rooftype[] eqs STANDARD_ROOF]
```

```
        Construction,
        rooftype[],
        SHINGLES[],
        SHEATHING[],
        RAFTER_INS[],
        ROOF_DRYWALL[];

        ComponentCost:LineItem,
        Total Cost of Roof,
        ,
        Construction,
        rooftype[],
        ,
        ,
        #[#[#[#[SHINGLES_COST[] + SHEATHING_COST[]] + RIGID_INS_COST[]] + ROOF_DRYWALL_COST[]] + RAFTER_INS_COST[]];

        ComponentCost:LineItem,
        Total GWP of Roof,
        ,
        Construction,
        rooftype[],
        ,
        ,
        #[#[#[#[SHINGLES_GWP[] + SHEATHING_GWP[]] + RIGID_INS_GWP[]] + ROOF_DRYWALL_GWP[]] + RAFTER_INS_GWP[]];

    ##else
    ##endif

##endif
```

# Appendix C Window Module EP-Macro Input Code

```
##if #[WINDOW_FRAME[] eqs WF1]

        ##if #[GLAZING[] eqs GZ1]

                Construction,
                GZ1,
                Clear,
                Air,
                Clear;

                WindowProperty:FrameAndDivider,
                Wood,
                0.110,
                ,
                ,
                1.73,
                1.08,
                0.900000,
                0.900000,
                0.9, , , , , , , , , , , , , , , ;

        ##elseif #[GLAZING[] eqs GZ2]

                Construction,
                GZ2,
                LowE_Out,
                Air,
                Clear;

                WindowProperty:FrameAndDivider,
                Wood,
                0.110,
                ,
                ,
                1.73,
                1.17,
                0.900000,
                0.900000,
                0.9, , , , , , , , , , , , , , , ;

        ##elseif #[GLAZING[] eqs GZ3]

                Construction,
                GZ3,
                LowE_Out,
                Argon,
                Clear;

                WindowProperty:FrameAndDivider,
                Wood,
                0.110,
                ,
                ,
                1.73,
                1.23,
                0.900000,
                0.900000,
                0.9, , , , , , , , , , , , , , , ;

        ##elseif #[GLAZING[] eqs GZ4]

                Construction,
                GZ4,
                Clear,
                Air,
                Clear,
                Air,
                Clear;
```

```
            WindowProperty:FrameAndDivider,
            Wood,
            0.110,
            ,
            ,
            1.73,
            1.17,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , ;

      ##elseif #[GLAZING[] eqs GZ5]

            Construction,
            GZ5,
            Clear,
            Air,
            LowE_Out,
            Air,
            LowE_In;

            WindowProperty:FrameAndDivider,
            Wood,
            0.110,
            ,
            ,
            1.73,
            1.37,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , ;

      ##else

            Construction,
            GZ6,
            Clear,
            Argon,
            LowE_Out,
            Argon,
            LowE_In;

            WindowProperty:FrameAndDivider,
            Wood,
            0.110,
            ,
            ,
            1.73,
            1.50,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , ;

      ##endif


ComponentCost:LineItem,
Total Cost of Window System,
,
General,
WoodFrame,
,
238,
,
,
,
,
,
,
1;

ComponentCost:LineItem,
```

```
            Total Cost of Window System,
            ,
            Construction,
            GLAZING[],
            ,
            ,
            #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

            ComponentCost:LineItem,
            Total GWP of Window System,
            ,
            Construction,
            GLAZING[],
            ,
            ,
            #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];

##elseif #[WINDOW_FRAME[] eqs WF2]

                ##if #[GLAZING[] eqs GZ1]

                        Construction,
                        GZ1,
                        Clear,
                        Air,
                        Clear;

                        WindowProperty:FrameAndDivider,
                        VinylCladWood,
                        0.11,
                        ,
                        ,
                        2.326112,
                        1.478003,
                        0.900000,
                        0.900000,
                        0.9, , , , , , , , , , , , , , , , ;

                ##elseif #[GLAZING[] eqs GZ2]

                        Construction,
                        GZ2,
                        LowE_Out,
                        Air,
                        Clear;

                        WindowProperty:FrameAndDivider,
                        VinylCladWood,
                        0.11,
                        ,
                        ,
                        2.326112,
                        1.478003,
                        0.900000,
                        0.900000,
                        0.9, , , , , , , , , , , , , , , , ;

                ##elseif #[GLAZING[] eqs GZ3]

                        Construction,
                        GZ3,
                        LowE_Out,
                        Argon,
                        Clear;

                        WindowProperty:FrameAndDivider,
                        VinylCladWood,
                        0.11,
                        ,
                        ,
                        2.326112,
                        1.478003,
```

```
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , , ;

    ##elseif #[GLAZING[] eqs GZ4]

            Construction,
            GZ4,
            Clear,
            Air,
            Clear,
            Air,
            Clear;

            WindowProperty:FrameAndDivider,
            VinylCladWood,
            0.11,
            ,
            ,
            2.326112,
            1.478003,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , , ;

    ##elseif #[GLAZING[] eqs GZ5]

            Construction,
            GZ5,
            Clear,
            Air,
            LowE_Out,
            Air,
            LowE_In;

            WindowProperty:FrameAndDivider,
            VinylCladWood,
            0.11,
            ,
            ,
            2.326112,
            1.478003,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , , ;

    ##else

            Construction,
            GZ6,
            Clear,
            Argon,
            LowE_Out,
            Argon,
            LowE_In;

            WindowProperty:FrameAndDivider,
            VinylCladWood,
            0.11,
            ,
            ,
            2.326112,
            1.478003,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , , ;

    ##endif


ComponentCost:LineItem,
Total Cost of Window System,
```

```
            ,
            General,
            VinylCladWood,
            ,
            141,
            ,
            ,
            ,
            ,
            ,
            ,
            1;

            ComponentCost:LineItem,
            Total Cost of Window System,
            ,
            Construction,
            GLAZING[],
            ,
            ,
            #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

            ComponentCost:LineItem,
            Total GWP of Window System,
            ,
            Construction,
            GLAZING[],
            ,
            ,
            #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];

##elseif #[WINDOW_FRAME[] eqs WF3]

                ##if #[GLAZING[] eqs GZ1]

                        Construction,
                        GZ1,
                        Clear,
                        Air,
                        Clear;

                        WindowProperty:FrameAndDivider,
                        Aluminum,
                        0.11,
                        ,
                        ,
                        6.57,
                        1.08,
                        0.900000,
                        0.900000,
                        0.9, , , , , , , , , , , , , , , , ;

                ##elseif #[GLAZING[] eqs GZ2]

                        Construction,
                        GZ2,
                        LowE_Out,
                        Air,
                        Clear;

                        WindowProperty:FrameAndDivider,
                        Aluminum,
                        0.11,
                        ,
                        ,
                        6.57,
                        1.18,
                        0.900000,
                        0.900000,
                        0.9, , , , , , , , , , , , , , , , ;

                ##elseif #[GLAZING[] eqs GZ3]
```

```
        Construction,
        GZ3,
        LowE_Out,
        Argon,
        Clear;

        WindowProperty:FrameAndDivider,
        Aluminum,
        0.11,
        ,
        ,
        6.57,
        1.23,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ4]

        Construction,
        GZ4,
        Clear,
        Air,
        Clear,
        Air,
        Clear;

        WindowProperty:FrameAndDivider,
        Aluminum,
        0.11,
        ,
        ,
        6.57,
        1.17,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ5]

        Construction,
        GZ5,
        Clear,
        Air,
        LowE_Out,
        Air,
        LowE_In;

        WindowProperty:FrameAndDivider,
        Aluminum,
        0.11,
        ,
        ,
        6.57,
        1.37,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##else

        Construction,
        GZ6,
        Clear,
        Argon,
        LowE_Out,
        Argon,
        LowE_In;

        WindowProperty:FrameAndDivider,
        Aluminum,
```

```
                    0.11,
                    ,
                    ,
                    6.57,
                    1.50,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##endif


     ComponentCost:LineItem,
     Total Cost of Window System,
     ,
     General,
     Aluminum,
     ,
     366,
     ,
     ,
     ,
     ,
     ,
     ,
     1;

     ComponentCost:LineItem,
     Total Cost of Window System,
     ,
     Construction,
     GLAZING[],
     ,
     ,
     #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

     ComponentCost:LineItem,
     Total GWP of Window System,
     ,
     Construction,
     GLAZING[],
     ,
     ,
     #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];

##elseif #[WINDOW_FRAME[] eqs WF4]

          ##if #[GLAZING[] eqs GZ1]

                    Construction,
                    GZ1,
                    Clear,
                    Air,
                    Clear;

                    WindowProperty:FrameAndDivider,
                    Vinyl,
                    0.110,
                    ,
                    ,
                    2.44,
                    1.48,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##elseif #[GLAZING[] eqs GZ2]

                    Construction,
                    GZ2,
                    LowE_Out,
                    Air,
```

```
        Clear;

        WindowProperty:FrameAndDivider,
        Vinyl,
        0.110,
        ,
        ,
        2.44,
        2.09
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ3]

        Construction,
        GZ3,
        LowE_Out,
        Argon,
        Clear;

        WindowProperty:FrameAndDivider,
        Vinyl,
        0.110,
        ,
        ,
        2.44,
        2.50,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ4]

        Construction,
        GZ4,
        Clear,
        Air,
        Clear,
        Air,
        Clear;

        WindowProperty:FrameAndDivider,
        Vinyl,
        0.110,
        ,
        ,
        2.44,
        2.00,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ5]

        Construction,
        GZ5,
        Clear,
        Air,
        LowE_Out,
        Air,
        LowE_In;

        WindowProperty:FrameAndDivider,
        Vinyl,
        0.110,
        ,
        ,
        2.44,
        3.81,
        0.900000,
        0.900000,
```

```
                    0.9, , , , , , , , , , , , , , , ;

          ##else

                    Construction,
                    GZ6,
                    Clear,
                    Argon,
                    LowE_Out,
                    Argon,
                    LowE_In;

                    WindowProperty:FrameAndDivider,
                    Vinyl,
                    0.110,
                    ,
                    ,
                    2.44,
                    4.0,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##endif

     ComponentCost:LineItem,
     Total Cost of Window System,
     ,
     General,
     Vinyl,
     ,
     65,
     ,
     ,
     ,
     ,
     ,
     ,
     1;

     ComponentCost:LineItem,
     Total Cost of Window System,
     ,
     Construction,
     GLAZING[],
     ,
     ,
     #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

     ComponentCost:LineItem,
     Total GWP of Window System,
     ,
     Construction,
     GLAZING[],
     ,
     ,
     #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];

##else

##endif
```

# Appendix D Mechanical System EP-Macro Input Code

```
SimulationControl,
    Yes,                    !- Do Zone Sizing Calculation
    Yes,                    !- Do System Sizing Calculation
    No,                     !- Do Plant Sizing Calculation
    No,                     !- Run Simulation for Sizing Periods
    Yes;                    !- Run Simulation for Weather File Run Periods

HVACTemplate:Thermostat,
        Zone Thermostat, !- Thermostat Name
        , !- Heating Setpoint Schedule
        20, !- Constant Heating Setpoint {C}
        , !- Cooling Setpoint Schedule
        27; !- Constant Cooling Setpoint {C}

HVACTemplate:Zone:Unitary,
        ZONE ONE, !- Zone Name
        Heat Pump, !- Template Unitary System Name
        Zone Thermostat, !- Template Thermostat Name
        autosize, !- Supply Air Maximum Flow Rate {m3/s}
        1, !- Zone Heating Sizing Factor
        1, !- Zone Cooling Sizing Factor
        flow/person, !- Outdoor Air Method
        0.00944, !- Outdoor Air Flow Rate per Person {m3/s} or 10 cfm/person
        0.0, !- Outdoor Air Flow Rate per Zone Floor Area {m3/s-m2}
        0.0, !- Outdoor Air Flow Rate per Zone {m3/s}
        , !- Supply Plenum Name
        , !- Return Plenum Name
        None, !- Baseboard Heating Type
        , !- Baseboard Heating Availability Schedule
        0; !- Baseboard Heating Capacity {W}

HVACTemplate:System:UnitaryHeatPump:AirToAir,
        Heat Pump, !- Name
        , !- System Availability Schedule Name
        ZONE ONE, !- Control Zone or Thermostat Location Name
        autosize, !- Cooling Supply Air Flow Rate {m3/s}
        autosize, !- Heating Supply Air Flow Rate {m3/s}
        autosize, !- No Load Supply Air Flow Rate {m3/s}
        Cycling, !- Supply Fan Operating Mode Schedule Name
        BlowThrough, !- Supply Fan Placement
        0.95, !- Supply Fan Total Efficiency
        600, !- Supply Fan Delta Pressure {Pa}
        0.95, !- Supply Fan Motor Efficiency
        1, !- Supply Fan Motor in Air Stream Fraction
        SingleSpeedDX, !- Cooling Coil Type
        Off, !- Cooling Coil Availability Schedule Name
        12.8, !- Cooling Design Supply Air Temperature {C}
        autosize, !- Cooling Coil Capacity {W}
        autosize, !- Cooling Coil Rated Sensible Heat Ratio
        3.8, !- Cooling Coil Rated COP
        SingleSpeedDXHeatPump, !- Heat Pump Heating Coil Type
        , !- Heat Pump Heating Coil Availability Schedule Name
        50, !- Heating Design Supply Air Temperature {C}
        autosize, !- Heat Pump Heating Coil Rated Capacity {W}
        3.1, !- Heat Pump Heating Coil Rated COP
        -8, !- Heat Pump Heating Minimum Outdoor Dry-Bulb Temperature {C}
        5, !- Heat Pump Defrost Maximum Outdoor Dry-Bulb Temperature {C}
        ReverseCycle, !- Heat Pump Defrost Strategy
        Timed, !- Heat Pump Defrost Control
        0.058333, !- Heat Pump Defrost Time Period Fraction
        Gas, !- Supplemental Heating Coil Type
        Off, !- Supplemental Heating Coil Availability Schedule Name
        autosize, !- Supplemental Heating Coil Capacity {W}
        21, !- Supplemental Heating Coil Max Outdoor Dry-Bulb Temperature {C}
        0.8, !- Supplemental Gas Heating Coil Efficiency
        , !- Supplemental Gas Heating Coil Parasitic Electric Load {W}
        0.092, !- Maximum Outdoor Air Flow Rate {m3/s}
        0.024, !- Minimum Outdoor Air Flow Rate {m3/s}
```

, !- Minimum Outdoor Air Schedule Name
**NoEconomizer, !- Economizer Type**
NoLockout, !- Economizer Lockout
19, !- Economizer Maximum Limit Dry-Bulb Temperature {C}
, !- Economizer Maximum Limit Enthalpy {J/kg}
, !- Economizer Maximum Limit Dewpoint Temperature {C}
4, !- Economizer Minimum Limit Dry-Bulb Temperature {C}
, !- Supply Plenum Name
, !- Return Plenum Name
CycleOnAny, !- Night Cycle Control
, !- Night Cycle Control Zone Name
**None, !- Heat Recovery Type**
0.8, !- Sensible Heat Recovery Effectiveness
0.65, !- Latent Heat Recovery Effectiveness
**None, !- Humidifier Type**
, !- Humidifier Availability Schedule Name
0.000001, !- Humidifier Rated Capacity {m3/s}
2690, !- Humidifier Rated Electric Power {W}
, !- Humidifier Control Zone Name
30; !- Humidifier Setpoint {percent}

ComponentCost:LineItem,
ASHP System Cost, !- Name
, !- Type
Coil:DX, !- Line Item Type
HEAT PUMP HEATING COIL, !- Item Name
, !- Object End Use Key
, !- Cost per Each {$}
, !- Cost per Area {$/m2}
754; !- Cost per Unit of Output Capacity {$/kW}

ComponentCost:LineItem,
Heat Pump System GWP, !- Name
, !- Type
Coil:DX, !- Line Item Type
HEAT PUMP HEATING COIL, !- Item Name
, !- Object End Use Key
, !- GWPt per Each {kg-CO2-eq}
, !- GWP per Area {kg-CO2-eq/m2}
20.2; !- GWP per Unit of Output Capacity {kg-CO2-eq/kW}

# Appendix E BESTEST Case 600 Main EnergyPlus Input Code General Materials Database

| ID | Material Name | Thickness (in) | Thickness (m) | RSMeans 2011 O&P Cost ($/m) | Replacement Cost ($/m2) | Vancouver Life Cycle Cost ($/m2) | R-Value | Conductivity (Continuous) | Effective Conductivity (24"o.c. Green Wood Framing) | Effective Conductivity (24"o.c. Kiln Dried Wood Framing) | Effective Conductivity (16"o.c. Green Wood Framing) | Effective Conductivity (16"o.c. Kiln Dried Wood Framing) | Density (kg/m3) | Specific Heat | Thermal Abs. | Solar Abs. | Visible Abs. | Global Warming Potential (kg CO2) | GWP (Unit Adjusted) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **INSULATION** | | | | | | | | | | | | | | | | | | |
| **IN1** | Fiberglass Batt.** | 3 1/2 | 0.0889 | $8.80 | $0.00 | $8.80 | 13 | 0.0388 | 0.0611 | 0.0511 | 0.0666 | 0.0541 | 12.1 | 840 | 0.9 | 0.6 | 0.6 | 3.19 | 11.34 |
| **IN2** | | 5 1/2 | 0.1397 | $11.26 | $0.00 | $11.26 | 18 | 0.0441 | 0.0653 | 0.0553 | 0.0706 | 0.0581 | 7 | 840 | 0.9 | 0.6 | 0.6 | 3.07 | 17.16 |
| **IN3** | | 7 1/4 | 0.1842 | $16.26 | $0.00 | $16.26 | 26 | 0.0402 | 0.0622 | 0.0522 | 0.0677 | 0.0552 | 12 | 840 | 0.9 | 0.6 | 0.6 | 2.91 | 21.44 |
| **IN4** | | 11 1/4 | 0.2858 | $16.67 | $0.00 | $16.67 | 37 | 0.0439 | 0.0651 | 0.0551 | 0.0704 | 0.0579 | 7.7 | 840 | 0.9 | 0.6 | 0.6 | 2.94 | 33.60 |
| **IN5** | Isocyanurate** | 1/2 | 0.0127 | $10.79 | $0.00 | $10.79 | 3 | 0.0219 | 0.0475 | 0.0375 | 0.0539 | 0.0414 | 32 | 1470 | 0.9 | 0.6 | 0.6 | 5.21 | 2.65 |
| **IN6** | | 1 | 0.0254 | $14.35 | $0.00 | $14.35 | 7 | 0.0222 | 0.0478 | 0.0378 | 0.0541 | 0.0416 | 32 | 1470 | 0.9 | 0.6 | 0.6 | 5.21 | 5.29 |
| **IN7** | | 2 | 0.0508 | $19.45 | $0.00 | $19.45 | 13 | 0.0222 | 0.0478 | 0.0378 | 0.0541 | 0.0416 | 32 | 1470 | 0.9 | 0.6 | 0.6 | 5.21 | 10.59 |
| **IN8** | | 3 | 0.0762 | $35.34 | $0.00 | $35.34 | 13 | 0.0222 | 0.0478 | 0.0378 | 0.0542 | 0.0417 | 32 | 1470 | 0.9 | 0.6 | 0.6 | 5.21 | 15.88 |
| **IN9** | | 4 | 0.1016 | $38.75 | $0.00 | $38.75 | 13 | 0.0222 | 0.0478 | 0.0378 | 0.0542 | 0.0417 | 32 | 1470 | 0.9 | 0.6 | 0.6 | 5.21 | 21.17 |
| **IN10** | Blown Cellulose** | 3 1/2 | 0.0889 | $5.96 | $0.00 | $5.96 | 13 | 0.0388 | 0.0611 | 0.0511 | 0.0666 | 0.0541 | 54 | 1300 | 0.9 | 0.6 | 0.6 | 2.57 | 9.14 |
| **IN11** | | 5 3/16 | 0.1318 | $8.28 | $0.00 | $8.28 | 19 | 0.0394 | 0.0615 | 0.0515 | 0.0670 | 0.0545 | 54 | 1300 | 0.9 | 0.6 | 0.6 | 2.57 | 13.55 |
| **IN12** | | 6 1/2 | 0.1651 | $10.57 | $0.00 | $10.57 | 22 | 0.0426 | 0.0641 | 0.0541 | 0.0695 | 0.0570 | 54 | 1300 | 0.9 | 0.6 | 0.6 | 2.57 | 16.97 |
| **IN13** | Mineral Wool | 3 1/2 | 0.0889 | $6.33 | $0.00 | $6.33 | 14 | 0.0361 | 0.0588 | 0.0488 | 0.0645 | 0.0520 | 32 | 800 | 0.9 | 0.6 | 0.6 | 3.69 | 13.12 |
| **IN14** | | 5 1/2 | 0.1397 | $9.87 | $0.00 | $9.87 | 22 | 0.0361 | 0.0588 | 0.0488 | 0.0645 | 0.0520 | 32 | 800 | 0.9 | 0.6 | 0.6 | 3.71 | 20.73 |
| **IN15** | EPS Wall | 1 | 0.0254 | $10.79 | $0.00 | $10.79 | 4 | 0.0375 | 0.0600 | 0.0500 | 0.0656 | 0.0531 | 25 | 1470 | 0.9 | 0.6 | 0.6 | 4.23 | 4.30 |
| **IN16** | | 2 | 0.0508 | $16.11 | $0.00 | $16.11 | 8 | 0.0375 | 0.0600 | 0.0500 | 0.0656 | 0.0531 | 25 | 1470 | 0.9 | 0.6 | 0.6 | 4.23 | 8.60 |
| **IN17** | | 3 | 0.0762 | $20.82 | $0.00 | $20.82 | 11 | 0.0377 | 0.0601 | 0.0501 | 0.0657 | 0.0532 | 25 | 1470 | 0.9 | 0.6 | 0.6 | 4.23 | 12.89 |
| **IN18** | EPS Roof | 4 | 0.1016 | $22.59 | $0.00 | $22.59 | 15 | 0.0375 | 0.0600 | 0.0500 | 0.0656 | 0.0531 | 25 | 1470 | 0.9 | 0.6 | 0.6 | 4.23 | 17.19 |
| **IN19** | | 5 | 0.1270 | $27.37 | $0.00 | $27.37 | 19 | 0.0375 | 0.0600 | 0.0500 | 0.0656 | 0.0531 | 25 | 1470 | 0.9 | 0.6 | 0.6 | 4.23 | 21.49 |
| **IN20** | | 6 | 0.1524 | $31.87 | $0.00 | $31.87 | 23 | 0.0372 | 0.0598 | 0.0498 | 0.0654 | 0.0529 | 25 | 1470 | 0.9 | 0.6 | 0.6 | 4.23 | 25.79 |
| **IN21** | XPS Wall | 1 | 0.0254 | $14.15 | $0.00 | $14.15 | 5 | 0.0288 | 0.0531 | 0.0431 | 0.0591 | 0.0466 | 33 | 1470 | 0.9 | 0.6 | 0.6 | 6.34 | 6.44 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **IN22** | | 2 | 0.0508 | $22.86 | $0.00 | $22.86 | 10 | 0.0288 | 0.0531 | 0.0431 | 0.0591 | 0.0466 | 33 | 1470 | 0.9 | 0.6 | 0.6 | 6.34 | 12.88 |
| **IN23** | | 3 | 0.0762 | $29.89 | $0.00 | $29.89 | 15 | 0.0288 | 0.0531 | 0.0431 | 0.0591 | 0.0466 | 33 | 1470 | 0.9 | 0.6 | 0.6 | 6.34 | 19.32 |
| **IN24** | XPS Roof | 4 | 0.1016 | $31.79 | $0.00 | $31.79 | 20 | 0.0288 | 0.0531 | 0.0431 | 0.0591 | 0.0466 | 33 | 1470 | 0.9 | 0.6 | 0.6 | 6.34 | 25.77 |
| **IN25** | Spray Polyurethane Foam (Closed Cell) | 1 | 0.0254 | $9.87 | $0.00 | $9.87 | 7 | 0.0222 | 0.0478 | 0.0378 | 0.0541 | 0.0416 | 32 | 1590 | 0.9 | 0.6 | 0.6 | 4.23 | 4.30 |
| **IN26** | | 2 | 0.0508 | $19.76 | $0.00 | $19.76 | 13 | 0.0222 | 0.0478 | 0.0378 | 0.0541 | 0.0416 | 32 | 1590 | 0.9 | 0.6 | 0.6 | 4.23 | 8.60 |
| **IN27** | | 3 | 0.0762 | $29.76 | $0.00 | $29.76 | 19 | 0.0222 | 0.0478 | 0.0378 | 0.0542 | 0.0417 | 32 | 1590 | 0.9 | 0.6 | 0.6 | 4.23 | 12.89 |
| **IN28** | | 3 1/2 | 0.0889 | $34.66 | $0.00 | $34.66 | 23 | 0.0222 | 0.0478 | 0.0378 | 0.0542 | 0.0417 | 32 | 1590 | 0.9 | 0.6 | 0.6 | 4.23 | 15.04 |
| **IN29** | | 4 | 0.1016 | $39.72 | $0.00 | $39.72 | 26 | 0.0222 | 0.0478 | 0.0378 | 0.0542 | 0.0417 | 32 | 1590 | 0.9 | 0.6 | 0.6 | 4.23 | 17.19 |
| **IN30** | | 5 | 0.1270 | $49.82 | $0.00 | $49.82 | 32 | 0.0222 | 0.0478 | 0.0378 | 0.0542 | 0.0417 | 32 | 1590 | 0.9 | 0.6 | 0.6 | 4.23 | 21.49 |
| **IN31** | | 5 1/2 | 0.1397 | $54.16 | $0.00 | $54.16 | 36 | 0.0222 | 0.0478 | 0.0378 | 0.0542 | 0.0417 | 32 | 1590 | 0.9 | 0.6 | 0.6 | 4.23 | 23.64 |
| **IN32** | | 6 | 0.1524 | $59.14 | $0.00 | $59.14 | 39 | 0.0222 | 0.0478 | 0.0378 | 0.0542 | 0.0417 | 32 | 1590 | 0.9 | 0.6 | 0.6 | 4.23 | 25.79 |
| | **STRUCTURAL INSULATED PANELS** | | | | | | | | | | | | | | | | | | |
| **SIP1** | SIP EPS (includes 7/16" OSB cost, EPS thickness only) | 3 1/2 | 0.0889 | $51.35 | $0.00 | $51.35 | ~ | 0.0375 | ~ | ~ | ~ | ~ | 25 | 1470 | 0.9 | 0.6 | 0.6 | | 25.41 |
| **SIP2** | | 5 1/2 | 0.1397 | $59.10 | $0.00 | $59.10 | ~ | 0.0375 | ~ | ~ | ~ | ~ | 25 | 1470 | 0.9 | 0.6 | 0.6 | | 29.24 |
| **SIP3** | | 7 1/4 | 0.1842 | $66.86 | $0.00 | $66.86 | ~ | 0.0375 | ~ | ~ | ~ | ~ | 25 | 1470 | 0.9 | 0.6 | 0.6 | | 32.52 |
| **SIP4** | | 9 1/4 | 0.2350 | $77.06 | $0.00 | $77.06 | ~ | 0.0375 | ~ | ~ | ~ | ~ | 25 | 1470 | 0.9 | 0.6 | 0.6 | | 37.13 |
| | **INSULATED CONCRETE FORMS** | | | | | | | | | | | | | | | | | | |
| **ICF1** | Insulated Concrete Forms (Below Grade, Concrete only) *Craftsman Cost | 6 | 0.1524 | $85.65 | $0.00 | $85.65 | ~ | 1.1000 | ~ | ~ | ~ | ~ | 2080 | 900 | 0.9 | 0.67 | 0.67 | | 78.38 |
| **ICF2** | | 8 | 0.2032 | $94.04 | $0.00 | $94.04 | ~ | 1.1000 | ~ | ~ | ~ | ~ | 2080 | 900 | 0.9 | 0.67 | 0.67 | | 97.05 |
| **ICF3** | Insulated Concrete Forms (Above Grade, Concrete only) * Craftsman Cost | 6 | 0.1524 | $94.58 | $0.00 | $94.58 | ~ | 1.1000 | ~ | ~ | ~ | ~ | 2080 | 900 | 0.9 | 0.67 | 0.67 | | 78.38 |
| **ICF4** | | 8 | 0.2032 | $103.53 | $0.00 | $103.53 | ~ | 1.1000 | ~ | ~ | ~ | ~ | 2080 | 900 | 0.9 | 0.67 | 0.67 | | 97.05 |
| | **SHEATHING** | | | | | | | | | | | | | | | | | | |
| **WS1** | Softwood Plywood | 1/2 | 0.0127 | $14.67 | $0.00 | $14.67 | ~ | 0.1400 | ~ | ~ | ~ | ~ | 460 | 1880 | 0.9 | 0.6 | 0.6 | 3.39 | 4.78 |
| **WS2** | OSB | 1/2 | 0.0127 | $10.27 | $0.00 | $10.27 | ~ | 0.1100 | ~ | ~ | ~ | ~ | 650 | 1880 | 0.9 | 0.6 | 0.6 | 4.02 | 5.67 |
| **WS3** | SIP OSB | 7/16 | 0.0111 | $0.00 | $0.00 | $0.00 | ~ | 0.1200 | ~ | ~ | ~ | ~ | 650 | 1880 | 0.9 | 0.6 | 0.6 | 3.83 | 4.73 |
| | **DRYWALL** | | | | | | | | | | | | | | | | | | |
| **DW1** | Regular Gypsum Board (Taped and Finished, wall) | 1/2 | 0.0127 | $15.17 | $0.00 | $15.17 | ~ | 0.1600 | ~ | ~ | ~ | ~ | 640 | 1150 | 0.9 | 0.6 | 0.6 | 4.81 | 4.81 |
| **DW2** | Gypsum-Fiber Board (Taped and Finished, wall) | 1/2 | 0.0127 | $27.95 | $0.00 | $27.95 | ~ | 0.3200 | ~ | ~ | ~ | ~ | 1150 | 1100 | 0.9 | 0.6 | 0.6 | 8.19 | 8.19 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DW3** | Regular Gypsum Board (Taped and Finished, ceiling) | 1/2 | 0.0127 | $17.80 | $0.00 | $17.80 | ~ | 0.1600 | ~ | ~ | ~ | ~ | 640 | 1150 | 0.9 | 0.6 | 0.6 | 4.81 | 4.81 |
| **DW4** | Gypsum-Fiber Board (Taped and Finished, ceiling) | 1/2 | 0.0127 | $30.88 | $0.00 | $30.88 | ~ | 0.3200 | ~ | ~ | ~ | ~ | 1150 | 1100 | 0.9 | 0.6 | 0.6 | 8.19 | 8.19 |
| | **CLADDING** | | | | | | | | | | | | | | | | | | |
| **CL1** | Wood Siding (Cedar) | 1/2 | 0.0127 | $72.09 | $16.68 | $88.77 | ~ | 0.0929 | ~ | ~ | ~ | ~ | 430 | 1170 | 0.9 | 0.7 | 0.7 | 12.59 | 25.18 |
| **CL2** | Fiber Cement Siding | 5/16 | 0.0079 | $42.07 | $9.73 | $51.80 | ~ | 0.0250 | ~ | ~ | ~ | ~ | 1400 | 840 | 0.9 | 0.7 | 0.7 | 16.41 | 32.82 |
| **CL3** | Residential 30 ga. Steel Siding | 1/64 | 0.0004 | $50.66 | $0.00 | $50.66 | ~ | 45.3000 | ~ | ~ | ~ | ~ | 7830 | 500 | 0.25 | 0.7 | 0.7 | 47.52 | 95.04 |
| **CL4** | Stucco on Mesh (White) | Soft | 0.0254 | $57.66 | $13.34 | $71.00 | ~ | 0.7200 | ~ | ~ | ~ | ~ | 1858 | 840 | 0.9 | 0.38 | 0.38 | 8.79 | 17.58 |
| **CL5** | Common Face Brick (Red) | 3 1/2 | 0.0889 | $198.74 | $0.00 | $198.74 | ~ | 0.5700 | ~ | ~ | ~ | ~ | 1441 | 790 | 0.9 | 0.7 | 0.7 | 52.4 | 104.80 |
| **CL6** | Vinyl Siding | 1/21 | 0.0012 | $37.14 | $8.59 | $45.73 | ~ | 0.0110 | ~ | ~ | ~ | ~ | 1220 | 1000 | 0.9 | 0.6 | 0.6 | 13.55 | 27.10 |
| | **CONCRETE** | | | | | | | | | | | | | | | | | | |
| **CN1** | Gravity Retaining Wall | 8 | 0.2032 | $614.46 | $0.00 | $614.46 | ~ | 1.1000 | ~ | ~ | ~ | ~ | 2080 | 900 | 0.9 | 0.67 | 0.67 | | 54.10 |
| **CN2** | | 12 | 0.3048 | $921.69 | $0.00 | $921.69 | ~ | 1.1000 | ~ | ~ | ~ | ~ | 2080 | 900 | 0.9 | 0.67 | 0.67 | | 81.15 |
| **CN3** | Slab On Grade | 4 | 0.1016 | $37.22 | $0.00 | $37.22 | ~ | 1.1000 | ~ | ~ | ~ | ~ | 2080 | 900 | 0.9 | 0.67 | 0.67 | | 27.05 |
| **CN4** | | 8 | 0.2032 | $65.90 | $0.00 | $65.90 | ~ | 1.1000 | ~ | ~ | ~ | ~ | 2080 | 900 | 0.9 | 0.67 | 0.67 | | 54.10 |
| | **ROOFING** | | | | | | | | | | | | | | | | | | |
| **RF1** | Asphalt Roof Shingles (inorganic, Pneumatic Nailed) | 1/8 | 0.003175 | $18.50 | $9.60 | $28.10 | ~ | 0.0407 | ~ | ~ | ~ | ~ | 920 | 1260 | 0.93 | 0.6 | 0.6 | 2.09 | 6.10 |
| **RF2** | Residential 30 ga. Steel Roof Panel | 1/64 | 0.0004 | $49.63 | $0.00 | $49.63 | ~ | 45.3000 | ~ | ~ | ~ | ~ | 7830 | 500 | 0.25 | 0.7 | 0.7 | 21.97 | 32.22 |
| | **CARPET** | | | | | | | | | | | | | | | | | | |
| **FL1** | Carpet and Urethane Pad | 3/4 | 0.0190 | $11.85 | $6.15 | $18.00 | ~ | 0.0600 | ~ | ~ | ~ | ~ | 110 | 1380 | 0.9 | 0.6 | 0.6 | | |
| **FL2** | Carpet and Rubber Pad | 3/8 | 0.0095 | $10.97 | $5.69 | $16.66 | ~ | 0.0792 | ~ | ~ | ~ | ~ | 320 | 1380 | 0.9 | 0.6 | 0.6 | | |

# Appendix F Wall and Roof Components Database

**Table B1 Wall stud insulation and framing material properties, cost, and global warming potential data.**

| ID Code | Stud Space | Stud Depth | Thickness | Framing Cost | Framing GWP | Insulation | Insulation Cost | Insulation GWP | Total Cost | Total GWP | Effective Conductivity | R-Value | Density | Specific Heat | Therm Abs | Solar Abs | Vis Abs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SDIN1** | 400mm | 2x4 | 0.089 | 14.31 | 1.79 | Fiberglass | 8.8 | 11.34 | 23.11 | 13.13 | 0.0541 | 9.34 | 12.1 | 840 | 0.9 | 0.6 | 0.6 |
| **SDIN2** | 400mm | 2x4 | 0.089 | 14.31 | 1.79 | Mineral Wool | 6.33 | 13.12 | 20.64 | 14.91 | 0.052 | 9.72 | 32 | 800 | 0.9 | 0.6 | 0.6 |
| **SDIN3** | 400mm | 2x4 | 0.089 | 14.31 | 1.79 | Blown Cell | 5.96 | 9.14 | 20.27 | 10.93 | 0.0541 | 9.34 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **SDIN4** | 400mm | 2x4 | 0.089 | 14.31 | 1.79 | Spray Foam | 34.66 | 15.04 | 48.97 | 16.83 | 0.0417 | 12.12 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **SDIN5** | 400mm | 2x4 | 0.089 | 14.31 | 1.79 | Airspace | 0 | 0 | 14.31 | 1.79 | 0.64 | 0.79 | 1.2 | 1005 | 0.9 | 0.6 | 0.6 |
| **SDIN6** | 400mm | 2x6 | 0.14 | 21.2 | 2.54 | Fiberglass | 11.26 | 17.16 | 32.46 | 19.7 | 0.0581 | 13.68 | 7 | 840 | 0.9 | 0.6 | 0.6 |
| **SDIN7** | 400mm | 2x6 | 0.14 | 21.2 | 2.54 | Mineral Wool | 9.87 | 20.73 | 31.07 | 23.27 | 0.052 | 15.29 | 32 | 800 | 0.9 | 0.6 | 0.6 |
| **SDIN8** | 400mm | 2x6 | 0.14 | 21.2 | 2.54 | Blown Cell | 8.28 | 13.55 | 29.48 | 16.09 | 0.0545 | 14.59 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **SDIN9** | 400mm | 2x6 | 0.14 | 21.2 | 2.54 | Spray Foam | 54.16 | 23.64 | 75.36 | 26.18 | 0.0417 | 19.06 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **SDIN10** | 400mm | 2x6 | 0.14 | 21.2 | 2.54 | Airspace | 0 | 0 | 21.2 | 2.54 | 0.56 | 1.42 | 1.2 | 1005 | 0.9 | 0.6 | 0.6 |
| **SDIN11** | 600mm | 2x4 | 0.089 | 9.9 | 1.56 | Fiberglass | 8.8 | 11.34 | 18.7 | 12.9 | 0.0511 | 9.89 | 12.1 | 840 | 0.9 | 0.6 | 0.6 |
| **SDIN12** | 600mm | 2x4 | 0.089 | 9.9 | 1.56 | Mineral Wool | 6.33 | 13.12 | 16.23 | 14.68 | 0.0488 | 10.36 | 32 | 800 | 0.9 | 0.6 | 0.6 |
| **SDIN13** | 600mm | 2x4 | 0.089 | 9.9 | 1.56 | Blown Cell | 5.96 | 9.14 | 15.86 | 10.7 | 0.0511 | 9.89 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **SDIN14** | 600mm | 2x4 | 0.089 | 9.9 | 1.56 | Spray Foam | 34.66 | 15.04 | 44.56 | 16.6 | 0.0378 | 13.37 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **SDIN15** | 600mm | 2x4 | 0.089 | 9.9 | 1.56 | Airspace | 0 | 0 | 9.9 | 1.56 | 0.64 | 0.79 | 1.2 | 1005 | 0.9 | 0.6 | 0.6 |
| **SDIN16** | 600mm | 2x6 | 0.14 | 14.2 | 2.21 | Fiberglass | 11.26 | 17.16 | 25.46 | 19.37 | 0.0553 | 14.37 | 7 | 840 | 0.9 | 0.6 | 0.6 |
| **SDIN17** | 600mm | 2x6 | 0.14 | 14.2 | 2.21 | Mineral Wool | 9.87 | 20.73 | 24.07 | 22.94 | 0.0488 | 16.29 | 32 | 800 | 0.9 | 0.6 | 0.6 |
| **SDIN18** | 600mm | 2x6 | 0.14 | 14.2 | 2.21 | Blown Cell | 8.28 | 13.55 | 22.48 | 15.76 | 0.0515 | 15.44 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **SDIN19** | 600mm | 2x6 | 0.14 | 14.2 | 2.21 | Spray Foam | 54.16 | 23.64 | 68.36 | 25.85 | 0.0378 | 21.03 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **SDIN20** | 600mm | 2x6 | 0.14 | 14.2 | 2.21 | Airspace | 0 | 0 | 14.2 | 2.21 | 0.56 | 1.42 | 1.2 | 1005 | 0.9 | 0.6 | 0.6 |

**Table B2 Roof rafter-space insulation and framing material properties, cost, and global warming potential data.**

| ID Code | Stud Space | Stud Depth | Thickness | Framing Cost | Framing GWP | Insulation | Insulation Cost | Insulation GWP | Total Cost | Total GWP | Effective Conductivity | R- Value | Density | Specific Heat | Therm Abs | Solar Abs | Vis Abs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RFIN1** | 600mm | 2x6 | 0.14 | 13.45 | 2.61 | Fiberglass | 11.26 | 17.16 | 24.71 | 19.77 | 0.0553 | 14.37468354 | 7 | 840 | 0.9 | 0.6 | 0.6 |
| **RFIN2** | 600mm | 2x6 | 0.14 | 13.45 | 2.61 | Blown Cell | 8.28 | 13.55 | 21.73 | 16.16 | 0.0511 | 15.55616438 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **RFIN3** | 600mm | 2x6 | 0.14 | 13.45 | 2.61 | Spray Foam | 54.16 | 23.65 | 67.61 | 26.26 | 0.0378 | 21.02962963 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **RFIN4** | 600mm | 2x8 | 0.184 | 19.05 | 3.24 | Fiberglass | 16.26 | 21.44 | 35.31 | 24.68 | 0.0522 | 20.01440613 | 7.3 | 840 | 0.9 | 0.6 | 0.6 |
| **RFIN5** | 600mm | 2x8 | 0.184 | 19.05 | 3.24 | Blown Cell | 11.56 | 18.82 | 30.61 | 22.06 | 0.0511 | 20.44524462 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **RFIN6** | 600mm | 2x8 | 0.184 | 19.05 | 3.24 | Spray Foam | 71.56 | 31.18 | 90.61 | 34.42 | 0.0378 | 27.6389418 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **RFIN7** | 600mm | 2x12 | 0.286 | 24 | 6.37 | Fiberglass | 16.67 | 33.60 | 40.67 | 39.97 | 0.0551 | 29.47201452 | 7.7 | 840 | 0.9 | 0.6 | 0.6 |
| **RFIN8** | 600mm | 2x12 | 0.286 | 24 | 6.37 | Blown Cell | 16.91 | 27.68 | 40.91 | 34.05 | 0.0511 | 31.77902153 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **RFIN9** | 600mm | 2x12 | 0.286 | 24 | 6.37 | Spray Foam | 111.04 | 48.38 | 135.04 | 54.75 | 0.0378 | 42.9605291 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **RFIN10** | 400mm | 2x6 | 0.14 | 18.18 | 3 | Fiberglass | 11.26 | 17.16 | 29.44 | 20.16 | 0.0581 | 13.68192771 | 7 | 840 | 0.9 | 0.6 | 0.6 |
| **RFIN11** | 400mm | 2x6 | 0.14 | 18.18 | 3 | Blown Cell | 8.28 | 13.55 | 26.46 | 16.55 | 0.0541 | 14.6935305 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **RFIN12** | 400mm | 2x6 | 0.14 | 18.18 | 3 | Spray Foam | 54.16 | 23.65 | 72.34 | 26.65 | 0.0417 | 19.06282974 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **RFIN13** | 400mm | 2x8 | 0.184 | 22.6 | 3.74 | Fiberglass | 16.26 | 21.44 | 38.86 | 25.18 | 0.0552 | 18.92666667 | 7.3 | 840 | 0.9 | 0.6 | 0.6 |
| **RFIN14** | 400mm | 2x8 | 0.184 | 22.6 | 3.74 | Blown Cell | 11.56 | 18.82 | 34.16 | 22.56 | 0.0541 | 19.31149723 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **RFIN15** | 400mm | 2x8 | 0.184 | 22.6 | 3.74 | Spray Foam | 71.56 | 31.18 | 94.16 | 34.92 | 0.0417 | 25.0540048 | 32 | 1590 | 0.9 | 0.6 | 0.6 |
| **RFIN16** | 400mm | 2x12 | 0.286 | 32.71 | 7.33 | Fiberglass | 16.67 | 33.60 | 49.38 | 40.93 | 0.0579 | 28.04677029 | 7.7 | 840 | 0.9 | 0.6 | 0.6 |
| **RFIN17** | 400mm | 2x12 | 0.286 | 32.71 | 7.33 | Blown Cell | 16.91 | 27.68 | 49.62 | 35.01 | 0.0541 | 30.01678373 | 54 | 1300 | 0.9 | 0.6 | 0.6 |
| **RFIN18** | 400mm | 2x12 | 0.286 | 32.71 | 7.33 | Spray Foam | 111.04 | 48.38 | 143.75 | 55.71 | 0.0417 | 38.94263789 | 32 | 1590 | 0.9 | 0.6 | 0.6 |

# Appendix G Window Database

**Table C1 Window cost and life cycle global warming potential data.**

| Frame | Unit GWP ($kgCO2eq/m^2$) | Unit Cost ($/m2) | Fixed Cost Premium ($) | Glazing Type | Unit GWP ($kgCO2eq/m^2$) | Unit Cost ($/m2) | Combined Total GWP | Combined Total Cost ($\$/m^2$) | Fixed Cost Premium ($) | Unit Cost ($\$/m^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Vinyl Operable** | 306.94 | 65 | 277 | Double Glazed No Coating Air | 79.04 | 353.07745 | 385.98 | 418.08 | 277 | 695.08 |
| **Vinyl Operable** | 306.94 | 65 | 277 | Double Glazed Soft Coated Air | 80.49 | 384.85442 | 387.43 | 449.85 | 277 | 726.85 |
| **Vinyl Operable** | 306.94 | 65 | 277 | Double Glazed Soft Coated Argon | 80.74 | 395.63442 | 387.68 | 460.63 | 277 | 737.63 |
| **Vinyl Operable** | 306.94 | 65 | 277 | Triple Glazed No Coating Air | 117.28 | 529.61617 | 424.22 | 594.62 | 277 | 871.62 |
| **Vinyl Operable** | 306.94 | 65 | 277 | Triple Glazed Soft Coated Air | 118.74 | 593.17011 | 425.68 | 658.17 | 277 | 935.17 |
| **Vinyl Operable** | 306.94 | 65 | 277 | Triple Glazed Soft Coated Argon | 119.23 | 603.95011 | 426.17 | 668.95 | 277 | 945.95 |
| **Wood Operable** | 234.85 | 183 | 238 | Double Glazed No Coating Air | 79.04 | 353.07745 | 313.89 | 536.08 | 238 | 774.08 |
| **Wood Operable** | 234.85 | 183 | 238 | Double Glazed Soft Coated Air | 80.49 | 384.85442 | 315.34 | 567.85 | 238 | 805.85 |
| **Wood Operable** | 234.85 | 183 | 238 | Double Glazed Soft Coated Argon | 80.74 | 395.63442 | 315.59 | 578.63 | 238 | 816.63 |
| **Wood Operable** | 234.85 | 183 | 238 | Triple Glazed No Coating Air | 117.28 | 529.61617 | 352.13 | 712.62 | 238 | 950.62 |
| **Wood Operable** | 234.85 | 183 | 238 | Triple Glazed Soft Coated Air | 118.74 | 593.17011 | 353.59 | 776.17 | 238 | 1014.17 |
| **Wood Operable** | 234.85 | 183 | 238 | Triple Glazed Soft Coated Argon | 119.23 | 603.95011 | 354.08 | 786.95 | 238 | 1024.95 |
| **Vinyl Clad Wood Operable** | 181.16 | 364 | 141 | Double Glazed No Coating Air | 79.04 | 353.07745 | 260.2 | 717.08 | 141 | 858.08 |
| **Vinyl Clad Wood Operable** | 181.16 | 364 | 141 | Double Glazed Soft Coated Air | 80.49 | 384.85442 | 261.65 | 748.85 | 141 | 889.85 |
| **Vinyl Clad Wood Operable** | 181.16 | 364 | 141 | Double Glazed Soft Coated Argon | 80.74 | 395.63442 | 261.9 | 759.63 | 141 | 900.63 |
| **Vinyl Clad Wood Operable** | 181.16 | 364 | 141 | Triple Glazed No Coating Air | 117.28 | 529.61617 | 298.44 | 893.62 | 141 | 1034.62 |
| **Vinyl Clad Wood Operable** | 181.16 | 364 | 141 | Triple Glazed Soft Coated Air | 118.74 | 593.17011 | 299.9 | 957.17 | 141 | 1098.17 |
| **Vinyl Clad Wood Operable** | 181.16 | 364 | 141 | Triple Glazed Soft Coated Argon | 119.23 | 603.95011 | 300.39 | 967.95 | 141 | 1108.95 |
| **Aluminum Operable** | 613.93 | 109 | 366 | Double Glazed No Coating Air | 79.04 | 353.07745 | 692.97 | 462.08 | 366 | 828.08 |
| **Aluminum Operable** | 613.93 | 109 | 366 | Double Glazed Soft Coated Air | 80.49 | 384.85442 | 694.42 | 493.85 | 366 | 859.85 |
| **Aluminum Operable** | 613.93 | 109 | 366 | Double Glazed Soft Coated Argon | 80.74 | 395.63442 | 694.67 | 504.63 | 366 | 870.63 |
| **Aluminum** | 613.93 | 109 | 366 | Triple Glazed No | 117.28 | 529.61617 | 731.21 | 638.62 | 366 | 1004.62 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Operable** | | | | Coating Air | | | | | | |
| **Aluminum Operable** | 613.93 | 109 | 366 | Triple Glazed Soft Coated Air | 118.74 | 593.17011 | 732.67 | 702.17 | 366 | 1068.17 |
| **Aluminum Operable** | 613.93 | 109 | 366 | Triple Glazed Soft Coated Argon | 119.23 | 603.95011 | 733.16 | 712.95 | 366 | 1078.95 |

## Appendix H jEPlus+EA Optimization Parameters

```
########################################################################
# GA engine settings file
########################################################################
# Default GA settings
        GAengine.PMutation = 0.2
        GAengine.PCrossover =0.8
        # Percent of population to be updated in each generation.
        # This parameter is ignored if elitism is used
        GAengine.PPopReplace = 0.95
        GAengine.PopSize = 50
        GAengine.MaxPops = 500

# More GA settings
# Population allows duplicated individuals or not
        GAengine.PopAllowDuplication = false
        # Choice of population initialization methods, from:
         # 0 - Default (create a random population)
         # 1 - Reserved
         # 2 - Reserved
         # 3 - N/A
         # 4 - N/A
         # 5 - N/A
        GAengine.PopInitialization = 0

# Snapshot file name of the seeds population
        GAengine.PopSeedsFN = PopSeeds.rec

# Assign the seeds population to the generation number
        GAengine.StartGenerationNumber = 0
        # Preferred Population ranking:
        # 0 - No ranking
        # 1 - OVLRanking from Zyyz
        # 2 - SORanking from J. Wright and R. Famani
        # 3 - Stochastic ranking from Yao
        # 4 - Deb's?
        # 5 - Powell and Skolnick's
        # 6 - (** not in use **)SORanking with sharing
        # 7 - (** not in use **)Stochastic ranking with sharing
        GAengine.PopRanking = 0

# Option for Population ranking method. Depends on the choise of ranking method, the option represents:
        # 0 - Not defined
        # 1 - Prominence of feasible solutions [0, 1.0] (The proportion of feasible solutions that the best infeasible solution ranks
behind)
        # 2 - Not defined
        # 3 - Probability for bubbling on objective only [0, 0.5)
        # 4 - Not defined
        # 5 - Not defined

GAengine.PopRankingOption = 0.1
        # Choice of selection option, from:
        # 0 - Roulette Wheel selector
        # 1 - Uniform Random selector
        # 2 - 1/2 Tournament selector
        # 3 - 1/3 Tournament selector
```

```
# 4 - 1/4 Tournament selector
GAengine.PreferredSelector = 2
# Choice of termination criteria for evolution, from:
# 0 - Number of generations
# 1 - N/A
# 2 - N/A
# 3 - N/A
# 4 - N/A
GAengine.PreferredTerminator = 0

# Output and Log Files
GAengine.OutputFolder = K:\Output
GAengine.WriteLogFile = false
GAengine.LogFileName = GAcore.log
GAengine.SaveSnapShots = false
GAengine.SnapShotsGap = 1
GAengine.SaveProgress = false
GAengine.ProgressFile = GA_Progress.sco
GAengine.SaveFamilyStat = false
GAengine.FamilyStatDumpDir = dump
GAengine.SaveOpStat = false
GAengine.OpStatFile = OpStat.sco
GAengine.SavePopStat = false
GAengine.PopStatFile = GA_PopStat.sta
GAengine.SaveEliteList = false
GAengine.EliteListFile = EliteList.sco
# End of settings
```

# Appendix I Roof Module EP-Macro Input Code

```
##if #[ewalltype[] eqs SIP]

    ##set1 rooftype SIP_Roof

    Construction,
    SIP_Roof,
    SHINGLES[],
    SHEATHING[],
    RIGID_INS[],
    WS3,
    ROOF_SIP[],
    WS3,
    ROOF_DRYWALL[];

    ComponentCost:LineItem,
    Total Cost of Roof,
    ,
    Construction,
    SIP_Roof,
    ,
    ,
    #[#[#[#[SHINGLES_COST[] + ROOF_SIP_COST[]] + ROOF_DRYWALL_COST[]] + SHEATHING_COST[]] + RIGID_INS_COST[]];

    ComponentCost:LineItem,
    Total GWP of Roof,
    ,
    Construction,
    SIP_Roof,
    ,
    ,
    #[#[#[#[SHEATHING_GWP[] + ROOF_SIP_GWP[]] + ROOF_DRYWALL_GWP[]] + SHEATHING_GWP[]] + RIGID_INS_GWP[]];

##else

    ##if #[rooftype[] eqs HPR]

        Construction,
        rooftype[],
        SHINGLES[],
        SHEATHING[],
        RIGID_INS[],
        RIGID_INS[],
        SHEATHING[],
        RAFTER_INS[],
        ROOF_DRYWALL[];

        ComponentCost:LineItem,
        Total Cost of Roof,
        ,
        Construction,
        rooftype[],
        ,
        ,
        #[#[#[#[#[#[SHINGLES_COST[] + SHEATHING_COST[]] + SHEATHING_COST[]] + RIGID_INS_COST[]] + RIGID_INS_COST[]] +
ROOF_DRYWALL_COST[]] + RAFTER_INS_COST[]];

        ComponentCost:LineItem,
        Total GWP of Roof,
        ,
        Construction,
        rooftype[],
        ,
        ,
        #[#[#[#[#[#[SHINGLES_GWP[] + SHEATHING_GWP[]] + SHEATHING_GWP[]] + RIGID_INS_GWP[]] + RIGID_INS_GWP[]] +
ROOF_DRYWALL_GWP[]] + RAFTER_INS_GWP[]];


    ##elseif #[rooftype[] eqs STANDARD_ROOF]
```

```
        Construction,
        rooftype[],
        SHINGLES[],
        SHEATHING[],
        RAFTER_INS[],
        ROOF_DRYWALL[];

        ComponentCost:LineItem,
        Total Cost of Roof,
        ,
        Construction,
        rooftype[],
        ,
        ,
        #[#[#[#[SHINGLES_COST[] + SHEATHING_COST[]] + RIGID_INS_COST[]] + ROOF_DRYWALL_COST[]] + RAFTER_INS_COST[]];

        ComponentCost:LineItem,
        Total GWP of Roof,
        ,
        Construction,
        rooftype[],
        ,
        ,
        #[#[#[#[SHINGLES_GWP[] + SHEATHING_GWP[]] + RIGID_INS_GWP[]] + ROOF_DRYWALL_GWP[]] + RAFTER_INS_GWP[]];

    ##else
    ##endif

##endif
```

# Appendix J Window Module EP-Macro Input Code

```
##if #[WINDOW_FRAME[] eqs WF1]

        ##if #[GLAZING[] eqs GZ1]

                Construction,
                GZ1,
                Clear,
                Air,
                Clear;

                WindowProperty:FrameAndDivider,
                Wood,
                0.110,
                ,
                ,
                1.73,
                1.08,
                0.900000,
                0.900000,
                0.9, , , , , , , , , , , , , , , , ;

        ##elseif #[GLAZING[] eqs GZ2]

                Construction,
                GZ2,
                LowE_Out,
                Air,
                Clear;

                WindowProperty:FrameAndDivider,
                Wood,
                0.110,
                ,
                ,
                1.73,
                1.17,
                0.900000,
                0.900000,
                0.9, , , , , , , , , , , , , , , , ;

        ##elseif #[GLAZING[] eqs GZ3]

                Construction,
                GZ3,
                LowE_Out,
                Argon,
                Clear;

                WindowProperty:FrameAndDivider,
                Wood,
                0.110,
                ,
                ,
                1.73,
                1.23,
                0.900000,
                0.900000,
                0.9, , , , , , , , , , , , , , , , ;

        ##elseif #[GLAZING[] eqs GZ4]

                Construction,
                GZ4,
                Clear,
                Air,
                Clear,
                Air,
                Clear;
```

```
        WindowProperty:FrameAndDivider,
        Wood,
        0.110,
        ,
        ,
        1.73,
        1.17,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

    ##elseif #[GLAZING[] eqs GZ5]

        Construction,
        GZ5,
        Clear,
        Air,
        LowE_Out,
        Air,
        LowE_In;

        WindowProperty:FrameAndDivider,
        Wood,
        0.110,
        ,
        ,
        1.73,
        1.37,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

    ##else

        Construction,
        GZ6,
        Clear,
        Argon,
        LowE_Out,
        Argon,
        LowE_In;

        WindowProperty:FrameAndDivider,
        Wood,
        0.110,
        ,
        ,
        1.73,
        1.50,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

    ##endif

ComponentCost:LineItem,
Total Cost of Window System,
,
General,
WoodFrame,
,
238,
,
,
,
,
,
,
1;

ComponentCost:LineItem,
```

```
            Total Cost of Window System,
            ,
            Construction,
            GLAZING[],
            ,
            ,
            #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

            ComponentCost:LineItem,
            Total GWP of Window System,
            ,
            Construction,
            GLAZING[],
            ,
            ,
            #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];

##elseif #[WINDOW_FRAME[] eqs WF2]

                    ##if #[GLAZING[] eqs GZ1]

                            Construction,
                            GZ1,
                            Clear,
                            Air,
                            Clear;

                            WindowProperty:FrameAndDivider,
                            VinylCladWood,
                            0.11,
                            ,
                            ,
                            2.326112,
                            1.478003,
                            0.900000,
                            0.900000,
                            0.9, , , , , , , , , , , , , , , ;

                    ##elseif #[GLAZING[] eqs GZ2]

                            Construction,
                            GZ2,
                            LowE_Out,
                            Air,
                            Clear;

                            WindowProperty:FrameAndDivider,
                            VinylCladWood,
                            0.11,
                            ,
                            ,
                            2.326112,
                            1.478003,
                            0.900000,
                            0.900000,
                            0.9, , , , , , , , , , , , , , , ;

                    ##elseif #[GLAZING[] eqs GZ3]

                            Construction,
                            GZ3,
                            LowE_Out,
                            Argon,
                            Clear;

                            WindowProperty:FrameAndDivider,
                            VinylCladWood,
                            0.11,
                            ,
                            ,
                            2.326112,
                            1.478003,
```

```
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##elseif #[GLAZING[] eqs GZ4]

                    Construction,
                    GZ4,
                    Clear,
                    Air,
                    Clear,
                    Air,
                    Clear;

                    WindowProperty:FrameAndDivider,
                    VinylCladWood,
                    0.11,
                    ,
                    ,
                    2.326112,
                    1.478003,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##elseif #[GLAZING[] eqs GZ5]

                    Construction,
                    GZ5,
                    Clear,
                    Air,
                    LowE_Out,
                    Air,
                    LowE_In;

                    WindowProperty:FrameAndDivider,
                    VinylCladWood,
                    0.11,
                    ,
                    ,
                    2.326112,
                    1.478003,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##else

                    Construction,
                    GZ6,
                    Clear,
                    Argon,
                    LowE_Out,
                    Argon,
                    LowE_In;

                    WindowProperty:FrameAndDivider,
                    VinylCladWood,
                    0.11,
                    ,
                    ,
                    2.326112,
                    1.478003,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##endif


ComponentCost:LineItem,
Total Cost of Window System,
```

```
            ,
            General,
            VinylCladWood,
            ,
            141,
            ,
            ,
            ,
            ,
            ,
            ,
            1;

            ComponentCost:LineItem,
            Total Cost of Window System,
            ,
            Construction,
            GLAZING[],
            ,
            ,
            #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

            ComponentCost:LineItem,
            Total GWP of Window System,
            ,
            Construction,
            GLAZING[],
            ,
            ,
            #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];

##elseif #[WINDOW_FRAME[] eqs WF3]

                        ##if #[GLAZING[] eqs GZ1]

                                    Construction,
                                    GZ1,
                                    Clear,
                                    Air,
                                    Clear;

                                    WindowProperty:FrameAndDivider,
                                    Aluminum,
                                    0.11,
                                    ,
                                    ,
                                    6.57,
                                    1.08,
                                    0.900000,
                                    0.900000,
                                    0.9, , , , , , , , , , , , , , , ;

                        ##elseif #[GLAZING[] eqs GZ2]

                                    Construction,
                                    GZ2,
                                    LowE_Out,
                                    Air,
                                    Clear;

                                    WindowProperty:FrameAndDivider,
                                    Aluminum,
                                    0.11,
                                    ,
                                    ,
                                    6.57,
                                    1.18,
                                    0.900000,
                                    0.900000,
                                    0.9, , , , , , , , , , , , , , , ;

                        ##elseif #[GLAZING[] eqs GZ3]
```

```
            Construction,
            GZ3,
            LowE_Out,
            Argon,
            Clear;

            WindowProperty:FrameAndDivider,
            Aluminum,
            0.11,
            ,
            ,
            6.57,
            1.23,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ4]

            Construction,
            GZ4,
            Clear,
            Air,
            Clear,
            Air,
            Clear;

            WindowProperty:FrameAndDivider,
            Aluminum,
            0.11,
            ,
            ,
            6.57,
            1.17,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ5]

            Construction,
            GZ5,
            Clear,
            Air,
            LowE_Out,
            Air,
            LowE_In;

            WindowProperty:FrameAndDivider,
            Aluminum,
            0.11,
            ,
            ,
            6.57,
            1.37,
            0.900000,
            0.900000,
            0.9, , , , , , , , , , , , , , , ;

##else

            Construction,
            GZ6,
            Clear,
            Argon,
            LowE_Out,
            Argon,
            LowE_In;

            WindowProperty:FrameAndDivider,
            Aluminum,
```

```
                    0.11,
                    ,
                    ,
                    6.57,
                    1.50,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##endif


     ComponentCost:LineItem,
     Total Cost of Window System,
     ,
     General,
     Aluminum,
     ,
     366,
     ,
     ,
     ,
     ,
     ,
     ,
     1;

     ComponentCost:LineItem,
     Total Cost of Window System,
     ,
     Construction,
     GLAZING[],
     ,
     ,
     #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

     ComponentCost:LineItem,
     Total GWP of Window System,
     ,
     Construction,
     GLAZING[],
     ,
     ,
     #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];

##elseif #[WINDOW_FRAME[] eqs WF4]

          ##if #[GLAZING[] eqs GZ1]

                    Construction,
                    GZ1,
                    Clear,
                    Air,
                    Clear;

                    WindowProperty:FrameAndDivider,
                    Vinyl,
                    0.110,
                    ,
                    ,
                    2.44,
                    1.48,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

          ##elseif #[GLAZING[] eqs GZ2]

                    Construction,
                    GZ2,
                    LowE_Out,
                    Air,
```

```
        Clear;

        WindowProperty:FrameAndDivider,
        Vinyl,
        0.110,
        ,
        ,
        2.44,
        2.09
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ3]

        Construction,
        GZ3,
        LowE_Out,
        Argon,
        Clear;

        WindowProperty:FrameAndDivider,
        Vinyl,
        0.110,
        ,
        ,
        2.44,
        2.50,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ4]

        Construction,
        GZ4,
        Clear,
        Air,
        Clear,
        Air,
        Clear;

        WindowProperty:FrameAndDivider,
        Vinyl,
        0.110,
        ,
        ,
        2.44,
        2.00,
        0.900000,
        0.900000,
        0.9, , , , , , , , , , , , , , , ;

##elseif #[GLAZING[] eqs GZ5]

        Construction,
        GZ5,
        Clear,
        Air,
        LowE_Out,
        Air,
        LowE_In;

        WindowProperty:FrameAndDivider,
        Vinyl,
        0.110,
        ,
        ,
        2.44,
        3.81,
        0.900000,
        0.900000,
```

```
                    0.9, , , , , , , , , , , , , , , ;

        ##else

                    Construction,
                    GZ6,
                    Clear,
                    Argon,
                    LowE_Out,
                    Argon,
                    LowE_In;

                    WindowProperty:FrameAndDivider,
                    Vinyl,
                    0.110,
                    ,
                    ,
                    2.44,
                    4.0,
                    0.900000,
                    0.900000,
                    0.9, , , , , , , , , , , , , , , ;

        ##endif

    ComponentCost:LineItem,
    Total Cost of Window System,
    ,
    General,
    Vinyl,
    ,
    65,
    ,
    ,
    ,
    ,
    ,
    ,
    1;

    ComponentCost:LineItem,
    Total Cost of Window System,
    ,
    Construction,
    GLAZING[],
    ,
    ,
    #[GLAZING_COST[] + WINDOW_FRAME_COST[]];

    ComponentCost:LineItem,
    Total GWP of Window System,
    ,
    Construction,
    GLAZING[],
    ,
    ,
    #[GLAZING_GWP[] + WINDOW_FRAME_GWP[]];

##else

##endif
```

# Appendix K Mechanical System EP-Macro Input Code

```
SimulationControl,
   Yes,                !- Do Zone Sizing Calculation
   Yes,                !- Do System Sizing Calculation
   No,                 !- Do Plant Sizing Calculation
   No,                 !- Run Simulation for Sizing Periods
   Yes;                !- Run Simulation for Weather File Run Periods

HVACTemplate:Thermostat,
        Zone Thermostat, !- Thermostat Name
        , !- Heating Setpoint Schedule
        20, !- Constant Heating Setpoint {C}
        , !- Cooling Setpoint Schedule
        27; !- Constant Cooling Setpoint {C}

HVACTemplate:Zone:Unitary,
        ZONE ONE, !- Zone Name
        Heat Pump, !- Template Unitary System Name
        Zone Thermostat, !- Template Thermostat Name
        autosize, !- Supply Air Maximum Flow Rate {m3/s}
        1, !- Zone Heating Sizing Factor
        1, !- Zone Cooling Sizing Factor
        flow/person, !- Outdoor Air Method
        0.00944, !- Outdoor Air Flow Rate per Person {m3/s} or 10 cfm/person
        0.0, !- Outdoor Air Flow Rate per Zone Floor Area {m3/s-m2}
        0.0, !- Outdoor Air Flow Rate per Zone {m3/s}
        , !- Supply Plenum Name
        , !- Return Plenum Name
        None, !- Baseboard Heating Type
        , !- Baseboard Heating Availability Schedule
        0; !- Baseboard Heating Capacity {W}

HVACTemplate:System:UnitaryHeatPump:AirToAir,
        Heat Pump, !- Name
        , !- System Availability Schedule Name
        ZONE ONE, !- Control Zone or Thermostat Location Name
        autosize, !- Cooling Supply Air Flow Rate {m3/s}
        autosize, !- Heating Supply Air Flow Rate {m3/s}
        autosize, !- No Load Supply Air Flow Rate {m3/s}
        Cycling, !- Supply Fan Operating Mode Schedule Name
        BlowThrough, !- Supply Fan Placement
        0.95, !- Supply Fan Total Efficiency
        600, !- Supply Fan Delta Pressure {Pa}
        0.95, !- Supply Fan Motor Efficiency
        1, !- Supply Fan Motor in Air Stream Fraction
        SingleSpeedDX, !- Cooling Coil Type
        Off, !- Cooling Coil Availability Schedule Name
        12.8, !- Cooling Design Supply Air Temperature {C}
        autosize, !- Cooling Coil Capacity {W}
        autosize, !- Cooling Coil Rated Sensible Heat Ratio
        3.8, !- Cooling Coil Rated COP
        SingleSpeedDXHeatPump, !- Heat Pump Heating Coil Type
        , !- Heat Pump Heating Coil Availability Schedule Name
        50, !- Heating Design Supply Air Temperature {C}
        autosize, !- Heat Pump Heating Coil Rated Capacity {W}
        3.1, !- Heat Pump Heating Coil Rated COP
        -8, !- Heat Pump Heating Minimum Outdoor Dry-Bulb Temperature {C}
        5, !- Heat Pump Defrost Maximum Outdoor Dry-Bulb Temperature {C}
        ReverseCycle, !- Heat Pump Defrost Strategy
        Timed, !- Heat Pump Defrost Control
        0.058333, !- Heat Pump Defrost Time Period Fraction
        Gas, !- Supplemental Heating Coil Type
        Off, !- Supplemental Heating Coil Availability Schedule Name
        autosize, !- Supplemental Heating Coil Capacity {W}
        21, !- Supplemental Heating Coil Max Outdoor Dry-Bulb Temperature {C}
        0.8, !- Supplemental Gas Heating Coil Efficiency
        , !- Supplemental Gas Heating Coil Parasitic Electric Load {W}
        0.092, !- Maximum Outdoor Air Flow Rate {m3/s}
        0.024, !- Minimum Outdoor Air Flow Rate {m3/s}
```

, !- Minimum Outdoor Air Schedule Name
**NoEconomizer, !- Economizer Type**
NoLockout, !- Economizer Lockout
19, !- Economizer Maximum Limit Dry-Bulb Temperature {C}
, !- Economizer Maximum Limit Enthalpy {J/kg}
, !- Economizer Maximum Limit Dewpoint Temperature {C}
4, !- Economizer Minimum Limit Dry-Bulb Temperature {C}
, !- Supply Plenum Name
, !- Return Plenum Name
CycleOnAny, !- Night Cycle Control
, !- Night Cycle Control Zone Name
**None, !- Heat Recovery Type**
0.8, !- Sensible Heat Recovery Effectiveness
0.65, !- Latent Heat Recovery Effectiveness
**None, !- Humidifier Type**
, !- Humidifier Availability Schedule Name
0.000001, !- Humidifier Rated Capacity {m3/s}
2690, !- Humidifier Rated Electric Power {W}
, !- Humidifier Control Zone Name
30; !- Humidifier Setpoint {percent}

ComponentCost:LineItem,
ASHP System Cost, !- Name
, !- Type
Coil:DX, !- Line Item Type
HEAT PUMP HEATING COIL, !- Item Name
, !- Object End Use Key
, !- Cost per Each {$}
, !- Cost per Area {$/m2}
754; !- Cost per Unit of Output Capacity {$/kW}

ComponentCost:LineItem,
Heat Pump System GWP, !- Name
, !- Type
Coil:DX, !- Line Item Type
HEAT PUMP HEATING COIL, !- Item Name
, !- Object End Use Key
, !- GWPt per Each {kg-CO2-eq}
, !- GWP per Area {kg-CO2-eq/m2}
20.2; !- GWP per Unit of Output Capacity {kg-CO2-eq/kW}

# Appendix L BESTEST Case 600 Main EnergyPlus Input Code

```
BESTEST_Case600.imf – EnergyPlus Input Code
##fileprefix K:\Optimization Project\include

!=====Macro Definitions=====

!====HVAC System Sizes======

!====Exterior Wall=====
##set1 ewalltype @@ewalltype@@

##set1 CLADDING @@cladding@@
##set1 SHEATHING @@sheathing@@
##set1 WALL_DRYWALL @@wall_drywall@@
##set1 EXT_INS @@ext_ins@@
##set1 STUD_INS @@stud_ins@@
##set1 SIP @@sip@@
##set1 AGICF @@agicf@@

##set1 CLADDING_COST @@cladding_cost@@
##set1 SHEATHING_COST @@sheathing_cost@@
##set1 WALL_DRYWALL_COST @@wall_drywall_cost@@
##set1 EXT_INS_COST @@ext_ins_cost@@
##set1 STUD_INS_COST @@stud_ins_cost@@
##set1 SIP_COST @@sip_cost@@
##set1 AGICF_COST @@agicf_cost@@

##set1 CLADDING_GWP @@cladding_gwp@@
##set1 SHEATHING_GWP @@sheathing_gwp@@
##set1 WALL_DRYWALL_GWP @@wall_drywall_gwp@@
##set1 EXT_INS_GWP @@ext_ins_gwp@@
##set1 STUD_INS_GWP @@stud_ins_gwp@@
##set1 SIP_GWP @@sip_gwp@@
##set1 AGICF_GWP @@agicf_gwp@@

!====Window Systems====

##set1 WINDOW_FRAME @@windowframetype@@
##set1 GLAZING @@glazingtype@@

##set1 WINDOW_FRAME_COST @@windowframe_cost@@
##set1 GLAZING_COST @@glazingtype_cost@@

##set1 WINDOW_FRAME_GWP @@windowframe_gwp@@
##set1 GLAZING_GWP @@glazingtype_gwp@@

!====Roof Type====

##set1 rooftype @@rooftype@@

##set1 SHINGLES @@shingles@@
##set1 RIGID_INS @@roof_rigid_ins@@
##set1 RAFTER_INS @@roof_stud_ins@@
##set1 ROOF_DRYWALL @@roof_drywall@@
##set1 ROOF_SIP @@roof_sip@@

##set1 SHINGLES_COST @@shingles_cost@@
##set1 RIGID_INS_COST @@roof_rigid_ins_cost@@
##set1 RAFTER_INS_COST @@roof_stud_ins_cost@@
##set1 ROOF_DRYWALL_COST @@roof_drywall_cost@@
##set1 ROOF_SIP_COST @@roof_sip_cost@@

##set1 SHINGLES_GWP @@shingles_gwp@@
##set1 RIGID_INS_GWP @@roof_rigid_ins_gwp@@
##set1 RAFTER_INS_GWP @@roof_stud_ins_gwp@@
##set1 ROOF_DRYWALL_GWP @@roof_drywall_gwp@@
##set1 ROOF_SIP_GWP @@roof_sip_gwp@@

!====Shading Devices====
```

```
!##set1 SHADING @@shading@@

!====PV System====

!##set1 PVSYSTEMSIZE @@pvsystemsize@@

!===== MAIN ENERGYPLUS INPUT=====

Version, 7.2.0.006;    !- Version Identifier

!-   ===========  ALL OBJECTS IN CLASS: BUILDING ===========

Building,
    BESTEST Case 600,        !- Name
    @@orientation@@,                    !- North Axis {deg}
    City,                !- Terrain
    3.9999999E-02,           !- Loads Convergence Tolerance Value
    4.0000002E-03,           !- Temperature Convergence Tolerance Value {deltaC}
    FullInteriorAndExterior, !- Solar Distribution
    ,                        !- Maximum Number of Warmup Days
    7;                       !- Minimum Number of Warmup Days

!-   ===========  ALL OBJECTS IN CLASS: SHADOWCALCULATION ===========

ShadowCalculation,
    1;                       !- Calculation Frequency

!-   ===========  ALL OBJECTS IN CLASS: SURFACECONVECTIONALGORITHM:INSIDE ===========

SurfaceConvectionAlgorithm:Inside,
    TARP;                    !- Algorithm

!-   ===========  ALL OBJECTS IN CLASS: SURFACECONVECTIONALGORITHM:OUTSIDE ===========

SurfaceConvectionAlgorithm:Outside,
    DOE-2;                   !- Algorithm

!-   ===========  ALL OBJECTS IN CLASS: TIMESTEP ===========

Timestep,
    4;                       !- Number of Timesteps per Hour

!-   ===========  ALL OBJECTS IN CLASS: SITE:LOCATION ===========

Site:Location,
    Vancouver,          !- Name
    49.17,                   !- Latitude {deg}
    -123.17,                 !- Longitude {deg}
    -8.0,              !- Time Zone {hr}
    2.0;                !- Elevation {m}

!-   ===========  ALL OBJECTS IN CLASS: RUNPERIOD ===========

RunPeriod,
    ,                        !- Name
    1,                       !- Begin Month
    1,                       !- Begin Day of Month
    12,                      !- End Month
    31,                      !- End Day of Month
    ,                        !- Day of Week for Start Day
    ,                        !- Use Weather File Holidays and Special Days
    ,                        !- Use Weather File Daylight Saving Period
    ,                        !- Apply Weekend Holiday Rule
    ,                        !- Use Weather File Rain Indicators
    ;                        !- Use Weather File Snow Indicators

!-   ===========  ALL OBJECTS IN CLASS: SITE:GROUNDTEMPERATURE:BUILDINGSURFACE ===========

Site:GroundTemperature:BuildingSurface,
    10.0,                    !- January Ground Temperature {C}
    10.0,                    !- February Ground Temperature {C}
    10.0,                    !- March Ground Temperature {C}
```

```
    10.0,                  !- April Ground Temperature {C}
    10.0,                  !- May Ground Temperature {C}
    10.0,                  !- June Ground Temperature {C}
    10.0,                  !- July Ground Temperature {C}
    10.0,                  !- August Ground Temperature {C}
    10.0,                  !- September Ground Temperature {C}
    10.0,                  !- October Ground Temperature {C}
    10.0,                  !- November Ground Temperature {C}
    10.0;                  !- December Ground Temperature {C}

!-   ===========  ALL OBJECTS IN CLASS: SITE:GROUNDREFLECTANCE ===========

Site:GroundReflectance,
    0.2,                   !- January Ground Reflectance {dimensionless}
    0.2,                   !- February Ground Reflectance {dimensionless}
    0.2,                   !- March Ground Reflectance {dimensionless}
    0.2,                   !- April Ground Reflectance {dimensionless}
    0.2,                   !- May Ground Reflectance {dimensionless}
    0.2,                   !- June Ground Reflectance {dimensionless}
    0.2,                   !- July Ground Reflectance {dimensionless}
    0.2,                   !- August Ground Reflectance {dimensionless}
    0.2,                   !- September Ground Reflectance {dimensionless}
    0.2,                   !- October Ground Reflectance {dimensionless}
    0.2,                   !- November Ground Reflectance {dimensionless}
    0.2;                   !- December Ground Reflectance {dimensionless}

!-   ===========  ALL OBJECTS IN CLASS: SCHEDULES ===========

##include Schedules.idf

!-   ===========  ALL OBJECTS IN CLASS: GLOBALGEOMETRYRULES ===========

! ZoneCapacitanceMultiplier,1;
GlobalGeometryRules,
    UpperLeftCorner,         !- Starting Vertex Position
    Counterclockwise,        !- Vertex Entry Direction
    WorldCoordinateSystem;   !- Coordinate System

!-   ===========  ALL OBJECTS IN CLASS: ZONE ===========

Zone,
    ZONE ONE,              !- Name
    0,                     !- Direction of Relative North {deg}
    0,                     !- X Origin {m}
    0,                     !- Y Origin {m}
    0,                     !- Z Origin {m}
    1,                     !- Type
    1,                     !- Multiplier
    2.7000,                !- Ceiling Height {m}
    129.6;                 !- Volume {m3}

!-   ===========  ALL OBJECTS IN CLASS: MATERIALS ===========

##include Materials.idf

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS ===========

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: WALL ===========

##include EWallType.imf

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: FLOOR ===========

!##include GFloorType.imf

Construction,
gfloor,
IN24,
CN3,
FL1;

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: ROOF ===========
```

```
##include RoofType.imf

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: WINDOW ===========

##include WindowType.imf

!-   ===========  ALL OBJECTS IN CLASS: BASELINE MATERIALS AND CONSTRUCTIONS ===========

!##include BaseCase.idf

!##include BaseCaseAdjusted.idf

!-   ===========  ALL OBJECTS IN CLASS: BUILDINGSURFACE:DETAILED ===========

BuildingSurface:Detailed,
    ZONE SURFACE NORTH,      !- Name
    Wall,                    !- Surface Type
    ewalltype[],             !- Construction Name
    ZONE ONE,                !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.5000000,               !- View Factor to Ground
    4,                       !- Number of Vertices
    8.000000,                !- Vertex 1 X-coordinate {m}
    6.000000,                !- Vertex 1 Y-coordinate {m}
    2.700000,                !- Vertex 1 Z-coordinate {m}
    8.000000,                !- Vertex 2 X-coordinate {m}
    6.000000,                !- Vertex 2 Y-coordinate {m}
    0,                       !- Vertex 2 Z-coordinate {m}
    0,                       !- Vertex 3 X-coordinate {m}
    6.000000,                !- Vertex 3 Y-coordinate {m}
    0,                       !- Vertex 3 Z-coordinate {m}
    0,                       !- Vertex 4 X-coordinate {m}
    6.000000,                !- Vertex 4 Y-coordinate {m}
    2.700000;                !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    ZONE SURFACE EAST,       !- Name
    Wall,                    !- Surface Type
    ewalltype[],             !- Construction Name
    ZONE ONE,                !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.5000000,               !- View Factor to Ground
    4,                       !- Number of Vertices
    8.000000,                !- Vertex 1 X-coordinate {m}
    0,                       !- Vertex 1 Y-coordinate {m}
    2.700000,                !- Vertex 1 Z-coordinate {m}
    8.000000,                !- Vertex 2 X-coordinate {m}
    0,                       !- Vertex 2 Y-coordinate {m}
    0,                       !- Vertex 2 Z-coordinate {m}
    8.000000,                !- Vertex 3 X-coordinate {m}
    6.000000,                !- Vertex 3 Y-coordinate {m}
    0,                       !- Vertex 3 Z-coordinate {m}
    8.000000,                !- Vertex 4 X-coordinate {m}
    6.000000,                !- Vertex 4 Y-coordinate {m}
    2.700000;                !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    ZONE SURFACE SOUTH,      !- Name
    Wall,                    !- Surface Type
    ewalltype[],             !- Construction Name
    ZONE ONE,                !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
```

```
    0.5000000,              !- View Factor to Ground
    4,                      !- Number of Vertices
    0,                      !- Vertex 1 X-coordinate {m}
    0,                      !- Vertex 1 Y-coordinate {m}
    2.700000,               !- Vertex 1 Z-coordinate {m}
    0,                      !- Vertex 2 X-coordinate {m}
    0,                      !- Vertex 2 Y-coordinate {m}
    0,                      !- Vertex 2 Z-coordinate {m}
    8.000000,               !- Vertex 3 X-coordinate {m}
    0,                      !- Vertex 3 Y-coordinate {m}
    0,                      !- Vertex 3 Z-coordinate {m}
    8.000000,               !- Vertex 4 X-coordinate {m}
    0,                      !- Vertex 4 Y-coordinate {m}
    2.700000;               !- Vertex 4 Z-coordinate {m}

  BuildingSurface:Detailed,
    ZONE SURFACE WEST,      !- Name
    Wall,                   !- Surface Type
    ewalltype[],            !- Construction Name
    ZONE ONE,               !- Zone Name
    Outdoors,               !- Outside Boundary Condition
    ,                       !- Outside Boundary Condition Object
    SunExposed,             !- Sun Exposure
    WindExposed,            !- Wind Exposure
    0.5000000,              !- View Factor to Ground
    4,                      !- Number of Vertices
    0,                      !- Vertex 1 X-coordinate {m}
    6.000000,               !- Vertex 1 Y-coordinate {m}
    2.700000,               !- Vertex 1 Z-coordinate {m}
    0,                      !- Vertex 2 X-coordinate {m}
    6.000000,               !- Vertex 2 Y-coordinate {m}
    0,                      !- Vertex 2 Z-coordinate {m}
    0,                      !- Vertex 3 X-coordinate {m}
    0,                      !- Vertex 3 Y-coordinate {m}
    0,                      !- Vertex 3 Z-coordinate {m}
    0,                      !- Vertex 4 X-coordinate {m}
    0,                      !- Vertex 4 Y-coordinate {m}
    2.700000;               !- Vertex 4 Z-coordinate {m}

  BuildingSurface:Detailed,
    ZONE SURFACE FLOOR,     !- Name
    Floor,                  !- Surface Type
    gfloor,                 !- Construction Name
    ZONE ONE,               !- Zone Name
    Ground,                 !- Outside Boundary Condition
    ,                       !- Outside Boundary Condition Object
    NoSun,                  !- Sun Exposure
    NoWind,                 !- Wind Exposure
    0,                      !- View Factor to Ground
    4,                      !- Number of Vertices
    0,                      !- Vertex 1 X-coordinate {m}
    0,                      !- Vertex 1 Y-coordinate {m}
    0,                      !- Vertex 1 Z-coordinate {m}
    0,                      !- Vertex 2 X-coordinate {m}
    6.000000,               !- Vertex 2 Y-coordinate {m}
    0,                      !- Vertex 2 Z-coordinate {m}
    8.000000,               !- Vertex 3 X-coordinate {m}
    6.000000,               !- Vertex 3 Y-coordinate {m}
    0,                      !- Vertex 3 Z-coordinate {m}
    8.000000,               !- Vertex 4 X-coordinate {m}
    0,                      !- Vertex 4 Y-coordinate {m}
    0;                      !- Vertex 4 Z-coordinate {m}

  BuildingSurface:Detailed,
    ZONE SURFACE ROOF,      !- Name
    Roof,                   !- Surface Type
    rooftype[],             !- Construction Name
    ZONE ONE,               !- Zone Name
    Outdoors,               !- Outside Boundary Condition
    ,                       !- Outside Boundary Condition Object
    SunExposed,             !- Sun Exposure
    WindExposed,            !- Wind Exposure
```

```
    0,                       !- View Factor to Ground
    4,                       !- Number of Vertices
    0,                       !- Vertex 1 X-coordinate {m}
    6.000000,                !- Vertex 1 Y-coordinate {m}
    2.700000,                !- Vertex 1 Z-coordinate {m}
    0,                       !- Vertex 2 X-coordinate {m}
    0,                       !- Vertex 2 Y-coordinate {m}
    2.700000,                !- Vertex 2 Z-coordinate {m}
    8.000000,                !- Vertex 3 X-coordinate {m}
    0,                       !- Vertex 3 Y-coordinate {m}
    2.700000,                !- Vertex 3 Z-coordinate {m}
    8.000000,                !- Vertex 4 X-coordinate {m}
    6.000000,                !- Vertex 4 Y-coordinate {m}
    2.700000;                !- Vertex 4 Z-coordinate {m}


!-   ===========  ALL OBJECTS IN CLASS: FENESTRATIONSURFACE:DETAILED ===========

FenestrationSurface:Detailed,
    ZONE SUBSURFACE 1,       !- Name
    Window,                  !- Surface Type
    GLAZING[],       !- Construction Name
    ZONE SURFACE SOUTH,      !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    0.5000000,               !- View Factor to Ground
    ,                        !- Shading Control Name
    @@frame_name@@,                        !- Frame and Divider Name
    1,                       !- Multiplier
    4,                       !- Number of Vertices
    0.5000000,               !- Vertex 1 X-coordinate {m}{{
    0,                       !- Vertex 1 Y-coordinate {m}
    2.200000,                !- Vertex 1 Z-coordinate {m}
    0.5000000,               !- Vertex 2 X-coordinate {m}
    0,                       !- Vertex 2 Y-coordinate {m}
    0.2000000,               !- Vertex 2 Z-coordinate {m}
    3.500000,                !- Vertex 3 X-coordinate {m}
    0,                       !- Vertex 3 Y-coordinate {m}
    0.2000000,               !- Vertex 3 Z-coordinate {m}
    3.500000,                !- Vertex 4 X-coordinate {m}
    0,                       !- Vertex 4 Y-coordinate {m}
    2.200000;                !- Vertex 4 Z-coordinate {m}

FenestrationSurface:Detailed,
    ZONE SUBSURFACE 2,       !- Name
    Window,                  !- Surface Type
    GLAZING[],       !- Construction Name
    ZONE SURFACE SOUTH,      !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    0.5000000,               !- View Factor to Ground
    ,                        !- Shading Control Name
    @@frame_name@@,                        !- Frame and Divider Name
    1,                       !- Multiplier
    4,                       !- Number of Vertices
    4.500000,                !- Vertex 1 X-coordinate {m}
    0,                       !- Vertex 1 Y-coordinate {m}
    2.200000,                !- Vertex 1 Z-coordinate {m}
    4.500000,                !- Vertex 2 X-coordinate {m}
    0,                       !- Vertex 2 Y-coordinate {m}
    0.2000000,               !- Vertex 2 Z-coordinate {m}
    7.500000,                !- Vertex 3 X-coordinate {m}
    0,                       !- Vertex 3 Y-coordinate {m}
    0.2000000,               !- Vertex 3 Z-coordinate {m}
    7.500000,                !- Vertex 4 X-coordinate {m}
    0,                       !- Vertex 4 Y-coordinate {m}
    2.200000;                !- Vertex 4 Z-coordinate {m}
!-   ===========  ALL OBJECTS IN CLASS: HVAC SYSTEM===========

##include DesignDay.idf
##include HVAC_@@hvactype@@.imf

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: PV System ===========
```

```
!##include PVSystem.imf

!-   ===========  ALL OBJECTS IN CLASS: SHADING DEVICES===========

!##include ShadingDevices.imf

!-   ===========  ALL OBJECTS IN CLASS: OTHEREQUIPMENT ===========

OtherEquipment,
    ZONE ONE OthEq 1,        !- Name
    ZONE ONE,                !- Zone Name
    Sch 1,                   !- Schedule Name
    EquipmentLevel,          !- Design Level Calculation Method
    200,                     !- Design Level {W}
    ,                        !- Watts per Zone Floor Area {W/m2}
    ,                        !- Watts per Person {W/Person}
    0.000,                   !- Fraction Latent
    0.600,                   !- Fraction Radiant
    0.000;                   !- Fraction Lost

!Lights,
        !Lights, !- Name (Assuming recessed fluorescent lighting)
        !ZONE ONE, !- Zone or ZoneList Name
        !Lights !- Schedule Name
        !Watts/Area, !- Design Level Calculation Method
        !,! !- Lighting Level {W}
        !12, !- Watts per Zone Floor Area {W/m2}
        !, !- Watts per Person {W/person}
        !0.0, !- Return Air Fraction
        !0.37, !- Fraction Radiant
        !0.18, !- Fraction Visible
        !0, !- Fraction Replaceable
        !GeneralLights; !- End-Use Subcategory


!-   ===========  ALL OBJECTS IN CLASS: ZONEINFILTRATION:DESIGNFLOWRATE ===========

ZoneInfiltration:DesignFlowRate,
    ZoneInfil,        !- Name
    ZONE ONE,                !- Zone or ZoneList Name
    On,                      !- Schedule Name
    AirChanges/Hour,         !- Design Flow Rate Calculation Method
    ,                        !- Design Flow Rate {m3/s}
    ,                        !- Flow per Zone Floor Area {m3/s-m2}
    ,                        !- Flow per Exterior Surface Area {m3/s-m2}
    1.5,                     !- Air Changes per Hour {1/hr}
    1.0,                     !- Constant Term Coefficient
    0.0,                     !- Temperature Term Coefficient
    0.0,                     !- Velocity Term Coefficient
    0.0;                     !- Velocity Squared Term Coefficient

!-   ===========  ALL OBJECTS IN CLASS: EMS:Control Window Opening Schedule ===========


EnergyManagementSystem:Sensor,
 ZoneTemp , ! Name
 ZONE ONE, ! Output:Variable or Output:Meter Index Key Name
 Zone Mean Air Temperature; ! Output:Variable or Output:Meter Name

EnergyManagementSystem:Actuator,
 InfiltrationRate, ! Name
 ZoneInfil, ! Component Name
 Zone Infiltration, ! Component Type
 Air Exchange Flow Rate; ! Control Type

EnergyManagementSystem:ProgramCallingManager,
 Zone Infiltration Control, ! Name
 BeginTimestepBeforePredictor , ! EnergyPlus Model Calling Point
 Infiltration_Controller ; ! Program Name 1

EnergyManagementSystem:Program,
 Infiltration_Controller , ! Name
```

```
 IF (ZoneTemp <= 23),
 SET InfiltrationRate = 0.054 , ! - Assume 1.5 ACH when windows closed
 ELSEIF (ZoneTemp > 23) && (ZoneTemp < 27),
 SET InfiltrationRate = 0.108 , ! - Assume 3 ACH when windows opened
 ELSEIF (ZoneTemp >= 27),
 SET InfiltrationRate = 0.108 , ! - Assume 3 ACH when windows opened
 ENDIF;

Output:EnergyManagementSystem,
 Verbose,
 Verbose,
 Verbose;



!-   ===========  ALL OBJECTS IN CLASS: PEOPLE ===========

People,
             ComfortMeasure, !- Name
             ZONE ONE, !- Zone or ZoneList Name
             On, !- Number of People Schedule Name
             People, !- Number of People Calculation Method
             1,,, !- Number of People, People per Zone Floor Area, Zone Floor Area per Person
             0.0, !- Fraction Radiant
             0.0, !- Sensible Heat Fraction
             Activity_Sch, !- Activity Level Schedule Name
             0, !- Carbon Dioxide Generation Rate {m3/s-W}
             No, !- Enable ASHRAE 55 Comfort Warnings
             ZoneAveraged, !- Mean Radiant Temperature Calculation Type
             , !- Surface Name/Angle Factor List Name
             WorkEff_Sch, !- Work Efficiency Schedule Name
             Clothing_Sch, !- Clothing Insulation Schedule Name
             AirVelocity_Sch, !- Air Velocity Schedule Name
             Fanger; !- Thermal Comfort Model 1 Type

!-   ===========  ALL OBJECTS IN CLASS: CURRENCYTYPE ===========

CurrencyType,
    CAD;                    !- Monetary Unit

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:VARIABLEDICTIONARY ===========

Output:VariableDictionary,
    IDF;                !- Key Field

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:SURFACES:DRAWING ===========

Output:Surfaces:List, Details;

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:CONSTRUCTIONS ===========

Output:Constructions,
    Constructions,          !- Details Type 1
    Materials;              !- Details Type 2

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:TABLE:SUMMARYREPORTS ===========

Output:Table:SummaryReports,
    AllSummary;             !- Report 1 Name

!-   ===========  ALL OBJECTS IN CLASS: OUTPUTCONTROL:TABLE:STYLE ===========

OutputControl:Table:Style,
    Comma,                  !- Column Separator
    JtoKWH;                 !- Unit Conversion

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:VARIABLE ===========

Output:Variable,
    *,                      !- Key Value
    Time Not Comfortable Summer Or Winter Clothes Any Zone ,  !- Variable Name
    RunPeriod,              !- Reporting Frequency
```

```
    On;                     !- Schedule Name

Output:Variable,
    *,                      !- Key Value
    FangerPPD,  !- Variable Name
    RunPeriod,              !- Reporting Frequency
    On;                     !- Schedule Name

Output:Variable,
    *,                      !- Key Value
    Zone/Sys Sensible Heating Energy ,  !- Variable Name
    Daily,              !- Reporting Frequency
    On;                     !- Schedule Name

Output:Variable,
        *,
        Total Electric Energy Produced,
        Annual,
        On;

Output:Variable,
        *,
        PV Generator DC Energy,
        Annual,
        On;

Output:Variable,
        *,
        Zone Mean Air Temperature,
        Hourly,
        On;


!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:METER ===========

Output:Meter,Electricity:*,RunPeriod;
Output:Meter,Gas:*,RunPeriod;
Output:Meter,Carbon Equivalent:*,RunPeriod;
Output:Meter,ElectricityNet:*,RunPeriod;
Output:Meter,ElectricityPurchased:*,RunPeriod;

!-   ===========  ALL OBJECTS IN CLASS: Utility Cost ===========

UtilityCost:Tariff,
        ElectricityRate, ! Name
        Electricity:Facility, ! Output Meter Name
        kWh, ! Conversion Factor Choice
        , ! Energy Conversion Factor
        , ! Demand Conversion Factor
        , ! Time of Use Period Schedule Name
        , ! Season Schedule Name
        , ! Month Schedule Name
        , ! Demand Window Length
        4.645; ! Monthly Charge or Variable Name

UtilityCost:Charge:Block,
        BlockEnergyCharge, ! Charge Variable Name
        ElectricityRate, ! Tariff Name
        totalEnergy, ! Source Variable
        Annual, ! Season
        EnergyCharges, ! Category Variable Name
        , ! Remaining Into Variable
        , ! Block Size Multiplier Value or Variable Name
        1350, ! Block Size 1 Value or Variable Name
        0.0752, ! Block 1 Cost per Unit Value or Variable Name (BC Hydro 2014 Update)
        Remaining, ! Block Size 2 Value or Variable Name
        0.1127; ! Block 2 Cost per Unit Value or Variable Name (BC Hydro 2014 Update)

UtilityCost:Tariff,
        GasRate, ! Name
        Gas:Facility, ! Output Meter Name
        kWh, ! Conversion Factor Choice
```

```
        , ! Energy Conversion Factor
        , ! Demand Conversion Factor
        , ! Time of Use Period Schedule Name
        , ! Season Schedule Name
        , ! Month Schedule Name
        , ! Demand Window Length
        11.67; ! Monthly Charge or Variable Name

UtilityCost:Charge:Simple,
        FlatEnergyCharge, ! Charge Variable Name
        GasRate, ! Tariff Name
        totalEnergy, ! Source Variable
        Annual, ! Season
        EnergyCharges, ! Category Variable Name
        0.03443; ! Cost Per Unit Value or Variable Name (April 2014 Fortis BC Rates)

UtilityCost:Tariff,
        ElectricitySold, !- Name
        ElectricitySurplusSold:Facility, !- Output Meter Name
        kWh, !- Conversion Factor Choice
        , !- Energy Conversion Factor
        , !- Demand Conversion Factor
        , !- Time of Use Period Schedule Name
        , !- Season Schedule Name
        , !- Month Schedule Name
        , !- Demand Window Length
        , !- Monthly Charge or Variable Name
        , !- Minimum Monthly Charge or Variable Name
        , !- Real Time Pricing Charge Schedule Name
        , !- Customer Baseline Load Schedule Name
        , !- Group Name
        sellToUtility; !- Buy Or Sell

!UtilityCost:Charge:Simple,
!       SummerOnPeak, ! Charge Variable Name
!       ElectricitySold, ! Tariff Name
!       peakEnergy, ! Source Variable
!       Summer, ! Season
!       EnergyCharges, ! Category Variable Name
!       -0.17151; ! Cost per Unit Value or Variable Name

!UtilityCost:Charge:Simple,
!       SummerOffPeak, ! Charge Variable Name
!       ElectricitySold, ! Tariff Name
!       offPeakEnergy, ! Source Variable
!       Summer, ! Season
!       EnergyCharges, ! Category Variable Name
!       -0.05554; ! Cost per Unit Value or Variable Name

!UtilityCost:Charge:Simple,
!       WinterOnPeak, ! Charge Variable Name
!       ElectricitySold, ! Tariff Name
!       peakEnergy, ! Source Variable
!       Winter, ! Season
!       EnergyCharges, ! Category Variable Name
!       -0.17151; ! Cost per Unit Value or Variable Name

!UtilityCost:Charge:Simple,
!       WinterOffPeak, ! Charge Variable Name
!       ElectricitySold, ! Tariff Name
!       offPeakEnergy, ! Source Variable
!       Winter, ! Season
!       EnergyCharges, ! Category Variable Name
!       -0.05554; ! Cost per Unit Value or Variable Name


!-   ===========  ALL OBJECTS IN CLASS: ENVRIONMENTAL IMPACT FACTORS ===========

EnvironmentalImpactFactors, ! 100-Year GWP (IPCC 2000)
0.3, !- Disctrict Heating Efficiency
3.0, !- District Cooling COP
0.25, !- Steam Conversion Efficiency
```

```
298, !- Total CO2 Equivalent Emission Factor From NOx
25, !- Total CO2 Equivalent Emission Factor From CH4
1; !- Total CO2 Equivalent Emission Factor From CO2

!-   ===========  ALL OBJECTS IN CLASS: FUEL FACTORS ===========

FuelFactors, ! BC Ministry of Environment
        Electricity, !- Existing Fuel Resource Name
        kg, !- Units of Measure (kg or m3)
        , !- Energy per Unit Factor
        1, !- Source Energy Factor {J/J}
        , !- Source Energy Schedule Name
        6.9, !- CO2 Emission Factor {g/MJ}
        , !- CO2 Emission Factor Schedule Name
        0, !- CO Emission Factor {g/MJ}
        , !- CO Emission Factor Schedule Name
        0, !- CH4 Emission Factor {g/MJ}
        , !- CH4 Emission Factor Schedule Name
        0, !- NOx Emission Factor {g/MJ}
        , !- NOx Emission Factor Schedule Name
        0, !- N2O Emission Factor {g/MJ}
        , !- N2O Emission Factor Schedule Name
        0, !- SO2 Emission Factor {g/MJ}
        , !- SO2 Emission Factor Schedule Name
        0, !- PM Emission Factor {g/MJ}
        , !- PM Emission Factor Schedule Name
        0, !- PM10 Emission Factor {g/MJ}
        , !- PM10 Emission Factor Schedule Name
        0, !- PM2.5 Emission Factor {g/MJ}
        , !- PM2.5 Emission Factor Schedule Name
        0, !- NH3 Emission Factor {g/MJ}
        , !- NH3 Emission Factor Schedule Name
        0, !- NMVOC Emission Factor {g/MJ}
        , !- NMVOC Emission Factor Schedule Name
        0, !- Hg Emission Factor {g/MJ}
        , !- Hg Emission Factor Schedule Name
        0, !- Pb Emission Factor {g/MJ}
        , !- Pb Emission Factor Schedule Name
        0, !- Water Emission Factor {L/MJ}
        , !- Water Emission Factor Schedule Name
        0, !- Nuclear High Level Emission Factor {g/MJ}
        , !- Nuclear High Level Emission Factor Schedule Name
        0; !- Nuclear Low Level Emission Factor {m3/MJ}

FuelFactors, ! BC Ministry of Environment
        Natural Gas, !- Existing Fuel Resource Name
        m3, !- Units of Measure (kg or m3)
        , !- Energy per Unit Factor
        1, !- Source Energy Factor {J/J}
        , !- Source Energy Schedule Name
        49.86, !- CO2 Emission Factor {g/MJ}
        , !- CO2 Emission Factor Schedule Name
        0, !- CO Emission Factor {g/MJ}
        , !- CO Emission Factor Schedule Name
        0.0010, !- CH4 Emission Factor {g/MJ}
        , !- CH4 Emission Factor Schedule Name
        0.0009, !- NOx Emission Factor {g/MJ}
        , !- NOx Emission Factor Schedule Name
        0.0009, !- N2O Emission Factor {g/MJ}
        , !- N2O Emission Factor Schedule Name
        0, !- SO2 Emission Factor {g/MJ}
        , !- SO2 Emission Factor Schedule Name
        0, !- PM Emission Factor {g/MJ}
        , !- PM Emission Factor Schedule Name
        0, !- PM10 Emission Factor {g/MJ}
        , !- PM10 Emission Factor Schedule Name
        0, !- PM2.5 Emission Factor {g/MJ}
        , !- PM2.5 Emission Factor Schedule Name
        0, !- NH3 Emission Factor {g/MJ}
        , !- NH3 Emission Factor Schedule Name
        0, !- NMVOC Emission Factor {g/MJ}
        , !- NMVOC Emission Factor Schedule Name
```

0, !- Hg Emission Factor {g/MJ}
, !- Hg Emission Factor Schedule Name
0, !- Pb Emission Factor {g/MJ}
, !- Pb Emission Factor Schedule Name
0, !- Water Emission Factor {L/MJ}
, !- Water Emission Factor Schedule Name
0, !- Nuclear High Level Emission Factor {g/MJ}
, !- Nuclear High Level Emission Factor Schedule Name
0; !- Nuclear Low Level Emission Factor {m3/MJ}

!- =========== ALL OBJECTS IN CLASS: OUTPUT:ENVIRONMENTAL IMPACT FACTORS ===========

Output:EnvironmentalImpactFactors,
RunPeriod; !- Reporting_Frequency

!- =========== ALL OBJECTS IN CLASS: OUTPUT:SQLITE ===========

Output:SQLite,
SimpleAndTabular; !- Option Type

# Appendix M BESTEST Case 600 Optimization Results

**Table M1 Optimization results for standard wall with high-performance roof Pareto solutions.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Exterior Insulation | Roof Stud Insulation | Ceiling Drywall | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **24** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33426 | 62547 | 17 | 18584 | 9809 | 14842 | 52738 |
| **25** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35705 | 59423 | 17 | 21442 | 10452 | 14263 | 48972 |
| **26** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 43435 | 56183 | 15 | 30321 | 11859 | 13114 | 44323 |
| **27** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36013 | 59214 | 17 | 21859 | 10735 | 14154 | 48479 |
| **28** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 36533 | 58867 | 16 | 22611 | 11219 | 13922 | 47648 |
| **29** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34241 | 60633 | 17 | 19935 | 11346 | 14307 | 49287 |
| **30** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35810 | 59365 | 16 | 21988 | 11805 | 13822 | 47560 |
| **31** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33638 | 61723 | 16 | 19003 | 10093 | 14635 | 51630 |
| **32** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37543 | 57709 | 15 | 23914 | 11194 | 13628 | 46515 |
| **33** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 42295 | 56394 | 15 | 28947 | 11490 | 13348 | 44904 |
| **34** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36047 | 59030 | 17 | 22002 | 11057 | 14045 | 47973 |
| **35** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 35008 | 60127 | 16 | 21022 | 12084 | 13986 | 48043 |
| **36** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34487 | 60470 | 17 | 20269 | 11600 | 14218 | 48870 |
| **37** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 34345 | 60625 | 16 | 20101 | 10830 | 14244 | 49795 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **38** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 42796 | 56274 | 15 | 29557 | 11652 | 13238 | 44621 |
| **39** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36001 | 59358 | 16 | 21843 | 10010 | 14158 | 49348 |
| **40** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 41311 | 56519 | 15 | 28247 | 12504 | 13065 | 44015 |
| **41** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39893 | 57078 | 16 | 26395 | 11559 | 13498 | 45519 |
| **42** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40670 | 56605 | 15 | 27483 | 12296 | 13187 | 44309 |
| **43** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 35871 | 59358 | 16 | 21690 | 9965 | 14181 | 49393 |
| **44** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40171 | 56728 | 15 | 26873 | 12134 | 13298 | 44594 |
| **45** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33582 | 61827 | 16 | 18920 | 10063 | 14662 | 51764 |
| **46** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37236 | 57923 | 16 | 23496 | 10910 | 13740 | 47013 |
| **47** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38081 | 57423 | 15 | 24668 | 11678 | 13414 | 45746 |
| **48** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37297 | 57870 | 16 | 23578 | 10940 | 13719 | 46929 |
| **49** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34520 | 60285 | 17 | 20413 | 11922 | 14108 | 48363 |
| **50** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38729 | 57372 | 15 | 25432 | 11885 | 13297 | 45487 |
| **51** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37577 | 57535 | 15 | 24057 | 11516 | 13520 | 46019 |
| **52** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33861 | 60782 | 16 | 19492 | 10668 | 14369 | 50114 |
| **53** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34476 | 60623 | 16 | 20254 | 10875 | 14223 | 49748 |
| **54** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35685 | 59476 | 16 | 21425 | 10057 | 14260 | 49420 |
| **55** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39701 | 57195 | 15 | 26132 | 10871 | 13569 | 46323 |
| **56** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35385 | 59514 | 16 | 21082 | 9803 | 14303 | 49711 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **57** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36921 | 58100 | 15 | 23136 | 10262 | 13785 | 47838 |
| **58** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39834 | 57129 | 16 | 26313 | 11529 | 13521 | 45600 |
| **59** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35766 | 59376 | 17 | 21524 | 10481 | 14242 | 48895 |
| **60** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34162 | 60741 | 16 | 19835 | 10922 | 14326 | 49820 |
| **61** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37221 | 58056 | 15 | 23479 | 10515 | 13741 | 47540 |
| **62** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34178 | 60681 | 17 | 19852 | 11317 | 14326 | 49365 |
| **63** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39517 | 57298 | 15 | 25952 | 10880 | 13565 | 46418 |
| **64** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Foam 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40139 | 56922 | 16 | 26729 | 11812 | 13410 | 45109 |

**Table M2 Optimization results for double-stud wall with standard roof Pareto solutions.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Stud Insulation | Ceiling Drywall | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35889 | 56692 | 17 | 22360 | 11624 | 13529 | 45068 |
| **2** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33279 | 60006 | 16 | 19044 | 10615 | 14235 | 49391 |
| **3** | Wood Siding (Cedar), 0.5 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 46076 | 54560 | 14 | 33223 | 11573 | 12852 | 42987 |
| **4** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35207 | 57229 | 16 | 21433 | 10370 | 13774 | 46860 |
| **5** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 36378 | 56535 | 16 | 22969 | 11786 | 13409 | 44750 |
| **6** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 37916 | 55046 | 15 | 25025 | 12245 | 12891 | 42801 |
| **7** | Fiber Cement Siding, 0.3125 | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 | Blown Cell 2x6 24 in. o.c. | Solid Wood | Double Glazed No Coating (Air | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. | Gypsum-Fiber Board (Ceiling), 0.5 | 35691 | 57076 | 16 | 22041 | 10532 | 13650 | 46544 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | in. | | in. | Framing | | Filled) | | Framing | in. | | | | | | | |
| **8** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39537 | 54823 | 15 | 26488 | 11438 | 13049 | 43384 |
| **9** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37413 | 55159 | 15 | 24413 | 12082 | 13000 | 43077 |
| **10** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40174 | 54698 | 15 | 27252 | 11645 | 12922 | 43053 |
| **11** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 34167 | 58342 | 16 | 20452 | 11397 | 13715 | 46945 |
| **12** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 37237 | 55683 | 14 | 24096 | 10991 | 13141 | 44692 |
| **13** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33682 | 58498 | 16 | 19843 | 11235 | 13839 | 47263 |
| **14** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35820 | 57042 | 16 | 22194 | 10577 | 13626 | 46465 |
| **15** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36735 | 55791 | 14 | 23485 | 10829 | 13251 | 44963 |
| **16** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35927 | 56663 | 15 | 22823 | 12948 | 13103 | 43716 |
| **17** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34363 | 57956 | 17 | 20770 | 12489 | 13593 | 45467 |
| **18** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40039 | 54700 | 15 | 27100 | 11600 | 12940 | 43100 |
| **19** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34293 | 58309 | 16 | 20605 | 11442 | 13689 | 46867 |
| **20** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38560 | 54953 | 14 | 25789 | 12452 | 12771 | 42502 |
| **21** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34983 | 57768 | 16 | 21533 | 12696 | 13450 | 45073 |
| **22** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40684 | 54620 | 14 | 27864 | 11808 | 12820 | 42812 |
| **23** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38049 | 55030 | 15 | 25178 | 12290 | 12871 | 42741 |
| **24** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 34853 | 57793 | 16 | 21380 | 12651 | 13473 | 45142 |
| **25** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37365 | 55663 | 14 | 24248 | 11036 | 13116 | 44628 |
| **26** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36509 | 56508 | 16 | 23123 | 11831 | 13386 | 44677 |

**Table M3 Optimization results for double stud wall with high performance roof.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Continuous Insulation | Roof Stud Insulation | Ceiling Drywall | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **27** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34125 | 59979 | 16 | 19941 | 10776 | 14184 | 49203 |
| **28** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 42259 | 54323 | 14 | 29558 | 12067 | 12701 | 42256 |
| **29** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36414 | 56892 | 17 | 22800 | 11418 | 13614 | 45474 |
| **30** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36713 | 56625 | 17 | 23216 | 11701 | 13497 | 44924 |
| **31** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34949 | 58092 | 17 | 21293 | 12313 | 13656 | 45780 |
| **32** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36755 | 56484 | 16 | 23360 | 12023 | 13395 | 44461 |
| **33** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38273 | 54915 | 15 | 25415 | 12482 | 12858 | 42433 |
| **34** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35184 | 57873 | 17 | 21627 | 12566 | 13558 | 45307 |
| **35** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38247 | 55145 | 15 | 25272 | 12160 | 12975 | 42985 |
| **36** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37941 | 55353 | 15 | 24855 | 11877 | 13085 | 43477 |
| **37** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 37257 | 56370 | 16 | 23972 | 12185 | 13284 | 44185 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **38** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 2 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38265 | 55134 | 15 | 25332 | 12385 | 12933 | 42748 |
| **39** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40136 | 54673 | 14 | 27483 | 12711 | 12654 | 41962 |
| **40** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36384 | 56904 | 16 | 22782 | 11023 | 13602 | 45881 |
| **41** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36511 | 56791 | 15 | 23346 | 12771 | 13165 | 44019 |
| **42** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 41565 | 54440 | 14 | 28866 | 12207 | 12699 | 42233 |
| **43** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36083 | 56942 | 16 | 22439 | 10769 | 13644 | 46173 |
| **44** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37997 | 55292 | 15 | 24935 | 11906 | 13062 | 43385 |
| **45** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35227 | 57739 | 16 | 21771 | 12888 | 13457 | 44851 |
| **46** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34558 | 58210 | 16 | 20849 | 11634 | 13708 | 46576 |
| **47** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 41601 | 54383 | 15 | 28791 | 11860 | 12809 | 42523 |
| **48** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40911 | 54506 | 14 | 28100 | 12000 | 12811 | 42506 |
| **49** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 39479 | 54729 | 15 | 26717 | 12504 | 12762 | 42225 |
| **50** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 39443 | 54781 | 14 | 26792 | 12851 | 12651 | 41930 |
| **51** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 35728 | 57620 | 16 | 22383 | 13050 | 13346 | 44570 |
| **52** | Fiber Cement Siding, | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35175 | 58026 | 15 | 21611 | 11841 | 13563 | 46184 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.3125 in. | | | | | Filled) | | | | | | | | | | | |
| **53** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39614 | 54725 | 14 | 26870 | 12549 | 12744 | 42176 |
| **54** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37614 | 55494 | 14 | 24493 | 11228 | 13121 | 44266 |
| **55** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36785 | 56407 | 15 | 23825 | 13347 | 12960 | 43060 |
| **56** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40396 | 54575 | 15 | 27489 | 11838 | 12907 | 42737 |
| **57** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41738 | 54382 | 14 | 28945 | 11905 | 12793 | 42478 |
| **58** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36474 | 56835 | 17 | 22882 | 11447 | 13592 | 45387 |
| **59** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41043 | 54501 | 14 | 28253 | 12045 | 12790 | 42456 |
| **60** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34889 | 58151 | 17 | 21211 | 12283 | 13678 | 45868 |
| **61** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36700 | 56760 | 15 | 23201 | 10976 | 13499 | 45783 |
| **62** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37914 | 55452 | 14 | 24836 | 11482 | 13078 | 43971 |
| **63** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34335 | 59149 | 16 | 20360 | 11059 | 13975 | 48090 |
| **64** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34281 | 59265 | 16 | 20277 | 11029 | 14004 | 48236 |
| **65** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36455 | 56855 | 15 | 23266 | 12742 | 13189 | 44113 |
| **66** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 35049 | 58067 | 16 | 21458 | 11797 | 13591 | 46270 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **67** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38787 | 54843 | 15 | 26026 | 12644 | 12762 | 42199 |
| **68** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34859 | 58173 | 16 | 21192 | 11888 | 13667 | 46285 |
| **69** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 37299 | 56336 | 14 | 24436 | 13509 | 12863 | 42827 |
| **70** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35859 | 57618 | 16 | 22533 | 13095 | 13326 | 44522 |

**Table M4 Optimization results for EIFS wall with standard roof Pareto solutions.**

| **ID** | **Exterior Cladding** | **Sheathing** | **Wall Drywall** | **Wall Continuous Insulation** | **Wall Stud Insulation** | **Window Frame** | **Glazing Type** | **Roofing Type** | **Roof Stud Insulation** | **Ceiling Drywall** | **LCC** | **LCGWP** | **PPD** | **Initial Cost** | **Initial GWP** | **Operational Cost** | **Operational GWP** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Wood Siding (Cedar), 0.5 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 45293 | 54735 | 14 | 32452 | 11878 | 12840 | 42857 |
| **2** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35033 | 57225 | 17 | 21374 | 11462 | 13659 | 45764 |
| **3** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34354 | 57763 | 16 | 20447 | 10208 | 13907 | 47555 |
| **4** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 35583 | 56645 | 16 | 22198 | 12091 | 13385 | 44554 |
| **5** | Wood Siding (Cedar), 0.5 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 44783 | 54809 | 15 | 31842 | 11716 | 12942 | 43093 |
| **6** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 32828 | 59030 | 16 | 18858 | 11073 | 13970 | 47957 |
| **7** | Wood Siding (Cedar), 0.5 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 44647 | 54812 | 15 | 31688 | 11671 | 12959 | 43142 |
| **8** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 37784 | 55164 | 14 | 25019 | 12757 | 12765 | 42407 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **9** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 32599 | 59031 | 16 | 18666 | 11229 | 13933 | 47802 |
| **10** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 32903 | 58683 | 16 | 19073 | 11540 | 13831 | 47143 |
| **11** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35960 | 55986 | 14 | 22716 | 11133 | 13244 | 44853 |
| **12** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35109 | 56879 | 17 | 21589 | 11928 | 13520 | 44950 |
| **13** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 37139 | 55243 | 15 | 24254 | 12549 | 12884 | 42694 |
| **14** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33508 | 58487 | 17 | 19784 | 12327 | 13724 | 46160 |
| **15** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 34057 | 57898 | 16 | 20608 | 12956 | 13449 | 44943 |
| **16** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36560 | 55703 | 15 | 23429 | 11921 | 13131 | 43783 |
| **17** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34427 | 57414 | 16 | 20662 | 10675 | 13765 | 46740 |
| **18** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39399 | 54905 | 15 | 26482 | 11950 | 12916 | 42955 |
| **19** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35075 | 57212 | 15 | 21839 | 12786 | 13235 | 44426 |
| **20** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36634 | 55356 | 15 | 23644 | 12387 | 12991 | 42969 |
| **21** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 39263 | 54910 | 15 | 26329 | 11905 | 12934 | 43005 |
| **22** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35886 | 56347 | 14 | 22501 | 10667 | 13385 | 45680 |
| **23** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 39909 | 54832 | 14 | 27093 | 12112 | 12816 | 42719 |
| **24** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33281 | 58487 | 17 | 19593 | 12483 | 13688 | 46004 |
| **25** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38760 | 55013 | 15 | 25719 | 11743 | 13041 | 43270 |
| **26** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36339 | 55725 | 15 | 23238 | 12077 | 13101 | 43648 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **27** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35149 | 56856 | 15 | 22055 | 13252 | 13095 | 43604 |
| **28** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33582 | 58138 | 17 | 19999 | 12793 | 13583 | 45345 |
| **29** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35665 | 56371 | 14 | 22310 | 10823 | 13355 | 45547 |
| **30** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37274 | 55239 | 15 | 24408 | 12594 | 12866 | 42645 |
| **31** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34124 | 57764 | 16 | 20256 | 10364 | 13869 | 47400 |
| **32** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34807 | 57229 | 17 | 21183 | 11618 | 13624 | 45611 |

**Table M5 Optimization results for EIFS wall and high performance roof.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Continuous Insulation | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Continuous Insulation | Roof Stud Insulation | Ceiling Drywall | LCC | LCGWP | PPD | Initial Cost | Initial GWP | Operational Cost | Operational GWP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **33** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33079 | 60823 | 16 | 18669 | 10367 | 14410 | 50455 |
| **34** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35750 | 56658 | 17 | 22242 | 11832 | 13508 | 44826 |
| **35** | Wood Siding (Cedar), 0.5 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 47065 | 54146 | 14 | 34409 | 12216 | 12656 | 41930 |
| **36** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34469 | 57736 | 17 | 20987 | 12951 | 13482 | 44785 |
| **37** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36051 | 56437 | 16 | 22720 | 12408 | 13331 | 44030 |
| **38** | Fiber Cement | OSB, 0.5 in. | Regular Gypsum | Mineral Wool, 5.5 | Blown Cell 2x4 24 in. | Vinyl | Double Glazed No | Asphalt Roof Shingles, 0.125 | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. | Regular Gypsum | 33080 | 60083 | 16 | 18887 | 10844 | 14194 | 49239 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Siding, 0.3125 in. | | Board (Wall), 0.5 in. | in. | o.c. Framing | | Coating (Air Filled) | in. | | o.c. Framing | Board (Ceiling), 0.5 in. | | | | | | | |
| **39** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36033 | 56446 | 15 | 23042 | 13409 | 12992 | 43036 |
| **40** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 36591 | 56257 | 14 | 23796 | 13894 | 12795 | 42363 |
| **41** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33295 | 59271 | 16 | 19306 | 11127 | 13989 | 48144 |
| **42** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35793 | 56639 | 15 | 22707 | 13156 | 13085 | 43484 |
| **43** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37534 | 55035 | 15 | 24631 | 12544 | 12903 | 42491 |
| **44** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34511 | 57610 | 16 | 21131 | 13273 | 13380 | 44338 |
| **45** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 35015 | 57493 | 16 | 21743 | 13435 | 13272 | 44058 |
| **46** | Wood Siding (Cedar), 0.5 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 46393 | 54206 | 15 | 33626 | 12004 | 12767 | 42202 |
| **47** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37218 | 55194 | 15 | 24215 | 12261 | 13003 | 42933 |
| **48** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 34311 | 57780 | 16 | 20820 | 12181 | 13491 | 45599 |
| **49** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 36554 | 56317 | 16 | 23333 | 12570 | 13221 | 43747 |
| **50** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33519 | 58351 | 16 | 19794 | 11702 | 13725 | 46648 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **51** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40385 | 54373 | 15 | 27546 | 12081 | 12839 | 42292 |
| **52** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 41571 | 54250 | 14 | 28939 | 12455 | 12631 | 41795 |
| **53** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35288 | 57155 | 16 | 21579 | 10678 | 13708 | 46478 |
| **54** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36906 | 55413 | 14 | 23853 | 11613 | 13053 | 43801 |
| **55** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35342 | 57038 | 16 | 21726 | 11091 | 13616 | 45948 |
| **56** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40899 | 54313 | 15 | 28157 | 12243 | 12742 | 42070 |
| **57** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36604 | 55799 | 14 | 23439 | 11296 | 13165 | 44503 |
| **58** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37208 | 55379 | 14 | 24196 | 11866 | 13012 | 43513 |
| **59** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38271 | 54778 | 15 | 25472 | 12725 | 12799 | 42053 |
| **60** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33240 | 59384 | 16 | 19222 | 11097 | 14017 | 48287 |
| **61** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33752 | 58343 | 16 | 19990 | 11543 | 13762 | 46800 |
| **62** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33830 | 57997 | 16 | 20210 | 12019 | 13620 | 45978 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **63** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36075 | 56321 | 15 | 23185 | 13731 | 12890 | 42589 |
| **64** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 39458 | 54657 | 14 | 26865 | 13099 | 12593 | 41558 |
| **65** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39646 | 54624 | 15 | 26706 | 11900 | 12940 | 42724 |
| **66** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38935 | 54711 | 14 | 26252 | 12937 | 12683 | 41774 |
| **67** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35368 | 56814 | 16 | 21799 | 11154 | 13569 | 45661 |
| **68** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35734 | 56703 | 15 | 22625 | 13126 | 13108 | 43577 |
| **69** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34118 | 57895 | 16 | 20552 | 12272 | 13566 | 45622 |
| **70** | Wood Siding (Cedar), 0.5 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 46543 | 54204 | 14 | 33796 | 12053 | 12748 | 42151 |
| **71** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33519 | 59087 | 16 | 19578 | 11226 | 13941 | 47861 |
| **72** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 35849 | 56603 | 16 | 22410 | 11316 | 13440 | 45287 |
| **73** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36829 | 55762 | 14 | 23634 | 11137 | 13196 | 44626 |
| **74** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38786 | 54722 | 15 | 26082 | 12888 | 12704 | 41834 |
| **75** | Fiber Cement | OSB, 0.5 in. | Regular Gypsum | Mineral Wool, 5.5 | Blown Cell 2x6 24 in. | Vinyl Clad | Triple Glazed No | Residential 30 ga. Steel Roof | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. | Regular Gypsum | 39688 | 54495 | 15 | 26849 | 12222 | 12838 | 42273 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Siding, 0.3125 in. | | Board (Wall), 0.5 in. | in. | o.c. Framing | Wood Core | Coating (Air Filled) | Panel, 0.016 in. | | o.c. Framing | Board (Ceiling), 0.5 in. | | | | | | | |
| **76** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35657 | 56717 | 16 | 22141 | 11407 | 13516 | 45309 |
| **77** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37574 | 54900 | 15 | 24775 | 12866 | 12799 | 42033 |
| **78** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 34451 | 57759 | 15 | 20987 | 12230 | 13464 | 45529 |
| **79** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41048 | 54308 | 14 | 28326 | 12292 | 12722 | 42016 |
| **80** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 33805 | 58220 | 16 | 20137 | 11956 | 13669 | 46264 |
| **81** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 36905 | 55756 | 14 | 23782 | 11549 | 13123 | 44207 |
| **82** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35990 | 56582 | 16 | 22576 | 11365 | 13414 | 45217 |
| **83** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38090 | 54835 | 15 | 25386 | 13029 | 12704 | 41806 |
| **84** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40204 | 54431 | 14 | 27460 | 12384 | 12744 | 42047 |
| **85** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 5.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 35057 | 57165 | 16 | 21384 | 10837 | 13673 | 46328 |

**Table M6 Optimization results for ICF wall with standard roof Pareto solutions.**

| ID | Exterior Cladding | Wall Drywall | ICF Type | Window Frame | Glazing Type | Roofing Type | Roof Stud Insulation | Ceiling Drywall | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 45231 | 57889 | 15 | 31902 | 12548 | 13329 | 45341 |
| **2** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37637 | 64306 | 17 | 22715 | 11422 | 14922 | 52884 |
| **3** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40567 | 59749 | 15 | 27190 | 14156 | 13378 | 45594 |
| **4** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38960 | 60939 | 17 | 25131 | 13697 | 13829 | 47242 |
| **5** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37703 | 62956 | 17 | 23122 | 11705 | 14581 | 51251 |
| **6** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38437 | 61001 | 17 | 24517 | 13535 | 13920 | 47467 |
| **7** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41541 | 58397 | 16 | 28165 | 13128 | 13376 | 45269 |
| **8** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38265 | 61322 | 16 | 24150 | 12281 | 14115 | 49041 |
| **9** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40458 | 59801 | 16 | 26416 | 10885 | 14042 | 48916 |
| **10** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39776 | 60204 | 16 | 25668 | 11317 | 14108 | 48887 |
| **11** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37735 | 61424 | 16 | 23591 | 12281 | 14144 | 49143 |
| **12** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 42574 | 58311 | 15 | 29267 | 13192 | 13307 | 45119 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **13** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40481 | 59788 | 17 | 26594 | 12571 | 13887 | 47217 |
| **14** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39808 | 60158 | 16 | 25740 | 11416 | 14068 | 48743 |
| **15** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40843 | 59201 | 14 | 26934 | 9928 | 13908 | 49272 |
| **16** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40849 | 58929 | 15 | 27238 | 11875 | 13611 | 47054 |
| **17** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39267 | 60429 | 16 | 24878 | 9469 | 14390 | 50959 |
| **18** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39981 | 59844 | 17 | 26106 | 12669 | 13875 | 47174 |
| **19** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 43635 | 58183 | 15 | 29936 | 10538 | 13699 | 47646 |
| **20** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 43121 | 58306 | 15 | 29828 | 13192 | 13293 | 45114 |
| **21** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41380 | 58828 | 15 | 27798 | 11875 | 13582 | 46953 |
| **22** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 42074 | 58368 | 15 | 28779 | 13291 | 13294 | 45077 |
| **23** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39274 | 60252 | 16 | 25180 | 11416 | 14094 | 48836 |
| **24** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40482 | 59766 | 16 | 26365 | 10723 | 14117 | 49043 |
| **25** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39949 | 59898 | 16 | 25804 | 10723 | 14146 | 49175 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **26** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 44729 | 57932 | 15 | 31414 | 12646 | 13315 | 45286 |
| **27** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 43653 | 57982 | 16 | 30239 | 12484 | 13413 | 45498 |
| **28** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38253 | 61347 | 16 | 24204 | 12443 | 14049 | 48904 |
| **29** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41350 | 58876 | 15 | 27726 | 11776 | 13624 | 47100 |
| **30** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41522 | 58592 | 15 | 27861 | 11182 | 13661 | 47410 |
| **31** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 38919 | 60976 | 16 | 24827 | 11750 | 14092 | 49225 |
| **32** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38409 | 61071 | 16 | 24214 | 11588 | 14195 | 49483 |
| **33** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 44184 | 57946 | 15 | 30854 | 12646 | 13330 | 45300 |
| **34** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38939 | 60948 | 17 | 25005 | 13436 | 13934 | 47512 |
| **35** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38943 | 60940 | 16 | 24775 | 11588 | 14168 | 49352 |
| **36** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 39792 | 60178 | 16 | 25794 | 11578 | 13999 | 48600 |
| **37** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 37729 | 61606 | 16 | 23288 | 10334 | 14440 | 51272 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **38** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38236 | 61374 | 16 | 24078 | 12182 | 14157 | 49192 |
| **39** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 44706 | 57938 | 15 | 31289 | 12386 | 13418 | 45552 |

### Table M7 Optimization results for ICF wall with high performance roof.

| **ID** | **Exterior Cladding** | **Sheathing** | **Wall Drywall** | **ICF Type** | **Window Frame** | **Glazing Type** | **Roofing Type** | **Roof Continuous Insulation** | **Roof Stud Insulation** | **Roof Drywall** | **LCC ($)** | **LCGWP (kgCO2eq)** | **PPD (%)** | **Initial Cost ($)** | **Initial GWP (kqCO2eq)** | **Operational Cost ($)** | **Operational GWP (kqCO2eq)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **40** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 38922 | 62862 | 16 | 24392 | 11668 | 14530 | 51195 |
| **41** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 46306 | 57651 | 15 | 33111 | 12892 | 13194 | 44759 |
| **42** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39123 | 62040 | 16 | 24809 | 11951 | 14314 | 50090 |
| **43** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 41385 | 59813 | 16 | 27498 | 11823 | 13887 | 47990 |
| **44** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39067 | 62371 | 16 | 24423 | 9975 | 14643 | 52396 |
| **45** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39619 | 61029 | 16 | 25636 | 12780 | 13983 | 48249 |
| **46** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40860 | 59874 | 16 | 26883 | 11661 | 13977 | 48213 |
| **47** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 42034 | 59378 | 16 | 28061 | 10969 | 13974 | 48409 |
| **48** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 40858 | 60103 | 15 | 26581 | 9715 | 14277 | 50388 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **49** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39069 | 62174 | 16 | 24725 | 11921 | 14344 | 50253 |
| **50** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 43093 | 58315 | 14 | 29558 | 11428 | 13536 | 46887 |
| **51** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 42026 | 59475 | 16 | 28113 | 11131 | 13913 | 48344 |
| **52** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41508 | 59554 | 16 | 27499 | 10969 | 14009 | 48586 |
| **53** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 42435 | 58873 | 14 | 28638 | 10174 | 13798 | 48699 |
| **54** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 39844 | 60978 | 16 | 25908 | 12689 | 13936 | 48290 |
| **55** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39967 | 60721 | 16 | 25910 | 11834 | 14057 | 48888 |
| **56** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 45771 | 57678 | 15 | 32496 | 12730 | 13275 | 44948 |
| **57** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 43598 | 58158 | 14 | 30170 | 11590 | 13428 | 46568 |
| **58** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 43659 | 58095 | 15 | 30422 | 13374 | 13238 | 44721 |
| **59** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 45741 | 57775 | 14 | 32194 | 10783 | 13547 | 46992 |
| **60** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 41162 | 59870 | 16 | 27225 | 11915 | 13937 | 47956 |
| **61** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 40486 | 60644 | 16 | 26524 | 11996 | 13962 | 48648 |
| **62** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 8 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 44197 | 58056 | 15 | 31038 | 13536 | 13159 | 44520 |
| **63** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. | Vinyl Clad Wood | Triple Glazed No Coating (Air | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 | 45250 | 57837 | 15 | 31937 | 12730 | 13313 | 45107 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.5 in. | Concrete Core | Core | Filled) | | | | in. | | | | | | | |
| **64** | Fiber Cement Siding, 0.3125 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 45207 | 57908 | 14 | 31633 | 10783 | 13574 | 47125 |
| **65** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 42728 | 58488 | 15 | 29283 | 12374 | 13445 | 46114 |
| **66** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 42449 | 58631 | 15 | 28942 | 12120 | 13507 | 46511 |
| **67** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 43140 | 58252 | 15 | 29863 | 13374 | 13277 | 44878 |
| **68** | Residential 30 ga. Steel Siding, 0.016 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 39318 | 61030 | 16 | 25294 | 12526 | 14024 | 48504 |

## Table M8 Optimization results for SIP wall with SIP roof Pareto Solutions

| ID | Exterior Cladding | Wall Drywall | Wall SIP Type | Window Frame | Glazing Type | Roofing Type | Ceiling Drywall | Roof SIP Type | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kqCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 36153 | 56172 | 16 | 22511 | 9624 | 13642 | 46548 |
| **2** | Wood Siding (Cedar), 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 9.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 48865 | 51532 | 14 | 36417 | 9930 | 12448 | 41602 |
| **3** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 3.5 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 35379 | 60200 | 15 | 21103 | 9390 | 14276 | 50810 |
| **4** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 35488 | 58434 | 15 | 21570 | 9624 | 13918 | 48809 |
| **5** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 38906 | 53457 | 16 | 25753 | 9195 | 13153 | 44262 |
| **6** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 35659 | 57530 | 15 | 21937 | 9782 | 13722 | 47748 |
| **7** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 39309 | 53332 | 15 | 26302 | 9487 | 13007 | 43844 |
| **8** | Fiber Cement Siding, 0.3125 | Gypsum-Fiber Board (Wall), 0.5 | SIP (7/16 in. OSB), 9.25 in. EPS Foam | Vinyl Clad Wood Core | Triple Glazed No Coating (Air | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam | 43711 | 51624 | 14 | 31270 | 10079 | 12441 | 41545 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | in. | in. | Core | | Filled) | | | Core | | | | | | | |
| **9** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 39446 | 53032 | 14 | 26514 | 9376 | 12932 | 43656 |
| **10** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 36436 | 55315 | 16 | 22982 | 9826 | 13453 | 45490 |
| **11** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 9.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 43486 | 51661 | 14 | 31058 | 10165 | 12428 | 41496 |
| **12** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 37781 | 54589 | 15 | 24712 | 10352 | 13069 | 44237 |
| **13** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 36637 | 54817 | 16 | 23339 | 9983 | 13298 | 44834 |
| **14** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 37962 | 54048 | 16 | 24572 | 8960 | 13389 | 45088 |
| **15** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 35886 | 57503 | 15 | 22149 | 9696 | 13737 | 47806 |
| **16** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 39956 | 52137 | 14 | 27199 | 9491 | 12757 | 42645 |
| **17** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 36356 | 55682 | 16 | 22868 | 9782 | 13488 | 45900 |
| **18** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 43251 | 51691 | 14 | 30648 | 9217 | 12603 | 42474 |
| **19** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 35938 | 56661 | 15 | 22408 | 9983 | 13530 | 46678 |
| **20** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 38164 | 53556 | 16 | 24929 | 9118 | 13235 | 44438 |
| **21** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 37882 | 54421 | 16 | 24457 | 8917 | 13425 | 45504 |
| **22** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 38395 | 53538 | 16 | 25142 | 9032 | 13252 | 44506 |
| **23** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 39030 | 53441 | 16 | 25904 | 9240 | 13127 | 44201 |
| **24** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 37273 | 54720 | 16 | 24101 | 10190 | 13172 | 44530 |
| **25** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 39725 | 52155 | 14 | 26986 | 9577 | 12739 | 42578 |
| **26** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 5.5 in. EPS Foam Core | 39526 | 52642 | 15 | 26629 | 9419 | 12897 | 43223 |
| **27** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 43020 | 51702 | 14 | 30435 | 9302 | 12585 | 42400 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **28** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 9.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 37741 | 54691 | 15 | 24724 | 11053 | 13018 | 43638 |
| **29** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 40898 | 52043 | 14 | 28361 | 9946 | 12537 | 42096 |
| **30** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 42081 | 51807 | 14 | 29273 | 8847 | 12808 | 42960 |
| **31** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 9.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 41590 | 51962 | 14 | 29196 | 10723 | 12393 | 41239 |
| **32** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 41127 | 52025 | 14 | 28574 | 9861 | 12553 | 42165 |
| **33** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 42726 | 51735 | 14 | 30036 | 9054 | 12690 | 42681 |
| **34** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 9.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 37614 | 54695 | 16 | 24572 | 11008 | 13042 | 43687 |
| **35** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 38799 | 53457 | 16 | 25691 | 9325 | 13108 | 44132 |
| **36** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 41849 | 51821 | 14 | 29060 | 8933 | 12789 | 42888 |
| **37** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 42600 | 51750 | 14 | 29885 | 9009 | 12715 | 42741 |
| **38** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 40476 | 52084 | 14 | 27810 | 9654 | 12665 | 42431 |
| **39** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 37149 | 54734 | 16 | 23950 | 10145 | 13199 | 44588 |
| **40** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 40373 | 52091 | 14 | 27749 | 9784 | 12624 | 42307 |
| **41** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl Clad Wood Core | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 42497 | 51755 | 14 | 29823 | 9140 | 12673 | 42615 |
| **42** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 9.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 41364 | 52000 | 14 | 28983 | 10809 | 12380 | 41192 |
| **43** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 37504 | 54707 | 16 | 24314 | 10105 | 13190 | 44602 |
| **44** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 38674 | 53475 | 16 | 25539 | 9280 | 13135 | 44195 |
| **45** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Vinyl | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 36870 | 54803 | 16 | 23552 | 9898 | 13317 | 44906 |
| **46** | Fiber Cement Siding, 0.3125 in. | Gypsum-Fiber Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Regular Gypsum Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 40603 | 52074 | 14 | 27962 | 9699 | 12641 | 42375 |
| **47** | Fiber Cement Siding, 0.3125 | Regular Gypsum Board (Wall), 0.5 | SIP (7/16 in. OSB), 7.25 in. EPS Foam | Vinyl Clad Wood Core | Triple Glazed No Coating (Air | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam | 42368 | 51762 | 14 | 29672 | 9095 | 12696 | 42667 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | in. | in. | Core | | Filled) | | | Core | | | | | | | |
| **48** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | Solid Wood | Triple Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 40246 | 52099 | 14 | 27598 | 9739 | 12648 | 42360 |
| **49** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | SIP (7/16 in. OSB), 9.25 in. EPS Foam Core | Solid Wood | Double Glazed No Coating (Air Filled) | Residential 30 ga. Steel Roof Panel, 0.016 in. | Gypsum-Fiber Board (Ceiling), 0.5 in. | SIP (7/16 in. OSB), 7.25 in. EPS Foam Core | 39141 | 53439 | 16 | 26162 | 10143 | 12979 | 43296 |

# Appendix N Harmony House Case Main EnergyPlus Input Code

```
##fileprefix K:\Optimization Project\include

!=====Macro Definitions=====

!====HVAC System Sizes======

!====Exterior Wall=====
##set1 ewalltype @@ewalltype@@

##set1 CLADDING @@cladding@@
##set1 SHEATHING @@sheathing@@
##set1 WALL_DRYWALL @@wall_drywall@@
##set1 EXT_INS @@ext_ins@@
##set1 STUD_INS @@stud_ins@@
##set1 SIP @@sip@@
##set1 AGICF @@agicf@@

##set1 CLADDING_COST @@cladding_cost@@
##set1 SHEATHING_COST @@sheathing_cost@@
##set1 WALL_DRYWALL_COST @@wall_drywall_cost@@
##set1 EXT_INS_COST @@ext_ins_cost@@
##set1 STUD_INS_COST @@stud_ins_cost@@
##set1 SIP_COST @@sip_cost@@
##set1 AGICF_COST @@agicf_cost@@

##set1 CLADDING_GWP @@cladding_gwp@@
##set1 SHEATHING_GWP @@sheathing_gwp@@
##set1 WALL_DRYWALL_GWP @@wall_drywall_gwp@@
##set1 EXT_INS_GWP @@ext_ins_gwp@@
##set1 STUD_INS_GWP @@stud_ins_gwp@@
##set1 SIP_GWP @@sip_gwp@@
##set1 AGICF_GWP @@agicf_gwp@@

!====Window Systems====

##set1 WINDOW_FRAME @@windowframetype@@
##set1 GLAZING @@glazingtype@@

##set1 WINDOW_FRAME_COST @@windowframe_cost@@
##set1 GLAZING_COST @@glazingtype_cost@@

##set1 WINDOW_FRAME_GWP @@windowframe_gwp@@
##set1 GLAZING_GWP @@glazingtype_gwp@@

!====Roof Type====

##set1 rooftype @@rooftype@@

##set1 SHINGLES @@shingles@@
##set1 RIGID_INS @@roof_rigid_ins@@
##set1 RAFTER_INS @@roof_stud_ins@@
##set1 ROOF_DRYWALL @@roof_drywall@@
##set1 ROOF_SIP @@roof_sip@@

##set1 SHINGLES_COST @@shingles_cost@@
##set1 RIGID_INS_COST @@roof_rigid_ins_cost@@
##set1 RAFTER_INS_COST @@roof_stud_ins_cost@@
##set1 ROOF_DRYWALL_COST @@roof_drywall_cost@@
##set1 ROOF_SIP_COST @@roof_sip_cost@@

##set1 SHINGLES_GWP @@shingles_gwp@@
##set1 RIGID_INS_GWP @@roof_rigid_ins_gwp@@
##set1 RAFTER_INS_GWP @@roof_stud_ins_gwp@@
##set1 ROOF_DRYWALL_GWP @@roof_drywall_gwp@@
##set1 ROOF_SIP_GWP @@roof_sip_gwp@@

!====Shading Devices====

##set1 SHADING @@shading@@
```

```
!====PV System====

!##set1 PVSYSTEMSIZE @@pvsystemsize@@

!===== MAIN ENERGYPLUS INPUT=====

Version, 7.2.0.006;     !- Version Identifier

!-   ===========  ALL OBJECTS IN CLASS: BUILDING ===========

Building,
    Harmony House,        !- Name
    @@orientation@@,                    !- North Axis {deg}
    City,               !- Terrain
    3.9999999E-02,          !- Loads Convergence Tolerance Value
    4.0000002E-03,          !- Temperature Convergence Tolerance Value {deltaC}
    FullExterior, !- Solar Distribution
    ,                   !- Maximum Number of Warmup Days
    7;                   !- Minimum Number of Warmup Days

!-   ===========  ALL OBJECTS IN CLASS: SHADOWCALCULATION ===========

ShadowCalculation,
    1;                   !- Calculation Frequency

!-   ===========  ALL OBJECTS IN CLASS: SURFACECONVECTIONALGORITHM:INSIDE ===========

SurfaceConvectionAlgorithm:Inside,
    TARP;                   !- Algorithm

!-   ===========  ALL OBJECTS IN CLASS: SURFACECONVECTIONALGORITHM:OUTSIDE ===========

SurfaceConvectionAlgorithm:Outside,
    DOE-2;                  !- Algorithm

!-   ===========  ALL OBJECTS IN CLASS: TIMESTEP ===========

Timestep,
    2;                   !- Number of Timesteps per Hour

!-   ===========  ALL OBJECTS IN CLASS: SITE:LOCATION ===========

Site:Location,
    Vancouver,        !- Name
    49.18,                 !- Latitude {deg}
    -123.17,                !- Longitude {deg}
    -8.0,              !- Time Zone {hr}
    64.4;                 !- Elevation {m}

!-   ===========  ALL OBJECTS IN CLASS: RUNPERIOD ===========

RunPeriod,
    ,                   !- Name
    1,                   !- Begin Month
    1,                   !- Begin Day of Month
    12,                   !- End Month
    31,                   !- End Day of Month
    ,                   !- Day of Week for Start Day
    ,                   !- Use Weather File Holidays and Special Days
    ,                   !- Use Weather File Daylight Saving Period
    ,                   !- Apply Weekend Holiday Rule
    ,                   !- Use Weather File Rain Indicators
    ;                   !- Use Weather File Snow Indicators

!-   ===========  ALL OBJECTS IN CLASS: SITE:GROUNDTEMPERATURE:BUILDINGSURFACE ===========

Site:GroundTemperature:BuildingSurface,
    10.0,                   !- January Ground Temperature {C}
    10.0,                   !- February Ground Temperature {C}
    10.0,                   !- March Ground Temperature {C}
    10.0,                   !- April Ground Temperature {C}
```

```
    10.0,                  !- May Ground Temperature {C}
    10.0,                  !- June Ground Temperature {C}
    10.0,                  !- July Ground Temperature {C}
    10.0,                  !- August Ground Temperature {C}
    10.0,                  !- September Ground Temperature {C}
    10.0,                  !- October Ground Temperature {C}
    10.0,                  !- November Ground Temperature {C}
    10.0;                  !- December Ground Temperature {C}

!-   ===========  ALL OBJECTS IN CLASS: SITE:GROUNDREFLECTANCE ===========

Site:GroundReflectance,
    0.2,                   !- January Ground Reflectance {dimensionless}
    0.2,                   !- February Ground Reflectance {dimensionless}
    0.2,                   !- March Ground Reflectance {dimensionless}
    0.2,                   !- April Ground Reflectance {dimensionless}
    0.2,                   !- May Ground Reflectance {dimensionless}
    0.2,                   !- June Ground Reflectance {dimensionless}
    0.2,                   !- July Ground Reflectance {dimensionless}
    0.2,                   !- August Ground Reflectance {dimensionless}
    0.2,                   !- September Ground Reflectance {dimensionless}
    0.2,                   !- October Ground Reflectance {dimensionless}
    0.2,                   !- November Ground Reflectance {dimensionless}
    0.2;                   !- December Ground Reflectance {dimensionless}

!-   ===========  ALL OBJECTS IN CLASS: SCHEDULES ===========

##include Schedules.idf

!-   ===========  ALL OBJECTS IN CLASS: GLOBALGEOMETRYRULES ===========

! ZoneCapacitanceMultiplier,1;
GlobalGeometryRules,
  UpperLeftCorner,                  !- Starting Vertex Position
  Counterclockwise,                 !- Vertex Entry Direction
  Relative,                         !- Coordinate System
  Relative,                         !- Daylighting Reference Point Coordinate System
  Relative;                         !- Rectangular Surface Coordinate System

!-   ===========  ALL OBJECTS IN CLASS: MATERIALS ===========

##include Materials.idf

Material,
  000 F08 Metal surface,            !- Name
  Smooth,                           !- Roughness
  0.0008,                           !- Thickness {m}
  45.28,                            !- Conductivity {W/m-K}
  7824,                             !- Density {kg/m3}
  500,                              !- Specific Heat {J/kg-K}
  0.9,                              !- Thermal Absorptance
  0.7,                              !- Solar Absorptance
  0.7;                              !- Visible Absorptance

Material,
  000 F16 Acoustic tile,            !- Name
  MediumSmooth,                     !- Roughness
  0.0191,                           !- Thickness {m}
  0.06,                             !- Conductivity {W/m-K}
  368,                              !- Density {kg/m3}
  590,                              !- Specific Heat {J/kg-K}
  0.9,                              !- Thermal Absorptance
  0.7,                              !- Solar Absorptance
  0.7;                              !- Visible Absorptance

Material,
  000 G01a 19mm gypsum board,       !- Name
  MediumSmooth,                     !- Roughness
  0.019,                            !- Thickness {m}
  0.16,                             !- Conductivity {W/m-K}
  800,                              !- Density {kg/m3}
  1090,                             !- Specific Heat {J/kg-K}
```

```
  0.9,                     !- Thermal Absorptance
  0.7,                     !- Solar Absorptance
  0.7;                     !- Visible Absorptance

Material,
  000 G05 25mm wood,       !- Name
  MediumSmooth,            !- Roughness
  0.0254,                  !- Thickness {m}
  0.15,                    !- Conductivity {W/m-K}
  608,                     !- Density {kg/m3}
  1630,                    !- Specific Heat {J/kg-K}
  0.9,                     !- Thermal Absorptance
  0.7,                     !- Solar Absorptance
  0.7;                     !- Visible Absorptance

Material,
  000 I01 25mm insulation board,  !- Name
  MediumRough,             !- Roughness
  0.0254,                  !- Thickness {m}
  0.03,                    !- Conductivity {W/m-K}
  43,                      !- Density {kg/m3}
  1210,                    !- Specific Heat {J/kg-K}
  0.9,                     !- Thermal Absorptance
  0.7,                     !- Solar Absorptance
  0.7;                     !- Visible Absorptance

Material,
  000 M11 100mm lightweight concrete,  !- Name
  MediumRough,             !- Roughness
  0.1016,                  !- Thickness {m}
  0.53,                    !- Conductivity {W/m-K}
  1280,                    !- Density {kg/m3}
  840,                     !- Specific Heat {J/kg-K}
  0.9,                     !- Thermal Absorptance
  0.7,                     !- Solar Absorptance
  0.7;                     !- Visible Absorptance

Material,
  1/2IN Gypsum,            !- Name
  Smooth,                  !- Roughness
  0.0127,                  !- Thickness {m}
  0.16,                    !- Conductivity {W/m-K}
  784.9,                   !- Density {kg/m3}
  830,                     !- Specific Heat {J/kg-K}
  0.9,                     !- Thermal Absorptance
  0.92,                    !- Solar Absorptance
  0.92;                    !- Visible Absorptance

Material,
  MAT-CC05 4 HW CONCRETE,  !- Name
  Rough,                   !- Roughness
  0.1016,                  !- Thickness {m}
  1.311,                   !- Conductivity {W/m-K}
  2240,                    !- Density {kg/m3}
  836.8,                   !- Specific Heat {J/kg-K}
  0.9,                     !- Thermal Absorptance
  0.7,                     !- Solar Absorptance
  0.7;                     !- Visible Absorptance

Material,
  Metal Decking,           !- Name
  MediumSmooth,            !- Roughness
  0.0015,                  !- Thickness {m}
  45.006,                  !- Conductivity {W/m-K}
  7680,                    !- Density {kg/m3}
  418.4,                   !- Specific Heat {J/kg-K}
  0.9,                     !- Thermal Absorptance
  0.7,                     !- Solar Absorptance
  0.3;                     !- Visible Absorptance

Material:AirGap,
  000 F04 Wall air space resistance,  !- Name
```

```
  0.15;                              !- Thermal Resistance {m2-K/W}

Material:AirGap,
  000 F05 Ceiling air space resistance,   !- Name
  0.18;                              !- Thermal Resistance {m2-K/W}

Material,
  OS:Material:AirWall 1,                 !- Name
  MediumSmooth,                          !- Roughness
  0.01,                              !- Thickness {m}
  0.6,                              !- Conductivity {W/m-K}
  800,                              !- Density {kg/m3}
  1000,                              !- Specific Heat {J/kg-K}
  0.95,                              !- Thermal Absorptance
  0.7,                              !- Solar Absorptance
  0.7;                              !- Visible Absorptance

Material:NoMass,
  CP02 CARPET PAD,                       !- Name
  VeryRough,                           !- Roughness
  0.2165,                              !- Thermal Resistance {m2-K/W}
  0.9,                              !- Thermal Absorptance
  0.7,                              !- Solar Absorptance
  0.8;                              !- Visible Absorptance

Material:NoMass,
  MAT-SHEATH,                            !- Name
  Rough,                               !- Roughness
  0.3626,                              !- Thermal Resistance {m2-K/W}
  0.9,                              !- Thermal Absorptance
  0.7,                              !- Solar Absorptance
  0.7;                              !- Visible Absorptance

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS ===========

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: WALL ===========

##include EWallType.imf

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: FLOOR ===========

!##include GFloorType.imf

Construction,
gfloor,
IN24,
CN4,
FL1;

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: ROOF ===========

##include RoofType.imf

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: WINDOW ===========

##include WindowType.imf

!-   ===========  ALL OBJECTS IN CLASS: BASELINE MATERIALS AND CONSTRUCTIONS ===========

!##include BaseCase.idf

!##include BaseCaseAdjusted.idf

!- ==== Other Constructions ====

Construction,
  000 Exterior Door,                     !- Name
  WS1,
  WS1;          !- Layer 2

Construction,
  000 Interior Ceiling,                  !- Name
```

```
CN3;                  !- Layer 3

Construction,
  000 Interior Door,                    !- Name
WS1,
WS1;                     !- Layer 1

Construction,
  000 Interior Floor,                   !- Name
CN3;     !- Layer 3

Construction,
  000 Interior Partition,               !- Name
WS1;                     !- Layer 1

Construction,
  000 Interior Wall,                    !- Name
DW1,            !- Layer 1
AL1,      !- Layer 2
DW1;            !- Layer 3

Construction,
BGICF,
CL6,
IN16,
ICF2,
IN16,
DW1;

! ====== Building Geometry ========

Zone,
  ZONE ONE,                       !- Name
  -0,                             !- Direction of Relative North {deg}
  29.9213493281234,                   !- X Origin {m}
  11.4790980144326,                   !- Y Origin {m}
  0,                              !- Z Origin {m}
  1,                              !- Type
  1,                              !- Multiplier
  ,                               !- Ceiling Height {m}
  1277.6,                              !- Volume {m3}
  437.6;                              !- Floor Area {m2}

BuildingSurface:Detailed,
  Surface 10,                       !- Name
  Wall,                           !- Surface Type
  BGICF,  !- Construction Name
  ZONE ONE,                       !- Zone Name
  Ground,                         !- Outside Boundary Condition
  ,                               !- Outside Boundary Condition Object
  NoSun,                          !- Sun Exposure
  NoWind,                          !- Wind Exposure
  ,                               !- View Factor to Ground
  ,                               !- Number of Vertices
  -9.877425, 6.6929, 2.4384,             !- X,Y,Z Vertex 1 {m}
  -9.877425, 6.6929, 0,               !- X,Y,Z Vertex 2 {m}
  -14.5589625, 6.6929, 0,               !- X,Y,Z Vertex 3 {m}
  -14.5589625, 6.6929, 2.4384;            !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 11,                       !- Name
  Wall,                           !- Surface Type
  BGICF,  !- Construction Name
  ZONE ONE,                       !- Zone Name
  Ground,                         !- Outside Boundary Condition
  ,                               !- Outside Boundary Condition Object
  NoSun,                          !- Sun Exposure
  NoWind,                          !- Wind Exposure
  ,                               !- View Factor to Ground
  ,                               !- Number of Vertices
  -9.877425, 8.042275, 2.4384,            !- X,Y,Z Vertex 1 {m}
  -9.877425, 8.042275, 0,               !- X,Y,Z Vertex 2 {m}
```

```
  -9.877425, 6.6929, 0,                 !- X,Y,Z Vertex 3 {m}
  -9.877425, 6.6929, 2.4384;            !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 12,                    !- Name
  Wall,                          !- Surface Type
  000 Interior Wall,             !- Construction Name
  ZONE ONE,                      !- Zone Name
  Surface,                       !- Outside Boundary Condition
  Surface 18,                    !- Outside Boundary Condition Object
  NoSun,                         !- Sun Exposure
  NoWind,                        !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  0, 8.042275, 2.4384,                !- X,Y,Z Vertex 1 {m}
  0, 8.042275, 1.2192,                !- X,Y,Z Vertex 2 {m}
  -9.877425, 8.042275, 1.2192,        !- X,Y,Z Vertex 3 {m}
  -9.877425, 8.042275, 2.4384;        !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 13,                    !- Name
  Wall,                          !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                      !- Zone Name
  Outdoors,                      !- Outside Boundary Condition
  ,                              !- Outside Boundary Condition Object
  SunExposed,                    !- Sun Exposure
  WindExposed,                   !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  0, 0, 2.4384,                  !- X,Y,Z Vertex 1 {m}
  0, 0, 0,                       !- X,Y,Z Vertex 2 {m}
  0, 2.99764087693718, 0,              !- X,Y,Z Vertex 3 {m}
  0, 2.99764087693718, 1.1255375,      !- X,Y,Z Vertex 4 {m}
  0, 8.042275, 2.06881362617294,       !- X,Y,Z Vertex 5 {m}
  0, 8.042275, 2.4384;                 !- X,Y,Z Vertex 6 {m}

FenestrationSurface:Detailed,
  Sub Surface 32,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 13,                    !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 1.12961547664487, 2.01903922610393,  !- X,Y,Z Vertex 1 {m}
  0, 1.12961547664487, 0.190239226103934, !- X,Y,Z Vertex 2 {m}
  0, 1.73921547664487, 0.190239226103934, !- X,Y,Z Vertex 3 {m}
  0, 1.73921547664487, 2.01903922610393;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 33,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 13,                    !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 0.356005966933571, 2.02413113787574, !- X,Y,Z Vertex 1 {m}
  0, 0.356005966933571, 0.195331137875739, !- X,Y,Z Vertex 2 {m}
  0, 0.965605966933571, 0.195331137875739, !- X,Y,Z Vertex 3 {m}
  0, 0.965605966933571, 2.02413113787574; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 34,                !- Name
  Window,                        !- Surface Type
```

```
  GLAZING[], !- Construction Name
  Surface 13,                !- Building Surface Name
  ,                          !- Outside Boundary Condition Object
  ,                          !- View Factor to Ground
  ,                          !- Shading Control Name
  @@frame_name@@,            !-Frame & Divider Name
  ,                          !- Multiplier
  ,                          !- Number of Vertices
  0, 1.93022860587302, 2.01642965422216,  !- X,Y,Z Vertex 1 {m}
  0, 1.93022860587302, 0.18762965422216,  !- X,Y,Z Vertex 2 {m}
  0, 2.53982860587302, 0.18762965422216,  !- X,Y,Z Vertex 3 {m}
  0, 2.53982860587302, 2.01642965422216;  !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 14,                !- Name
  Roof,                      !- Surface Type
  000 Interior Floor, !- Construction Name
  ZONE ONE,                  !- Zone Name
  Surface,                   !- Outside Boundary Condition
  Surface 54,                !- Outside Boundary Condition Object
  NoSun,                     !- Sun Exposure
  NoWind,                    !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  0, 0, 2.4384,              !- X,Y,Z Vertex 1 {m}
  0, 8.042275, 2.4384,       !- X,Y,Z Vertex 2 {m}
  -9.877425, 8.042275, 2.4384,     !- X,Y,Z Vertex 3 {m}
  -9.877425, 6.6929, 2.4384,       !- X,Y,Z Vertex 4 {m}
  -14.5589625, 6.6929, 2.4384,     !- X,Y,Z Vertex 5 {m}
  -14.5589625, 0, 2.4384;          !- X,Y,Z Vertex 6 {m}

BuildingSurface:Detailed,
  Surface 21,                !- Name
  Roof,                      !- Surface Type
  000 Interior Floor, !- Construction Name
  ZONE ONE,                  !- Zone Name
  Surface,                   !- Outside Boundary Condition
  Surface 2,                 !- Outside Boundary Condition Object
  NoSun,                     !- Sun Exposure
  NoWind,                    !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  -14.5589625, 1.44382283906452e-015, 2.4384, !- X,Y,Z Vertex 1 {m}
  -14.5589625, 6.6929, 2.4384,     !- X,Y,Z Vertex 2 {m}
  -17.4228125, 6.6929, 2.4384,     !- X,Y,Z Vertex 3 {m}
  -17.4228125, 1.44382283906452e-015, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 22,                !- Name
  Wall,                      !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                  !- Zone Name
  Outdoors,                  !- Outside Boundary Condition
  ,                          !- Outside Boundary Condition Object
  SunExposed,                !- Sun Exposure
  WindExposed,               !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  0, 0, 5.1435,              !- X,Y,Z Vertex 1 {m}
  0, 0, 2.4384,              !- X,Y,Z Vertex 2 {m}
  0, 10.8791375, 2.4384,     !- X,Y,Z Vertex 3 {m}
  0, 10.8791375, 5.1435;     !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 23,            !- Name
  Window,                    !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                !- Building Surface Name
  ,                          !- Outside Boundary Condition Object
  ,                          !- View Factor to Ground
  ,                          !- Shading Control Name
  @@frame_name@@,            !-Frame & Divider Name
```

```
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 0.34293427544141, 4.53576985203885,  !- X,Y,Z Vertex 1 {m}
  0, 0.34293427544141, 2.70696985203885,  !- X,Y,Z Vertex 2 {m}
  0, 0.95253427544141, 2.70696985203885,  !- X,Y,Z Vertex 3 {m}
  0, 0.95253427544141, 4.53576985203885;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 24,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                    !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 1.11654378515271, 4.53067794026705,  !- X,Y,Z Vertex 1 {m}
  0, 1.11654378515271, 2.70187794026705,  !- X,Y,Z Vertex 2 {m}
  0, 1.72614378515271, 2.70187794026705,  !- X,Y,Z Vertex 3 {m}
  0, 1.72614378515271, 4.53067794026705;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 25,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                    !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 1.91715691438085, 4.52806836838527,  !- X,Y,Z Vertex 1 {m}
  0, 1.91715691438085, 2.69926836838527,  !- X,Y,Z Vertex 2 {m}
  0, 2.52675691438085, 2.69926836838527,  !- X,Y,Z Vertex 3 {m}
  0, 2.52675691438085, 4.52806836838527;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 26,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                    !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 3.67409092590474, 4.51756908857866,  !- X,Y,Z Vertex 1 {m}
  0, 3.67409092590474, 2.68876908857866,  !- X,Y,Z Vertex 2 {m}
  0, 4.28369092590474, 2.68876908857866,  !- X,Y,Z Vertex 3 {m}
  0, 4.28369092590474, 4.51756908857866;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 27,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                    !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 5.24831356484419, 4.50986760492508,  !- X,Y,Z Vertex 1 {m}
  0, 5.24831356484419, 2.68106760492508,  !- X,Y,Z Vertex 2 {m}
  0, 5.85791356484419, 2.68106760492508,  !- X,Y,Z Vertex 3 {m}
  0, 5.85791356484419, 4.50986760492508;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
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  Sub Surface 28,                  !- Name
  Window,                          !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                      !- Building Surface Name
  ,                                !- Outside Boundary Condition Object
  ,                                !- View Factor to Ground
  ,                                !- Shading Control Name
  @@frame_name@@,                  !-Frame & Divider Name
  ,                                !- Multiplier
  ,                                !- Number of Vertices
  0, 4.44770043561604, 4.51247717680686,  !- X,Y,Z Vertex 1 {m}
  0, 4.44770043561604, 2.68367717680686,  !- X,Y,Z Vertex 2 {m}
  0, 5.05730043561605, 2.68367717680686,  !- X,Y,Z Vertex 3 {m}
  0, 5.05730043561605, 4.51247717680686;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 29,                  !- Name
  Window,                          !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                      !- Building Surface Name
  ,                                !- Outside Boundary Condition Object
  ,                                !- View Factor to Ground
  ,                                !- Shading Control Name
  @@frame_name@@,                  !-Frame & Divider Name
  ,                                !- Multiplier
  ,                                !- Number of Vertices
  0, 6.99331977988271, 4.51889647955049,  !- X,Y,Z Vertex 1 {m}
  0, 6.99331977988271, 2.69009647955049,  !- X,Y,Z Vertex 2 {m}
  0, 7.60291977988271, 2.69009647955049,  !- X,Y,Z Vertex 3 {m}
  0, 7.60291977988271, 4.51889647955049;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 30,                  !- Name
  Window,                          !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                      !- Building Surface Name
  ,                                !- Outside Boundary Condition Object
  ,                                !- View Factor to Ground
  ,                                !- Shading Control Name
  @@frame_name@@,                  !-Frame & Divider Name
  ,                                !- Multiplier
  ,                                !- Number of Vertices
  0, 8.56754241882215, 4.51119499589691,  !- X,Y,Z Vertex 1 {m}
  0, 8.56754241882215, 2.68239499589691,  !- X,Y,Z Vertex 2 {m}
  0, 9.17714241882215, 2.68239499589691,  !- X,Y,Z Vertex 3 {m}
  0, 9.17714241882215, 4.51119499589691;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 31,                  !- Name
  Window,                          !- Surface Type
  GLAZING[], !- Construction Name
  Surface 22,                      !- Building Surface Name
  ,                                !- Outside Boundary Condition Object
  ,                                !- View Factor to Ground
  ,                                !- Shading Control Name
  @@frame_name@@,                  !-Frame & Divider Name
  ,                                !- Multiplier
  ,                                !- Number of Vertices
  0, 7.76692928959401, 4.51380456777868,  !- X,Y,Z Vertex 1 {m}
  0, 7.76692928959401, 2.68500456777868,  !- X,Y,Z Vertex 2 {m}
  0, 8.37652928959401, 2.68500456777868,  !- X,Y,Z Vertex 3 {m}
  0, 8.37652928959401, 4.51380456777868;  !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 23,                      !- Name
  Wall,                            !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                        !- Zone Name
  Outdoors,                        !- Outside Boundary Condition
  ,                                !- Outside Boundary Condition Object
  SunExposed,                      !- Sun Exposure
  WindExposed,                     !- Wind Exposure
```

```
 ,                          !- View Factor to Ground
 ,                          !- Number of Vertices
 -17.4228125, 1.44382283906452e-015, 5.1435, !- X,Y,Z Vertex 1 {m}
 -17.4228125, 1.44382283906452e-015, 2.4384, !- X,Y,Z Vertex 2 {m}
 0, 0, 2.4384,              !- X,Y,Z Vertex 3 {m}
 0, 0, 5.1435;              !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
 Sub Surface 3,             !- Name
 Window,                    !- Surface Type
 GLAZING[], !- Construction Name
 Surface 23,                !- Building Surface Name
 ,                          !- Outside Boundary Condition Object
 ,                          !- View Factor to Ground
 ,                          !- Shading Control Name
 @@frame_name@@,            !-Frame & Divider Name
 ,                          !- Multiplier
 ,                          !- Number of Vertices
 -6.25057109584294, 0, 4.76764563826474, !- X,Y,Z Vertex 1 {m}
 -6.25057109584294, 0, 3.23094563826474, !- X,Y,Z Vertex 2 {m}
 -3.96457109584294, 0, 3.23094563826474, !- X,Y,Z Vertex 3 {m}
 -3.96457109584294, 0, 4.76764563826474; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
 Sub Surface 38,            !- Name
 Window,                    !- Surface Type
 GLAZING[], !- Construction Name
 Surface 23,                !- Building Surface Name
 ,                          !- Outside Boundary Condition Object
 ,                          !- View Factor to Ground
 ,                          !- Shading Control Name
 @@frame_name@@,            !-Frame & Divider Name
 ,                          !- Multiplier
 ,                          !- Number of Vertices
 -1.11033882408055, 0, 4.51654235841066, !- X,Y,Z Vertex 1 {m}
 -1.11033882408055, 0, 2.68774235841066, !- X,Y,Z Vertex 2 {m}
 -0.50073882408055, 0, 2.68774235841066, !- X,Y,Z Vertex 3 {m}
 -0.50073882408055, 0, 4.51654235841066; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
 Sub Surface 39,            !- Name
 Window,                    !- Surface Type
 GLAZING[], !- Construction Name
 Surface 23,                !- Building Surface Name
 ,                          !- Outside Boundary Condition Object
 ,                          !- View Factor to Ground
 ,                          !- Shading Control Name
 @@frame_name@@,            !-Frame & Divider Name
 ,                          !- Multiplier
 ,                          !- Number of Vertices
 -1.91095195330869, 0, 4.51915193029243, !- X,Y,Z Vertex 1 {m}
 -1.91095195330869, 0, 2.69035193029243, !- X,Y,Z Vertex 2 {m}
 -1.30135195330869, 0, 2.69035193029243, !- X,Y,Z Vertex 3 {m}
 -1.30135195330869, 0, 4.51915193029243; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
 Sub Surface 4,             !- Name
 Window,                    !- Surface Type
 GLAZING[], !- Construction Name
 Surface 23,                !- Building Surface Name
 ,                          !- Outside Boundary Condition Object
 ,                          !- View Factor to Ground
 ,                          !- Shading Control Name
 @@frame_name@@,            !-Frame & Divider Name
 ,                          !- Multiplier
 ,                          !- Number of Vertices
 -10.7091082847475, 0, 4.80110566481855, !- X,Y,Z Vertex 1 {m}
 -10.7091082847475, 0, 3.22376566481855, !- X,Y,Z Vertex 2 {m}
 -8.38246828474746, 0, 3.22376566481855, !- X,Y,Z Vertex 3 {m}
 -8.38246828474746, 0, 4.80110566481855; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
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  Sub Surface 40,                          !- Name
  Window,                                  !- Surface Type
  GLAZING[], !- Construction Name
  Surface 23,                              !- Building Surface Name
  ,                                        !- Outside Boundary Condition Object
  ,                                        !- View Factor to Ground
  ,                                        !- Shading Control Name
  @@frame_name@@,                          !-Frame & Divider Name
  ,                                        !- Multiplier
  ,                                        !- Number of Vertices
  -2.68456146301999, 0, 4.52424384206424, !- X,Y,Z Vertex 1 {m}
  -2.68456146301999, 0, 2.69544384206424, !- X,Y,Z Vertex 2 {m}
  -2.07496146301999, 0, 2.69544384206424, !- X,Y,Z Vertex 3 {m}
  -2.07496146301999, 0, 4.52424384206424; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 5,                           !- Name
  Window,                                  !- Surface Type
  GLAZING[], !- Construction Name
  Surface 23,                              !- Building Surface Name
  ,                                        !- Outside Boundary Condition Object
  ,                                        !- View Factor to Ground
  ,                                        !- Shading Control Name
  @@frame_name@@,                          !-Frame & Divider Name
  ,                                        !- Multiplier
  ,                                        !- Number of Vertices
  -13.9641521758904, 0, 4.80110566481855, !- X,Y,Z Vertex 1 {m}
  -13.9641521758904, 0, 3.67461566481855, !- X,Y,Z Vertex 2 {m}
  -12.2471121758904, 0, 3.67461566481855, !- X,Y,Z Vertex 3 {m}
  -12.2471121758904, 0, 4.80110566481855; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 24,                              !- Name
  Wall,                                    !- Surface Type
  000 Interior Wall,                       !- Construction Name
  ZONE ONE,                                !- Zone Name
  Surface,                                 !- Outside Boundary Condition
  Surface 32,                              !- Outside Boundary Condition Object
  NoSun,                                   !- Sun Exposure
  NoWind,                                  !- Wind Exposure
  ,                                        !- View Factor to Ground
  ,                                        !- Number of Vertices
  -9.877425, 10.8791375, 5.1435,           !- X,Y,Z Vertex 1 {m}
  -9.877425, 10.8791375, 2.4384,           !- X,Y,Z Vertex 2 {m}
  -9.877425, 6.6929, 2.4384,               !- X,Y,Z Vertex 3 {m}
  -9.877425, 6.6929, 5.1435;               !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 25,                              !- Name
  Wall,                                    !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                                !- Zone Name
  Outdoors,                                !- Outside Boundary Condition
  ,                                        !- Outside Boundary Condition Object
  SunExposed,                              !- Sun Exposure
  WindExposed,                             !- Wind Exposure
  ,                                        !- View Factor to Ground
  ,                                        !- Number of Vertices
  0, 10.8791375, 5.1435,                   !- X,Y,Z Vertex 1 {m}
  0, 10.8791375, 2.4384,                   !- X,Y,Z Vertex 2 {m}
  -9.877425, 10.8791375, 2.4384,           !- X,Y,Z Vertex 3 {m}
  -9.877425, 10.8791375, 5.1435;           !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 13,                          !- Name
  Window,                                  !- Surface Type
  GLAZING[], !- Construction Name
  Surface 25,                              !- Building Surface Name
  ,                                        !- Outside Boundary Condition Object
  ,                                        !- View Factor to Ground
  ,                                        !- Shading Control Name
  @@frame_name@@,                          !-Frame & Divider Name
```

```
 ,                              !- Multiplier
 ,                              !- Number of Vertices
 -2.18304873479909, 10.8791375, 4.60523319491817, !- X,Y,Z Vertex 1 {m}
 -2.18304873479909, 10.8791375, 3.38603319491817, !- X,Y,Z Vertex 2 {m}
 -4.01184873479909, 10.8791375, 3.38603319491817, !- X,Y,Z Vertex 3 {m}
 -4.01184873479909, 10.8791375, 4.60523319491817; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
 Sub Surface 15,                !- Name
 Window,                        !- Surface Type
 GLAZING[], !- Construction Name
 Surface 25,                    !- Building Surface Name
 ,                              !- Outside Boundary Condition Object
 ,                              !- View Factor to Ground
 ,                              !- Shading Control Name
 @@frame_name@@,                !-Frame & Divider Name
 ,                              !- Multiplier
 ,                              !- Number of Vertices
 -5.52292392418909, 10.8791375, 4.63679034767218, !- X,Y,Z Vertex 1 {m}
 -5.52292392418909, 10.8791375, 2.60479034767218, !- X,Y,Z Vertex 2 {m}
 -6.43732392418909, 10.8791375, 2.60479034767218, !- X,Y,Z Vertex 3 {m}
 -6.43732392418909, 10.8791375, 4.63679034767218; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 26,                    !- Name
 Wall,                          !- Surface Type
 000 Interior Wall,             !- Construction Name
 ZONE ONE,                      !- Zone Name
 Surface,                       !- Outside Boundary Condition
 Surface 31,                    !- Outside Boundary Condition Object
 NoSun,                         !- Sun Exposure
 NoWind,                        !- Wind Exposure
 ,                              !- View Factor to Ground
 ,                              !- Number of Vertices
 -9.877425, 6.6929, 5.1435,     !- X,Y,Z Vertex 1 {m}
 -9.877425, 6.6929, 2.4384,     !- X,Y,Z Vertex 2 {m}
 -17.4228125, 6.6929, 2.4384,   !- X,Y,Z Vertex 3 {m}
 -17.4228125, 6.6929, 5.1435;   !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 28,                    !- Name
 Ceiling,                       !- Surface Type
 000 Interior Ceiling,          !- Construction Name
 ZONE ONE,                      !- Zone Name
 Surface,                       !- Outside Boundary Condition
 Surface 61,                    !- Outside Boundary Condition Object
 NoSun,                         !- Sun Exposure
 NoWind,                        !- Wind Exposure
 ,                              !- View Factor to Ground
 ,                              !- Number of Vertices
 -9.877425, 6.0023375, 5.1435,  !- X,Y,Z Vertex 1 {m}
 -9.877425, 6.6929, 5.1435,     !- X,Y,Z Vertex 2 {m}
 -17.4228125, 6.6929, 5.1435,   !- X,Y,Z Vertex 3 {m}
 -17.4228125, 6.0023375, 5.1435; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 35,                    !- Name
 Wall,                          !- Surface Type
 ewalltype[], !- Construction Name
 ZONE ONE,                      !- Zone Name
 Outdoors,                      !- Outside Boundary Condition
 ,                              !- Outside Boundary Condition Object
 SunExposed,                    !- Sun Exposure
 WindExposed,                   !- Wind Exposure
 ,                              !- View Factor to Ground
 ,                              !- Number of Vertices
 0, 10.8791375, 7.4295,         !- X,Y,Z Vertex 1 {m}
 0, 10.8791375, 5.1435,         !- X,Y,Z Vertex 2 {m}
 -9.877425, 10.8791375, 5.1435, !- X,Y,Z Vertex 3 {m}
 -9.877425, 10.8791375, 7.4295; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
```

```
  Sub Surface 17,                    !- Name
  Window,                            !- Surface Type
  GLAZING[], !- Construction Name
  Surface 35,                        !- Building Surface Name
  ,                                  !- Outside Boundary Condition Object
  ,                                  !- View Factor to Ground
  ,                                  !- Shading Control Name
  @@frame_name@@,                    !-Frame & Divider Name
  ,                                  !- Multiplier
  ,                                  !- Number of Vertices
  -3.82561909674316, 10.8791375, 7.04485026902424, !- X,Y,Z Vertex 1 {m}
  -3.82561909674316, 10.8791375, 5.82565026902424, !- X,Y,Z Vertex 2 {m}
  -5.04481909674316, 10.8791375, 5.82565026902424, !- X,Y,Z Vertex 3 {m}
  -5.04481909674316, 10.8791375, 7.04485026902424; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 18,                    !- Name
  Window,                            !- Surface Type
  GLAZING[], !- Construction Name
  Surface 35,                        !- Building Surface Name
  ,                                  !- Outside Boundary Condition Object
  ,                                  !- View Factor to Ground
  ,                                  !- Shading Control Name
  @@frame_name@@,                    !-Frame & Divider Name
  ,                                  !- Multiplier
  ,                                  !- Number of Vertices
  -7.39732893040591, 10.8791375, 6.97294771984254, !- X,Y,Z Vertex 1 {m}
  -7.39732893040591, 10.8791375, 6.36334771984254, !- X,Y,Z Vertex 2 {m}
  -9.22612893040591, 10.8791375, 6.36334771984254, !- X,Y,Z Vertex 3 {m}
  -9.22612893040591, 10.8791375, 6.97294771984254; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 36,                        !- Name
  Wall,                              !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                          !- Zone Name
  Outdoors,                          !- Outside Boundary Condition
  ,                                  !- Outside Boundary Condition Object
  SunExposed,                        !- Sun Exposure
  WindExposed,                       !- Wind Exposure
  ,                                  !- View Factor to Ground
  ,                                  !- Number of Vertices
  0, 6.0023375, 9.1821,              !- X,Y,Z Vertex 1 {m}
  0, 3.1194375, 8.3058,              !- X,Y,Z Vertex 2 {m}
  0, 3.1194375, 5.1435,              !- X,Y,Z Vertex 3 {m}
  0, 10.8791375, 5.1435,             !- X,Y,Z Vertex 4 {m}
  0, 10.8791375, 7.4295;             !- X,Y,Z Vertex 5 {m}

FenestrationSurface:Detailed,
  Sub Surface 35,                    !- Name
  Window,                            !- Surface Type
  GLAZING[], !- Construction Name
  Surface 36,                        !- Building Surface Name
  ,                                  !- Outside Boundary Condition Object
  ,                                  !- View Factor to Ground
  ,                                  !- Shading Control Name
  @@frame_name@@,                    !-Frame & Divider Name
  ,                                  !- Multiplier
  ,                                  !- Number of Vertices
  0, 3.93176281799246, 7.517198563232,    !- X,Y,Z Vertex 1 {m}
  0, 3.93176281799246, 6.297998563232,    !- X,Y,Z Vertex 2 {m}
  0, 5.15096281799246, 6.297998563232,    !- X,Y,Z Vertex 3 {m}
  0, 5.15096281799246, 7.517198563232;    !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 36,                    !- Name
  Window,                            !- Surface Type
  GLAZING[], !- Construction Name
  Surface 36,                        !- Building Surface Name
  ,                                  !- Outside Boundary Condition Object
  ,                                  !- View Factor to Ground
  ,                                  !- Shading Control Name
```

```
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 6.29170064198897, 7.517198563232,    !- X,Y,Z Vertex 1 {m}
  0, 6.29170064198897, 6.297998563232,    !- X,Y,Z Vertex 2 {m}
  0, 6.90130064198897, 6.297998563232,    !- X,Y,Z Vertex 3 {m}
  0, 6.90130064198897, 7.517198563232;    !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 37,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 36,                    !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  0, 7.17535746298017, 7.517198563232,    !- X,Y,Z Vertex 1 {m}
  0, 7.17535746298017, 6.297998563232,    !- X,Y,Z Vertex 2 {m}
  0, 8.69935746298017, 6.297998563232,    !- X,Y,Z Vertex 3 {m}
  0, 8.69935746298017, 7.517198563232;    !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 37,                    !- Name
  Roof,                          !- Surface Type
  rooftype[], !- Construction Name
  ZONE ONE,                      !- Zone Name
  Outdoors,                      !- Outside Boundary Condition
  ,                              !- Outside Boundary Condition Object
  SunExposed,                    !- Sun Exposure
  WindExposed,                   !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  0, 6.0023375, 9.1821,                !- X,Y,Z Vertex 1 {m}
  0, 10.8791375, 7.4295,               !- X,Y,Z Vertex 2 {m}
  -9.877425, 10.8791375, 7.4295,       !- X,Y,Z Vertex 3 {m}
  -9.877425, 6.0023375, 9.1821;        !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 38,                    !- Name
  Wall,                          !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                      !- Zone Name
  Outdoors,                      !- Outside Boundary Condition
  ,                              !- Outside Boundary Condition Object
  SunExposed,                    !- Sun Exposure
  WindExposed,                   !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  -17.4228125, 6.0023375, 9.1821,      !- X,Y,Z Vertex 1 {m}
  -17.4228125, 6.0023375, 5.1435,      !- X,Y,Z Vertex 2 {m}
  -17.4228125, 0, 5.1435;              !- X,Y,Z Vertex 3 {m}

BuildingSurface:Detailed,
  Surface 39,                    !- Name
  Wall,                          !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                      !- Zone Name
  Outdoors,                      !- Outside Boundary Condition
  ,                              !- Outside Boundary Condition Object
  SunExposed,                    !- Sun Exposure
  WindExposed,                   !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  -9.877425, 6.0023375, 9.1821,        !- X,Y,Z Vertex 1 {m}
  -9.877425, 10.8791375, 7.4295,       !- X,Y,Z Vertex 2 {m}
  -9.877425, 10.8791375, 5.88773483802443; !- X,Y,Z Vertex 3 {m}

BuildingSurface:Detailed,
  Surface 40,                    !- Name
```

```
  Wall,                    !- Surface Type
  000 Interior Wall,              !- Construction Name
  ZONE ONE,                !- Zone Name
  Surface,                 !- Outside Boundary Condition
  Surface 43,              !- Outside Boundary Condition Object
  NoSun,                   !- Sun Exposure
  NoWind,                  !- Wind Exposure
  ,                        !- View Factor to Ground
  ,                        !- Number of Vertices
  -9.877425, 6.0023375, 9.1821,          !- X,Y,Z Vertex 1 {m}
  -9.877425, 6.0023375, 5.1435,          !- X,Y,Z Vertex 2 {m}
  -17.4228125, 6.0023375, 5.1435,        !- X,Y,Z Vertex 3 {m}
  -17.4228125, 6.0023375, 9.1821;        !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 41,              !- Name
  Roof,                    !- Surface Type
  rooftype[], !- Construction Name
  ZONE ONE,                !- Zone Name
  Outdoors,                !- Outside Boundary Condition
  ,                        !- Outside Boundary Condition Object
  SunExposed,              !- Sun Exposure
  WindExposed,             !- Wind Exposure
  ,                        !- View Factor to Ground
  ,                        !- Number of Vertices
  -17.4228125, 6.0023375, 9.1821,        !- X,Y,Z Vertex 1 {m}
  -17.4228125, 0, 5.1435,                !- X,Y,Z Vertex 2 {m}
  -2.6050875, 0, 5.1435,                 !- X,Y,Z Vertex 3 {m}
  -2.6050875, 3.1194375, 7.24237569426078, !- X,Y,Z Vertex 4 {m}
  -11.2029875, 3.1194375, 7.24237569426078, !- X,Y,Z Vertex 5 {m}
  -11.2029875, 6.0023375, 9.1821;        !- X,Y,Z Vertex 6 {m}

BuildingSurface:Detailed,
  Surface 42,              !- Name
  Wall,                    !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                !- Zone Name
  Outdoors,                !- Outside Boundary Condition
  ,                        !- Outside Boundary Condition Object
  SunExposed,              !- Sun Exposure
  WindExposed,             !- Wind Exposure
  ,                        !- View Factor to Ground
  ,                        !- Number of Vertices
  -11.2029875, 3.1194375, 8.3058,        !- X,Y,Z Vertex 1 {m}
  -11.2029875, 3.1194375, 7.24237569426078, !- X,Y,Z Vertex 2 {m}
  -2.6050875, 3.1194375, 7.24237569426078, !- X,Y,Z Vertex 3 {m}
  -2.6050875, 3.1194375, 5.1435,         !- X,Y,Z Vertex 4 {m}
  0, 3.1194375, 5.1435,                  !- X,Y,Z Vertex 5 {m}
  0, 3.1194375, 8.3058;                  !- X,Y,Z Vertex 6 {m}

FenestrationSurface:Detailed,
  Sub Surface 1,           !- Name
  Window,                  !- Surface Type
  GLAZING[], !- Construction Name
  Surface 42,              !- Building Surface Name
  ,                        !- Outside Boundary Condition Object
  ,                        !- View Factor to Ground
  ,                        !- Shading Control Name
  @@frame_name@@,          !-Frame & Divider Name
  ,                        !- Multiplier
  ,                        !- Number of Vertices
  -2.08799760070738, 3.1194375, 7.63818765693723, !- X,Y,Z Vertex 1 {m}
  -2.08799760070738, 3.1194375, 5.44108765693723, !- X,Y,Z Vertex 2 {m}
  -0.411597600707379, 3.1194375, 5.44108765693723, !- X,Y,Z Vertex 3 {m}
  -0.411597600707379, 3.1194375, 7.63818765693723; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 6,           !- Name
  Window,                  !- Surface Type
  GLAZING[], !- Construction Name
  Surface 42,              !- Building Surface Name
  ,                        !- Outside Boundary Condition Object
```

```
 ,                          !- View Factor to Ground
 ,                          !- Shading Control Name
 @@frame_name@@,            !-Frame & Divider Name
 ,                          !- Multiplier
 ,                          !- Number of Vertices
 -10.7916916994408, 3.1194375, 8.11727083999932, !- X,Y,Z Vertex 1 {m}
 -10.7916916994408, 3.1194375, 7.45687083999932, !- X,Y,Z Vertex 2 {m}
 -9.06449169944076, 3.1194375, 7.45687083999932, !- X,Y,Z Vertex 3 {m}
 -9.06449169944076, 3.1194375, 8.11727083999932; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
 Sub Surface 7,             !- Name
 Window,                    !- Surface Type
 GLAZING[], !- Construction Name
 Surface 42,                !- Building Surface Name
 ,                          !- Outside Boundary Condition Object
 ,                          !- View Factor to Ground
 ,                          !- Shading Control Name
 @@frame_name@@,            !-Frame & Divider Name
 ,                          !- Multiplier
 ,                          !- Number of Vertices
 -8.81674048896297, 3.1194375, 8.11727083999932, !- X,Y,Z Vertex 1 {m}
 -8.81674048896297, 3.1194375, 7.45687083999932, !- X,Y,Z Vertex 2 {m}
 -7.08954048896297, 3.1194375, 7.45687083999932, !- X,Y,Z Vertex 3 {m}
 -7.08954048896297, 3.1194375, 8.11727083999932; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
 Sub Surface 8,             !- Name
 Window,                    !- Surface Type
 GLAZING[], !- Construction Name
 Surface 42,                !- Building Surface Name
 ,                          !- Outside Boundary Condition Object
 ,                          !- View Factor to Ground
 ,                          !- Shading Control Name
 @@frame_name@@,            !-Frame & Divider Name
 ,                          !- Multiplier
 ,                          !- Number of Vertices
 -6.87960619211245, 3.1194375, 8.11727083999932, !- X,Y,Z Vertex 1 {m}
 -6.87960619211245, 3.1194375, 7.45687083999932, !- X,Y,Z Vertex 2 {m}
 -5.15240619211245, 3.1194375, 7.45687083999932, !- X,Y,Z Vertex 3 {m}
 -5.15240619211245, 3.1194375, 8.11727083999932; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
 Sub Surface 9,             !- Name
 Window,                    !- Surface Type
 GLAZING[], !- Construction Name
 Surface 42,                !- Building Surface Name
 ,                          !- Outside Boundary Condition Object
 ,                          !- View Factor to Ground
 ,                          !- Shading Control Name
 @@frame_name@@,            !-Frame & Divider Name
 ,                          !- Multiplier
 ,                          !- Number of Vertices
 -4.89262611053254, 3.1194375, 8.11727083999932, !- X,Y,Z Vertex 1 {m}
 -4.89262611053254, 3.1194375, 7.45687083999932, !- X,Y,Z Vertex 2 {m}
 -3.16542611053254, 3.1194375, 7.45687083999932, !- X,Y,Z Vertex 3 {m}
 -3.16542611053254, 3.1194375, 8.11727083999932; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 44,                !- Name
 Wall,                      !- Surface Type
 ewalltype[], !- Construction Name
 ZONE ONE,                  !- Zone Name
 Outdoors,                  !- Outside Boundary Condition
 ,                          !- Outside Boundary Condition Object
 SunExposed,                !- Sun Exposure
 WindExposed,               !- Wind Exposure
 ,                          !- View Factor to Ground
 ,                          !- Number of Vertices
 -11.2029875, 6.0023375, 9.1821,        !- X,Y,Z Vertex 1 {m}
 -11.2029875, 3.1194375, 7.24237569426078, !- X,Y,Z Vertex 2 {m}
 -11.2029875, 3.1194375, 8.3058;        !- X,Y,Z Vertex 3 {m}
```

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BuildingSurface:Detailed,
  Surface 45,                !- Name
  Roof,                      !- Surface Type
  rooftype[], !- Construction Name
  ZONE ONE,                  !- Zone Name
  Outdoors,                  !- Outside Boundary Condition
  ,                          !- Outside Boundary Condition Object
  SunExposed,                !- Sun Exposure
  WindExposed,               !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  -11.2029875, 6.0023375, 9.1821,        !- X,Y,Z Vertex 1 {m}
  -11.2029875, 3.1194375, 8.3058,        !- X,Y,Z Vertex 2 {m}
  0, 3.1194375, 8.3058,                  !- X,Y,Z Vertex 3 {m}
  0, 6.0023375, 9.1821;                  !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 48,                !- Name
  Wall,                      !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                  !- Zone Name
  Outdoors,                  !- Outside Boundary Condition
  ,                          !- Outside Boundary Condition Object
  SunExposed,                !- Sun Exposure
  WindExposed,               !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  -2.6050875, 3.1194375, 7.24237569426078, !- X,Y,Z Vertex 1 {m}
  -2.6050875, 0, 5.1435,                 !- X,Y,Z Vertex 2 {m}
  -2.6050875, 3.1194375, 5.1435;         !- X,Y,Z Vertex 3 {m}

BuildingSurface:Detailed,
  Surface 53,                !- Name
  Wall,                      !- Surface Type
  000 Interior Wall,         !- Construction Name
  ZONE ONE,                  !- Zone Name
  Surface,                   !- Outside Boundary Condition
  Surface 62,                !- Outside Boundary Condition Object
  NoSun,                     !- Sun Exposure
  NoWind,                    !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  -9.877425, 6.0023375, 9.1821,          !- X,Y,Z Vertex 1 {m}
  -9.877425, 10.8791375, 5.88773483802443, !- X,Y,Z Vertex 2 {m}
  -9.877425, 10.8791375, 5.1435,         !- X,Y,Z Vertex 3 {m}
  -9.877425, 6.0023375, 5.1435;          !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 54,                !- Name
  Roof,                      !- Surface Type
  000 Interior Floor, !- Construction Name
  ZONE ONE,                  !- Zone Name
  Surface,                   !- Outside Boundary Condition
  Surface 14,                !- Outside Boundary Condition Object
  NoSun,                     !- Sun Exposure
  NoWind,                    !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  -6.72106350615568e-034, 5.35162634805961e-034, 2.4384, !- X,Y,Z Vertex 1 {m}
  1.61357591226454e-035, 8.042275, 2.4384, !- X,Y,Z Vertex 2 {m}
  -9.877425, 8.042275, 2.4384,           !- X,Y,Z Vertex 3 {m}
  -9.877425, 6.6929, 2.4384,             !- X,Y,Z Vertex 4 {m}
  -14.5589625, 6.6929, 2.4384,           !- X,Y,Z Vertex 5 {m}
  -14.5589625, 1.44382283906452e-015, 2.4384; !- X,Y,Z Vertex 6 {m}

BuildingSurface:Detailed,
  Surface 55,                !- Name
  Roof,                      !- Surface Type
  000 Interior Floor, !- Construction Name
  ZONE ONE,                  !- Zone Name
  Surface,                   !- Outside Boundary Condition
```

```
  Surface 20,                              !- Outside Boundary Condition Object
  NoSun,                          !- Sun Exposure
  NoWind,                          !- Wind Exposure
  ,                               !- View Factor to Ground
  ,                               !- Number of Vertices
  0, 8.042275, 2.4384,                   !- X,Y,Z Vertex 1 {m}
  0, 10.8791375, 2.4384,                 !- X,Y,Z Vertex 2 {m}
  -9.877425, 10.8791375, 2.4384,         !- X,Y,Z Vertex 3 {m}
  -9.877425, 8.042275, 2.4384;           !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 56,                     !- Name
  Wall,                           !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                       !- Zone Name
  Outdoors,                       !- Outside Boundary Condition
  ,                               !- Outside Boundary Condition Object
  SunExposed,                     !- Sun Exposure
  WindExposed,                    !- Wind Exposure
  ,                               !- View Factor to Ground
  ,                               !- Number of Vertices
  -17.4228125, 6.6929, 5.1435,           !- X,Y,Z Vertex 1 {m}
  -17.4228125, 6.6929, 2.4384,           !- X,Y,Z Vertex 2 {m}
  -17.4228125, 1.44382283906452e-015, 2.4384, !- X,Y,Z Vertex 3 {m}
  -17.4228125, 1.44382283906452e-015, 5.1435; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 41,                 !- Name
  Window,                         !- Surface Type
  GLAZING[], !- Construction Name
  Surface 56,                     !- Building Surface Name
  ,                               !- Outside Boundary Condition Object
  ,                               !- View Factor to Ground
  ,                               !- Shading Control Name
  @@frame_name@@,                 !-Frame & Divider Name
  ,                               !- Multiplier
  ,                               !- Number of Vertices
  -17.4228125, 4.85901185646, 4.55256729440324, !- X,Y,Z Vertex 1 {m}
  -17.4228125, 4.85901185646, 3.02856729440324, !- X,Y,Z Vertex 2 {m}
  -17.4228125, 4.24941185646, 3.02856729440324, !- X,Y,Z Vertex 3 {m}
  -17.4228125, 4.24941185646, 4.55256729440324; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 42,                 !- Name
  Window,                         !- Surface Type
  GLAZING[], !- Construction Name
  Surface 56,                     !- Building Surface Name
  ,                               !- Outside Boundary Condition Object
  ,                               !- View Factor to Ground
  ,                               !- Shading Control Name
  @@frame_name@@,                 !-Frame & Divider Name
  ,                               !- Multiplier
  ,                               !- Number of Vertices
  -17.4228125, 4.00118364712758, 4.55256729440324, !- X,Y,Z Vertex 1 {m}
  -17.4228125, 4.00118364712758, 2.72376729440324, !- X,Y,Z Vertex 2 {m}
  -17.4228125, 3.08678364712758, 2.72376729440324, !- X,Y,Z Vertex 3 {m}
  -17.4228125, 3.08678364712758, 4.55256729440324; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 43,                 !- Name
  Window,                         !- Surface Type
  GLAZING[], !- Construction Name
  Surface 56,                     !- Building Surface Name
  ,                               !- Outside Boundary Condition Object
  ,                               !- View Factor to Ground
  ,                               !- Shading Control Name
  @@frame_name@@,                 !-Frame & Divider Name
  ,                               !- Multiplier
  ,                               !- Number of Vertices
  -17.4228125, 2.23827923363903, 4.79860165565252, !- X,Y,Z Vertex 1 {m}
  -17.4228125, 2.23827923363903, 3.57940165565252, !- X,Y,Z Vertex 2 {m}
  -17.4228125, 0.409479233639032, 3.57940165565252, !- X,Y,Z Vertex 3 {m}
```

```
  -17.4228125, 0.409479233639032, 4.79860165565252; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 58,                !- Name
  Wall,                      !- Surface Type
  BGICF,  !- Construction Name
  ZONE ONE,                  !- Zone Name
  Ground,                    !- Outside Boundary Condition
  ,                          !- Outside Boundary Condition Object
  NoSun,                     !- Sun Exposure
  NoWind,                    !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  -14.5589625, 6.6929, 1.2192,      !- X,Y,Z Vertex 1 {m}
  -14.5589625, 6.6929, 0,           !- X,Y,Z Vertex 2 {m}
  -14.5589625, 0, 0,                !- X,Y,Z Vertex 3 {m}
  -14.5589625, 0, 1.2192;           !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 59,                !- Name
  Wall,                      !- Surface Type
  BGICF,  !- Construction Name
  ZONE ONE,                  !- Zone Name
  Ground,                    !- Outside Boundary Condition
  ,                          !- Outside Boundary Condition Object
  NoSun,                     !- Sun Exposure
  NoWind,                    !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  0, 8.042275, 1.2192,              !- X,Y,Z Vertex 1 {m}
  0, 8.042275, 0,                   !- X,Y,Z Vertex 2 {m}
  -9.877425, 8.042275, 0,           !- X,Y,Z Vertex 3 {m}
  -9.877425, 8.042275, 1.2192;      !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 63,                !- Name
  Wall,                      !- Surface Type
  BGICF,  !- Construction Name
  ZONE ONE,                  !- Zone Name
  Ground,                    !- Outside Boundary Condition
  ,                          !- Outside Boundary Condition Object
  NoSun,                     !- Sun Exposure
  NoWind,                    !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  -14.5589625, 7.8623918677738e-016, 2.4384, !- X,Y,Z Vertex 1 {m}
  -14.5589625, 5.68947487981696e-016, -5.07002814095635e-032, !- X,Y,Z Vertex 2 {m}
  4.35989742494155e-033, 1.52376325747341e-016, -1.35786215050378e-032, !- X,Y,Z Vertex 3 {m}
  5.74421522830457e-033, 2.00757569612479e-016, 0.542923755001249, !- X,Y,Z Vertex 4 {m}
  -11.5494201284153, 5.58540045062981e-016, 0.849530132308784, !- X,Y,Z Vertex 5 {m}
  -11.5494201284153, 6.20785062947161e-016, 1.54803013230878; !- X,Y,Z Vertex 6 {m}

BuildingSurface:Detailed,
  Surface 64,                !- Name
  Wall,                      !- Surface Type
  BGICF,  !- Construction Name
  ZONE ONE,                  !- Zone Name
  Ground,                    !- Outside Boundary Condition
  ,                          !- Outside Boundary Condition Object
  NoSun,                     !- Sun Exposure
  NoWind,                    !- Wind Exposure
  ,                          !- View Factor to Ground
  ,                          !- Number of Vertices
  0, 8.042275, 2.06881362617294,    !- X,Y,Z Vertex 1 {m}
  0, 2.99764087693718, 1.1255375,   !- X,Y,Z Vertex 2 {m}
  0, 2.99764087693718, 0,           !- X,Y,Z Vertex 3 {m}
  0, 8.042275, 0;                   !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 68,                !- Name
  Roof,                      !- Surface Type
  rooftype[], !- Construction Name
```

```
  ZONE ONE,                       !- Zone Name
  Outdoors,                       !- Outside Boundary Condition
  ,                               !- Outside Boundary Condition Object
  SunExposed,                     !- Sun Exposure
  WindExposed,                    !- Wind Exposure
  ,                               !- View Factor to Ground
  ,                               !- Number of Vertices
  0, 0, 5.1435,                   !- X,Y,Z Vertex 1 {m}
  0, 3.1194375, 5.1435,           !- X,Y,Z Vertex 2 {m}
  -2.6050875, 3.1194375, 5.1435,  !- X,Y,Z Vertex 3 {m}
  -2.6050875, -1.44382283906452e-015, 5.1435; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 7,                      !- Name
  Floor,                          !- Surface Type
  gfloor,  !- Construction Name
  ZONE ONE,                       !- Zone Name
  Ground,                         !- Outside Boundary Condition
  ,                               !- Outside Boundary Condition Object
  NoSun,                          !- Sun Exposure
  NoWind,                         !- Wind Exposure
  ,                               !- View Factor to Ground
  ,                               !- Number of Vertices
  0, 8.042275, 0,                 !- X,Y,Z Vertex 1 {m}
  0, 0, 0,                        !- X,Y,Z Vertex 2 {m}
  -14.5589625, 0, 0,              !- X,Y,Z Vertex 3 {m}
  -14.5589625, 6.6929, 0,         !- X,Y,Z Vertex 4 {m}
  -9.877425, 6.6929, 0,           !- X,Y,Z Vertex 5 {m}
  -9.877425, 8.042275, 0;         !- X,Y,Z Vertex 6 {m}

BuildingSurface:Detailed,
  Surface 8,                      !- Name
  Wall,                           !- Surface Type
  ewalltype[], !- Construction Name
  ZONE ONE,                       !- Zone Name
  Outdoors,                       !- Outside Boundary Condition
  ,                               !- Outside Boundary Condition Object
  SunExposed,                     !- Sun Exposure
  WindExposed,                    !- Wind Exposure
  ,                               !- View Factor to Ground
  ,                               !- Number of Vertices
  -14.5589625, 6.79920332554044e-016, 2.4384, !- X,Y,Z Vertex 1 {m}
  -11.5494201284153, 8.62154569559298e-016, 1.54803013230878, !- X,Y,Z Vertex 2 {m}
  -11.5494201284153, 1.1683974610465e-015, 0.849530132308784, !- X,Y,Z Vertex 3 {m}
  3.4862092216728e-032, 5.04102853628999e-016, 0.542923755001249, !- X,Y,Z Vertex 4 {m}
  -2.26093695821812e-032, -3.26929538659796e-016, 2.4384; !- X,Y,Z Vertex 5 {m}

FenestrationSurface:Detailed,
  Sub Surface 10,                 !- Name
  Window,                         !- Surface Type
  GLAZING[], !- Construction Name
  Surface 8,                      !- Building Surface Name
  ,                               !- Outside Boundary Condition Object
  ,                               !- View Factor to Ground
  ,                               !- Shading Control Name
  @@frame_name@@,                 !-Frame & Divider Name
  ,                               !- Multiplier
  ,                               !- Number of Vertices
  -8.30408690149664, 0, 1.9754723854881,  !- X,Y,Z Vertex 1 {m}
  -8.30408690149664, 0, 1.1220323854881,  !- X,Y,Z Vertex 2 {m}
  -6.68864690149664, 0, 1.1220323854881,  !- X,Y,Z Vertex 3 {m}
  -6.68864690149664, 0, 1.9754723854881;  !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 11,                 !- Name
  Window,                         !- Surface Type
  GLAZING[], !- Construction Name
  Surface 8,                      !- Building Surface Name
  ,                               !- Outside Boundary Condition Object
  ,                               !- View Factor to Ground
  ,                               !- Shading Control Name
  @@frame_name@@,                 !-Frame & Divider Name
```

```
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  -2.82939706022455, 0, 1.95125409497799, !- X,Y,Z Vertex 1 {m}
  -2.82939706022455, 0, 0.996214094977989, !- X,Y,Z Vertex 2 {m}
  -0.80755706022455, 0, 0.996214094977989, !- X,Y,Z Vertex 3 {m}
  -0.80755706022455, 0, 1.95125409497799; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 12,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 8,                     !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  -5.86708347728594, 0, 1.95125409497799, !- X,Y,Z Vertex 1 {m}
  -5.86708347728594, 0, 1.14861409497799, !- X,Y,Z Vertex 2 {m}
  -4.60724347728595, 0, 1.14861409497799, !- X,Y,Z Vertex 3 {m}
  -4.60724347728595, 0, 1.95125409497799; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 14,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 8,                     !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  -11.1832501629187, 0, 1.96512898525169, !- X,Y,Z Vertex 1 {m}
  -11.1832501629187, 0, 1.11168898525169, !- X,Y,Z Vertex 2 {m}
  -9.56781016291872, 0, 1.11168898525169, !- X,Y,Z Vertex 3 {m}
  -9.56781016291872, 0, 1.96512898525169; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 9,                     !- Name
  Wall,                          !- Surface Type
  000 Interior Wall,             !- Construction Name
  ZONE ONE,                      !- Zone Name
  Surface,                       !- Outside Boundary Condition
  Surface 4,                     !- Outside Boundary Condition Object
  NoSun,                         !- Sun Exposure
  NoWind,                        !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  -14.5589625, 6.6929, 2.4384,   !- X,Y,Z Vertex 1 {m}
  -14.5589625, 6.6929, 1.2192,   !- X,Y,Z Vertex 2 {m}
  -14.5589625, 0, 1.2192,        !- X,Y,Z Vertex 3 {m}
  -14.5589625, 0, 2.4384;        !- X,Y,Z Vertex 4 {m}

InternalMass,
  Interior Partition Surface 2,  !- Name
  000 Interior Ceiling,          !- Construction Name
  ZONE ONE,                      !- Zone Name
  144.621419425938;              !- Surface Area {m2}

Zone,
  ZONE TWO,                      !- Name
  -0,                            !- Direction of Relative North {deg}
  12.5152214689445,              !- X Origin {m}
  11.4718441476066,              !- Y Origin {m}
  0,                             !- Z Origin {m}
  1,                             !- Type
  1,                             !- Multiplier
  ,                              !- Ceiling Height {m}
  0,                             !- Volume {m3}
  0;                             !- Floor Area {m2}
```

```
BuildingSurface:Detailed,
  Surface 1,                    !- Name
  Floor,                        !- Surface Type
  gfloor,  !- Construction Name
  ZONE TWO,                     !- Zone Name
  Ground,                       !- Outside Boundary Condition
  ,                             !- Outside Boundary Condition Object
  NoSun,                        !- Sun Exposure
  NoWind,                       !- Wind Exposure
  ,                             !- View Factor to Ground
  ,                             !- Number of Vertices
  2.8471653591789, 6.700153866826, 1.2192, !- X,Y,Z Vertex 1 {m}
  2.8471653591789, 0.00725386682600124, 1.2192, !- X,Y,Z Vertex 2 {m}
  -0.0166846408210963, 0.00725386682600124, 1.2192, !- X,Y,Z Vertex 3 {m}
  -0.0166846408210963, 6.700153866826, 1.2192; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 15,                   !- Name
  Floor,                        !- Surface Type
  gfloor,  !- Construction Name
  ZONE TWO,                     !- Zone Name
  Ground,                       !- Outside Boundary Condition
  ,                             !- Outside Boundary Condition Object
  NoSun,                        !- Sun Exposure
  NoWind,                       !- Wind Exposure
  ,                             !- View Factor to Ground
  ,                             !- Number of Vertices
  17.4061278591789, 10.886391366826, 1.2192, !- X,Y,Z Vertex 1 {m}
  17.4061278591789, 8.049528866826, 1.2192, !- X,Y,Z Vertex 2 {m}
  7.5287028591789, 8.049528866826, 1.2192, !- X,Y,Z Vertex 3 {m}
  7.5287028591789, 10.886391366826, 1.2192; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 16,                   !- Name
  Wall,                         !- Surface Type
  ewalltype[], !- Construction Name
  ZONE TWO,                     !- Zone Name
  Outdoors,                     !- Outside Boundary Condition
  ,                             !- Outside Boundary Condition Object
  SunExposed,                   !- Sun Exposure
  WindExposed,                  !- Wind Exposure
  ,                             !- View Factor to Ground
  ,                             !- Number of Vertices
  17.4061278591789, 8.049528866826, 2.4384, !- X,Y,Z Vertex 1 {m}
  17.4061278591789, 8.049528866826, 2.06881362617294, !- X,Y,Z Vertex 2 {m}
  17.4061278591789, 10.886391366826, 2.06881362617294, !- X,Y,Z Vertex 3 {m}
  17.4061278591789, 10.886391366826, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 17,                   !- Name
  Wall,                         !- Surface Type
  ewalltype[], !- Construction Name
  ZONE TWO,                     !- Zone Name
  Outdoors,                     !- Outside Boundary Condition
  ,                             !- Outside Boundary Condition Object
  SunExposed,                   !- Sun Exposure
  WindExposed,                  !- Wind Exposure
  ,                             !- View Factor to Ground
  ,                             !- Number of Vertices
  17.4061278591789, 10.886391366826, 2.4384, !- X,Y,Z Vertex 1 {m}
  17.4061278591789, 10.886391366826, 2.06881362617294, !- X,Y,Z Vertex 2 {m}
  12.9617983159158, 10.886391366826, 2.4384; !- X,Y,Z Vertex 3 {m}

BuildingSurface:Detailed,
  Surface 18,                   !- Name
  Wall,                         !- Surface Type
  000 Interior Wall,            !- Construction Name
  ZONE TWO,                     !- Zone Name
  Surface,                      !- Outside Boundary Condition
  Surface 12,                   !- Outside Boundary Condition Object
  NoSun,                        !- Sun Exposure
```

```
  NoWind,                  !- Wind Exposure
  ,                        !- View Factor to Ground
  ,                        !- Number of Vertices
  7.5287028591789, 8.049528866826, 2.4384, !- X,Y,Z Vertex 1 {m}
  7.5287028591789, 8.049528866826, 1.2192, !- X,Y,Z Vertex 2 {m}
  17.4061278591789, 8.049528866826, 1.2192, !- X,Y,Z Vertex 3 {m}
  17.4061278591789, 8.049528866826, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 19,              !- Name
  Wall,                    !- Surface Type
  BGICF,  !- Construction Name
  ZONE TWO,                !- Zone Name
  Ground,                  !- Outside Boundary Condition
  ,                        !- Outside Boundary Condition Object
  NoSun,                   !- Sun Exposure
  NoWind,                  !- Wind Exposure
  ,                        !- View Factor to Ground
  ,                        !- Number of Vertices
  7.5287028591789, 10.886391366826, 2.4384, !- X,Y,Z Vertex 1 {m}
  7.5287028591789, 10.886391366826, 1.2192, !- X,Y,Z Vertex 2 {m}
  7.5287028591789, 8.049528866826, 1.2192, !- X,Y,Z Vertex 3 {m}
  7.5287028591789, 8.049528866826, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 2,               !- Name
  Roof,                    !- Surface Type
  000 Interior Floor, !- Construction Name
  ZONE TWO,                !- Zone Name
  Surface,                 !- Outside Boundary Condition
  Surface 21,              !- Outside Boundary Condition Object
  NoSun,                   !- Sun Exposure
  NoWind,                  !- Wind Exposure
  ,                        !- View Factor to Ground
  ,                        !- Number of Vertices
  2.8471653591789, 0.00725386682600124, 2.4384, !- X,Y,Z Vertex 1 {m}
  2.8471653591789, 6.700153866826, 2.4384, !- X,Y,Z Vertex 2 {m}
  -0.0166846408210963, 6.700153866826, 2.4384, !- X,Y,Z Vertex 3 {m}
  -0.0166846408210963, 0.00725386682600124, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 20,              !- Name
  Roof,                    !- Surface Type
  000 Interior Floor, !- Construction Name
  ZONE TWO,                !- Zone Name
  Surface,                 !- Outside Boundary Condition
  Surface 55,              !- Outside Boundary Condition Object
  NoSun,                   !- Sun Exposure
  NoWind,                  !- Wind Exposure
  ,                        !- View Factor to Ground
  ,                        !- Number of Vertices
  17.4061278591789, 8.049528866826, 2.4384, !- X,Y,Z Vertex 1 {m}
  17.4061278591789, 10.886391366826, 2.4384, !- X,Y,Z Vertex 2 {m}
  7.5287028591789, 10.886391366826, 2.4384, !- X,Y,Z Vertex 3 {m}
  7.5287028591789, 8.049528866826, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 29,              !- Name
  Floor,                   !- Surface Type
  gfloor,  !- Construction Name
  ZONE TWO,                !- Zone Name
  Ground,                  !- Outside Boundary Condition
  ,                        !- Outside Boundary Condition Object
  NoSun,                   !- Sun Exposure
  NoWind,                  !- Wind Exposure
  ,                        !- View Factor to Ground
  ,                        !- Number of Vertices
  7.5287028591789, 11.988116366826, 2.4384, !- X,Y,Z Vertex 1 {m}
  7.5287028591789, 6.700153866826, 2.4384, !- X,Y,Z Vertex 2 {m}
  -0.0166846408211008, 6.700153866826, 2.4384, !- X,Y,Z Vertex 3 {m}
  -0.0166846408211008, 11.988116366826, 2.4384; !- X,Y,Z Vertex 4 {m}
```

```
BuildingSurface:Detailed,
  Surface 3,                !- Name
  Wall,                     !- Surface Type
  BGICF,  !- Construction Name
  ZONE TWO,                 !- Zone Name
  Ground,                   !- Outside Boundary Condition
  ,                         !- Outside Boundary Condition Object
  NoSun,                    !- Sun Exposure
  NoWind,                   !- Wind Exposure
  ,                         !- View Factor to Ground
  ,                         !- Number of Vertices
  2.8471653591789, 6.700153866826, 2.4384, !- X,Y,Z Vertex 1 {m}
  2.8471653591789, 6.700153866826, 1.2192, !- X,Y,Z Vertex 2 {m}
  -0.0166846408210963, 6.700153866826, 1.2192, !- X,Y,Z Vertex 3 {m}
  -0.0166846408210963, 6.700153866826, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 31,               !- Name
  Wall,                     !- Surface Type
  000 Interior Wall,        !- Construction Name
  ZONE TWO,                 !- Zone Name
  Surface,                  !- Outside Boundary Condition
  Surface 26,               !- Outside Boundary Condition Object
  NoSun,                    !- Sun Exposure
  NoWind,                   !- Wind Exposure
  ,                         !- View Factor to Ground
  ,                         !- Number of Vertices
  -0.0166846408211008, 6.700153866826, 5.1435, !- X,Y,Z Vertex 1 {m}
  -0.0166846408211008, 6.700153866826, 2.4384, !- X,Y,Z Vertex 2 {m}
  7.5287028591789, 6.700153866826, 2.4384, !- X,Y,Z Vertex 3 {m}
  7.5287028591789, 6.700153866826, 5.1435; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 32,               !- Name
  Wall,                     !- Surface Type
  000 Interior Wall,        !- Construction Name
  ZONE TWO,                 !- Zone Name
  Surface,                  !- Outside Boundary Condition
  Surface 24,               !- Outside Boundary Condition Object
  NoSun,                    !- Sun Exposure
  NoWind,                   !- Wind Exposure
  ,                         !- View Factor to Ground
  ,                         !- Number of Vertices
  7.5287028591789, 6.700153866826, 5.1435, !- X,Y,Z Vertex 1 {m}
  7.5287028591789, 6.700153866826, 2.4384, !- X,Y,Z Vertex 2 {m}
  7.5287028591789, 10.886391366826, 2.4384, !- X,Y,Z Vertex 3 {m}
  7.5287028591789, 10.886391366826, 5.1435; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 33,               !- Name
  Wall,                     !- Surface Type
  ewalltype[], !- Construction Name
  ZONE TWO,                 !- Zone Name
  Outdoors,                 !- Outside Boundary Condition
  ,                         !- Outside Boundary Condition Object
  SunExposed,               !- Sun Exposure
  WindExposed,              !- Wind Exposure
  ,                         !- View Factor to Ground
  ,                         !- Number of Vertices
  7.5287028591789, 11.988116366826, 5.1435, !- X,Y,Z Vertex 1 {m}
  7.5287028591789, 11.988116366826, 2.4384, !- X,Y,Z Vertex 2 {m}
  -0.0166846408211008, 11.988116366826, 2.4384, !- X,Y,Z Vertex 3 {m}
  -0.0166846408211008, 11.988116366826, 5.1435; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 19,           !- Name
  Window,                   !- Surface Type
  GLAZING[], !- Construction Name
  Surface 33,               !- Building Surface Name
  ,                         !- Outside Boundary Condition Object
  ,                         !- View Factor to Ground
  ,                         !- Shading Control Name
```

```
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  6.28120941448383, 11.988116366826, 4.66727607836736, !- X,Y,Z Vertex 1 {m}
  6.28120941448383, 11.988116366826, 3.75287607836736, !- X,Y,Z Vertex 2 {m}
  5.06200941448383, 11.988116366826, 3.75287607836736, !- X,Y,Z Vertex 3 {m}
  5.06200941448383, 11.988116366826, 4.66727607836736; !- X,Y,Z Vertex 4 {m}

FenestrationSurface:Detailed,
  Sub Surface 20,                !- Name
  Window,                        !- Surface Type
  GLAZING[], !- Construction Name
  Surface 33,                    !- Building Surface Name
  ,                              !- Outside Boundary Condition Object
  ,                              !- View Factor to Ground
  ,                              !- Shading Control Name
  @@frame_name@@,                !-Frame & Divider Name
  ,                              !- Multiplier
  ,                              !- Number of Vertices
  2.83564320615873, 11.988116366826, 4.69410277490345, !- X,Y,Z Vertex 1 {m}
  2.83564320615873, 11.988116366826, 3.77970277490345, !- X,Y,Z Vertex 2 {m}
  1.61644320615873, 11.988116366826, 3.77970277490345, !- X,Y,Z Vertex 3 {m}
  1.61644320615873, 11.988116366826, 4.69410277490345; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 34,                    !- Name
  Wall,                          !- Surface Type
  ewalltype[], !- Construction Name
  ZONE TWO,                      !- Zone Name
  Outdoors,                      !- Outside Boundary Condition
  ,                              !- Outside Boundary Condition Object
  SunExposed,                    !- Sun Exposure
  WindExposed,                   !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  -0.0166846408211008, 11.988116366826, 5.1435, !- X,Y,Z Vertex 1 {m}
  -0.0166846408211008, 11.988116366826, 2.4384, !- X,Y,Z Vertex 2 {m}
  -0.0166846408211008, 6.700153866826, 2.4384, !- X,Y,Z Vertex 3 {m}
  -0.0166846408211008, 6.700153866826, 5.1435; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 4,                     !- Name
  Wall,                          !- Surface Type
  000 Interior Wall,             !- Construction Name
  ZONE TWO,                      !- Zone Name
  Surface,                       !- Outside Boundary Condition
  Surface 9,                     !- Outside Boundary Condition Object
  NoSun,                         !- Sun Exposure
  NoWind,                        !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  2.8471653591789, 0.00725386682600124, 2.4384, !- X,Y,Z Vertex 1 {m}
  2.8471653591789, 0.00725386682600124, 1.2192, !- X,Y,Z Vertex 2 {m}
  2.8471653591789, 6.700153866826, 1.2192, !- X,Y,Z Vertex 3 {m}
  2.8471653591789, 6.700153866826, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 43,                    !- Name
  Wall,                          !- Surface Type
  000 Interior Wall,             !- Construction Name
  ZONE TWO,                      !- Zone Name
  Surface,                       !- Outside Boundary Condition
  Surface 40,                    !- Outside Boundary Condition Object
  NoSun,                         !- Sun Exposure
  NoWind,                        !- Wind Exposure
  ,                              !- View Factor to Ground
  ,                              !- Number of Vertices
  -0.0166846408211008, 6.009591366826, 9.1821, !- X,Y,Z Vertex 1 {m}
  -0.0166846408211008, 6.009591366826, 5.1435, !- X,Y,Z Vertex 2 {m}
  7.5287028591789, 6.009591366826, 5.1435, !- X,Y,Z Vertex 3 {m}
  7.5287028591789, 6.009591366826, 9.1821; !- X,Y,Z Vertex 4 {m}
```

```
BuildingSurface:Detailed,
  Surface 47,                        !- Name
  Wall,                              !- Surface Type
  ewalltype[], !- Construction Name
  ZONE TWO,                          !- Zone Name
  Outdoors,                          !- Outside Boundary Condition
  ,                                  !- Outside Boundary Condition Object
  SunExposed,                        !- Sun Exposure
  WindExposed,                       !- Wind Exposure
  ,                                  !- View Factor to Ground
  ,                                  !- Number of Vertices
  -0.0166846408211008, 6.009591366826, 9.1821, !- X,Y,Z Vertex 1 {m}
  -0.0166846408211008, 11.988116366826, 5.1435, !- X,Y,Z Vertex 2 {m}
  -0.0166846408211008, 6.009591366826, 5.1435; !- X,Y,Z Vertex 3 {m}

BuildingSurface:Detailed,
  Surface 5,                         !- Name
  Wall,                              !- Surface Type
  BGICF,  !- Construction Name
  ZONE TWO,                          !- Zone Name
  Ground,                            !- Outside Boundary Condition
  ,                                  !- Outside Boundary Condition Object
  SunExposed,                        !- Sun Exposure
  WindExposed,                       !- Wind Exposure
  ,                                  !- View Factor to Ground
  ,                                  !- Number of Vertices
  -0.0166846408210963, 6.700153866826, 2.4384, !- X,Y,Z Vertex 1 {m}
  -0.0166846408210963, 6.700153866826, 1.2192, !- X,Y,Z Vertex 2 {m}
  -0.0166846408210963, 0.00725386682600124, 1.2192, !- X,Y,Z Vertex 3 {m}
  -0.0166846408210963, 0.00725386682600124, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 50,                        !- Name
  Roof,                              !- Surface Type
  rooftype[], !- Construction Name
  ZONE TWO,                          !- Zone Name
  Outdoors,                          !- Outside Boundary Condition
  ,                                  !- Outside Boundary Condition Object
  SunExposed,                        !- Sun Exposure
  WindExposed,                       !- Wind Exposure
  ,                                  !- View Factor to Ground
  ,                                  !- Number of Vertices
  7.5287028591789, 6.009591366826, 9.1821, !- X,Y,Z Vertex 1 {m}
  7.5287028591789, 11.988116366826, 5.1435, !- X,Y,Z Vertex 2 {m}
  -0.0166846408211008, 11.988116366826, 5.1435, !- X,Y,Z Vertex 3 {m}
  -0.0166846408211008, 6.009591366826, 9.1821; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
  Surface 52,                        !- Name
  Wall,                              !- Surface Type
  ewalltype[], !- Construction Name
  ZONE TWO,                          !- Zone Name
  Outdoors,                          !- Outside Boundary Condition
  ,                                  !- Outside Boundary Condition Object
  SunExposed,                        !- Sun Exposure
  WindExposed,                       !- Wind Exposure
  ,                                  !- View Factor to Ground
  ,                                  !- Number of Vertices
  7.5287028591789, 10.886391366826, 5.88773483802443, !- X,Y,Z Vertex 1 {m}
  7.5287028591789, 10.886391366826, 5.1435, !- X,Y,Z Vertex 2 {m}
  7.5287028591789, 11.988116366826, 5.1435; !- X,Y,Z Vertex 3 {m}

BuildingSurface:Detailed,
  Surface 6,                         !- Name
  Wall,                              !- Surface Type
  BGICF,  !- Construction Name
  ZONE TWO,                          !- Zone Name
  Ground,                            !- Outside Boundary Condition
  ,                                  !- Outside Boundary Condition Object
  NoSun,                             !- Sun Exposure
  NoWind,                            !- Wind Exposure
  ,                                  !- View Factor to Ground
```

```
 ,                              !- Number of Vertices
 -0.0166846408210963, 0.00725386682600124, 2.4384, !- X,Y,Z Vertex 1 {m}
 -0.0166846408210963, 0.00725386682600124, 1.2192, !- X,Y,Z Vertex 2 {m}
 2.8471653591789, 0.00725386682600124, 1.2192, !- X,Y,Z Vertex 3 {m}
 2.8471653591789, 0.00725386682600124, 2.4384; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 60,                    !- Name
 Wall,                          !- Surface Type
 ewalltype[], !- Construction Name
 ZONE TWO,                      !- Zone Name
 Outdoors,                      !- Outside Boundary Condition
 ,                              !- Outside Boundary Condition Object
 SunExposed,                    !- Sun Exposure
 WindExposed,                   !- Wind Exposure
 ,                              !- View Factor to Ground
 ,                              !- Number of Vertices
 7.5287028591789, 10.886391366826, 5.1435, !- X,Y,Z Vertex 1 {m}
 7.5287028591789, 10.886391366826, 2.4384, !- X,Y,Z Vertex 2 {m}
 7.5287028591789, 11.988116366826, 2.4384, !- X,Y,Z Vertex 3 {m}
 7.5287028591789, 11.988116366826, 5.1435; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 61,                    !- Name
 Floor,                         !- Surface Type
 000 Interior Floor,            !- Construction Name
 ZONE TWO,                      !- Zone Name
 Surface,                       !- Outside Boundary Condition
 Surface 28,                    !- Outside Boundary Condition Object
 NoSun,                         !- Sun Exposure
 NoWind,                        !- Wind Exposure
 ,                              !- View Factor to Ground
 ,                              !- Number of Vertices
 7.5287028591789, 6.700153866826, 5.1435, !- X,Y,Z Vertex 1 {m}
 7.5287028591789, 6.009591366826, 5.1435, !- X,Y,Z Vertex 2 {m}
 -0.0166846408211008, 6.009591366826, 5.1435, !- X,Y,Z Vertex 3 {m}
 -0.0166846408211008, 6.700153866826, 5.1435; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 62,                    !- Name
 Wall,                          !- Surface Type
 000 Interior Wall,             !- Construction Name
 ZONE TWO,                      !- Zone Name
 Surface,                       !- Outside Boundary Condition
 Surface 53,                    !- Outside Boundary Condition Object
 NoSun,                         !- Sun Exposure
 NoWind,                        !- Wind Exposure
 ,                              !- View Factor to Ground
 ,                              !- Number of Vertices
 7.5287028591789, 6.009591366826, 9.1821, !- X,Y,Z Vertex 1 {m}
 7.5287028591789, 6.009591366826, 5.1435, !- X,Y,Z Vertex 2 {m}
 7.5287028591789, 10.886391366826, 5.1435, !- X,Y,Z Vertex 3 {m}
 7.5287028591789, 10.886391366826, 5.88773483802443; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 65,                    !- Name
 Wall,                          !- Surface Type
 BGICF,  !- Construction Name
 ZONE TWO,                      !- Zone Name
 Ground,                        !- Outside Boundary Condition
 ,                              !- Outside Boundary Condition Object
 NoSun,                         !- Sun Exposure
 NoWind,                        !- Wind Exposure
 ,                              !- View Factor to Ground
 ,                              !- Number of Vertices
 17.4061278591789, 8.049528866826, 2.06881362617294, !- X,Y,Z Vertex 1 {m}
 17.4061278591789, 8.049528866826, 1.2192, !- X,Y,Z Vertex 2 {m}
 17.4061278591789, 10.886391366826, 1.2192, !- X,Y,Z Vertex 3 {m}
 17.4061278591789, 10.886391366826, 2.06881362617294; !- X,Y,Z Vertex 4 {m}

BuildingSurface:Detailed,
 Surface 66,                    !- Name
```

```
  Wall,                                  !- Surface Type
  BGICF,  !- Construction Name
  ZONE TWO,                          !- Zone Name
  Ground,                              !- Outside Boundary Condition
  ,                                  !- Outside Boundary Condition Object
  NoSun,                               !- Sun Exposure
  WindExposed,                           !- Wind Exposure
  ,                                  !- View Factor to Ground
  ,                                  !- Number of Vertices
  12.9617983159158, 10.886391366826, 2.4384, !- X,Y,Z Vertex 1 {m}
  17.4061278591789, 10.886391366826, 2.06881362617294, !- X,Y,Z Vertex 2 {m}
  17.4061278591789, 10.886391366826, 1.2192, !- X,Y,Z Vertex 3 {m}
  7.5287028591789, 10.886391366826, 1.2192, !- X,Y,Z Vertex 4 {m}
  7.5287028591789, 10.886391366826, 2.4384; !- X,Y,Z Vertex 5 {m}

!-   ===========  ALL OBJECTS IN CLASS: HVAC SYSTEM===========

##include DesignDay.idf
##include HVAC_@@hvactype@@.imf

!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTIONS: PV System ===========

!##include PVSystem.imf

!-   ===========  ALL OBJECTS IN CLASS: SHADING DEVICES===========

!##include ShadingDevices.imf

!-   ===========  ALL OBJECTS IN CLASS: OTHEREQUIPMENT ===========

Lights,
            Lights, !- Name (Assuming recessed fluorescent lighting)
            ZONE ONE, !- Zone or ZoneList Name
            Lights, !- Schedule Name
            Watts/Area, !- Design Level Calculation Method
            ,! !- Lighting Level {W}
            1.0, !- Watts per Zone Floor Area {W/m2}
            , !- Watts per Person {W/person}
            0.0, !- Return Air Fraction
            1.0, !- Fraction Radiant 0.37
            0.0, !- Fraction Visible 0.18
            0, !- Fraction Replaceable
            GeneralLights; !- End-Use Subcategory

ElectricEquipment,
            Appliances, !- Name
            ZONE ONE, !- Zone or ZoneList Name
            On, !- Schedule Name
            Watts/Area, !- Design Level Calculation Method
            , !- Design Level {W}
            0.25, !- Watts per Zone Floor Area {W/m2}
            , !- Watts per Person {W/person}
            0.0, !- Fraction Latent
            0.0, !- Fraction Radiant
            0.0; !- Fraction Lost


!-   ===========  ALL OBJECTS IN CLASS: ZONEINFILTRATION:DESIGNFLOWRATE ===========

ZoneInfiltration:DesignFlowRate,
   ZoneInfil1,        !- Name
   ZONE ONE,               !- Zone or ZoneList Name
   On,                 !- Schedule Name
   AirChanges/Hour,         !- Design Flow Rate Calculation Method
   ,                    !- Design Flow Rate {m3/s}
   ,                    !- Flow per Zone Floor Area {m3/s-m2}
   ,                    !- Flow per Exterior Surface Area {m3/s-m2}
   @@ZoneInfiltration@@,                  !- Air Changes per Hour {1/hr}
   0.606,                  !- Constant Term Coefficient 0.606
   0.03636,                   !- Temperature Term Coefficient 0.03636
   0.1177,                  !- Velocity Term Coefficient 0.1177
   0.0;                  !- Velocity Squared Term Coefficient 0.0
```

```
ZoneInfiltration:DesignFlowRate,
    ZoneInfil2,         !- Name
    ZONE TWO,               !- Zone or ZoneList Name
    On,                  !- Schedule Name
    AirChanges/Hour,         !- Design Flow Rate Calculation Method
    ,                      !- Design Flow Rate {m3/s}
    ,                      !- Flow per Zone Floor Area {m3/s-m2}
    ,                      !- Flow per Exterior Surface Area {m3/s-m2}
    @@ZoneInfiltration@@,                  !- Air Changes per Hour {1/hr}
    0.606,                   !- Constant Term Coefficient
    0.03636,                   !- Temperature Term Coefficient
    0.1177,                  !- Velocity Term Coefficient
    0.0;                   !- Velocity Squared Term Coefficient

!-   ===========  ALL OBJECTS IN CLASS: EMS:Control Window Opening Schedule ===========


!EnergyManagementSystem:Sensor,
! ZoneTemp , ! Name
! ZONE ONE, ! Output:Variable or Output:Meter Index Key Name
! Zone Mean Air Temperature; ! Output:Variable or Output:Meter Name

!EnergyManagementSystem:Actuator,
! InfiltrationRate, ! Name
! ZoneInfil1, ! Component Name
! Zone Infiltration, ! Component Type
! Air Exchange Flow Rate; ! Control Type

!EnergyManagementSystem:ProgramCallingManager,
! Zone Infiltration Control, ! Name
! BeginTimestepBeforePredictor , ! EnergyPlus Model Calling Point
! Infiltration_Controller ; ! Program Name 1

!EnergyManagementSystem:Program,
! Infiltration_Controller , ! Name
! IF (ZoneTemp <= 23),
! SET InfiltrationRate = 0.2662 , ! - Assume 0.75 ACH when windows closed
! ELSEIF (ZoneTemp > 23) && (ZoneTemp < 27),
! SET InfiltrationRate = 1.0647 , ! - Assume 3 ACH when windows opened
! ELSEIF (ZoneTemp >= 27),
! SET InfiltrationRate = 1.0647 , ! - Assume 3 ACH when windows opened
! ENDIF;

!Output:EnergyManagementSystem,
! Verbose,
! Verbose,
! Verbose;



!-   ===========  ALL OBJECTS IN CLASS: PEOPLE ===========

People,
        ComfortMeasure, !- Name
        ZONE ONE, !- Zone or ZoneList Name
        On, !- Number of People Schedule Name
        People, !- Number of People Calculation Method
        4,,, !- Number of People, People per Zone Floor Area, Zone Floor Area per Person
        0.0, !- Fraction Radiant
        1.0, !- Sensible Heat Fraction
        Activity_Sch, !- Activity Level Schedule Name
        0, !- Carbon Dioxide Generation Rate {m3/s-W}
        No, !- Enable ASHRAE 55 Comfort Warnings
        ZoneAveraged, !- Mean Radiant Temperature Calculation Type
        , !- Surface Name/Angle Factor List Name
        WorkEff_Sch, !- Work Efficiency Schedule Name
        Clothing_Sch, !- Clothing Insulation Schedule Name
        AirVelocity_Sch, !- Air Velocity Schedule Name
        Fanger; !- Thermal Comfort Model 1 Type

!-   ===========  ALL OBJECTS IN CLASS: CURRENCYTYPE ===========
```

```
CurrencyType,
    CAD;                    !- Monetary Unit

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:VARIABLEDICTIONARY ===========

Output:VariableDictionary,
    IDF;                 !- Key Field

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:SURFACES:DRAWING ===========

Output:Surfaces:List, Details;

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:CONSTRUCTIONS ===========

Output:Constructions,
    Constructions,          !- Details Type 1
    Materials;              !- Details Type 2

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:TABLE:SUMMARYREPORTS ===========

Output:Table:SummaryReports,
    AllSummary;             !- Report 1 Name

!-   ===========  ALL OBJECTS IN CLASS: OUTPUTCONTROL:TABLE:STYLE ===========

OutputControl:Table:Style,
    Comma,                  !- Column Separator
    JtoKWH;                 !- Unit Conversion

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:VARIABLE ===========

Output:Variable,
    *,                      !- Key Value
    Time Not Comfortable Summer Or Winter Clothes Any Zone ,  !- Variable Name
    RunPeriod,              !- Reporting Frequency
    On;                     !- Schedule Name

Output:Variable,
    *,                      !- Key Value
    FangerPPD,  !- Variable Name
    RunPeriod,              !- Reporting Frequency
    On;                     !- Schedule Name

Output:Variable,
    *,                      !- Key Value
    Zone/Sys Sensible Heating Energy ,  !- Variable Name
    Daily,              !- Reporting Frequency
    On;                     !- Schedule Name

Output:Variable,
             *,
             Total Electric Energy Produced,
             Annual,
             On;

Output:Variable,
             *,
             PV Generator DC Energy,
             Annual,
             On;

Output:Variable,
             *,
             Zone Mean Air Temperature,
             Hourly,
             On;


!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:METER ===========

Output:Meter,Electricity:*,RunPeriod;
```

```
Output:Meter,Gas:*,RunPeriod;
Output:Meter,Carbon Equivalent:*,RunPeriod;
Output:Meter,ElectricityNet:*,RunPeriod;
Output:Meter,ElectricityPurchased:*,RunPeriod;

!-   ===========  ALL OBJECTS IN CLASS: Utility Cost ===========

UtilityCost:Tariff,
        ElectricityRate, ! Name
        ElectricityPurchased:Facility, ! Output Meter Name
        kWh, ! Conversion Factor Choice
        , ! Energy Conversion Factor
        , ! Demand Conversion Factor
        , ! Time of Use Period Schedule Name
        , ! Season Schedule Name
        , ! Month Schedule Name
        , ! Demand Window Length
        4.645; ! Monthly Charge or Variable Name

UtilityCost:Charge:Block,
        BlockEnergyCharge, ! Charge Variable Name
        ElectricityRate, ! Tariff Name
        totalEnergy, ! Source Variable
        Annual, ! Season
        EnergyCharges, ! Category Variable Name
        , ! Remaining Into Variable
        , ! Block Size Multiplier Value or Variable Name
        675, ! Block Size 1 Value or Variable Name
        0.0752, ! Block 1 Cost per Unit Value or Variable Name
        Remaining, ! Block Size 2 Value or Variable Name
        0.1132; ! Block 2 Cost per Unit Value or Variable Name

UtilityCost:Tariff,
        GasRate, ! Name
        Gas:Facility, ! Output Meter Name
        kWh, ! Conversion Factor Choice
        , ! Energy Conversion Factor
        , ! Demand Conversion Factor
        , ! Time of Use Period Schedule Name
        , ! Season Schedule Name
        , ! Month Schedule Name
        , ! Demand Window Length
        11.832; ! Monthly Charge or Variable Name

UtilityCost:Charge:Simple,
        FlatEnergyCharge, ! Charge Variable Name
        GasRate, ! Tariff Name
        totalEnergy, ! Source Variable
        Annual, ! Season
        EnergyCharges, ! Category Variable Name
        0.03597; ! Cost Per Unit Value or Variable Name

UtilityCost:Tariff,
        ElectricitySold, !- Name
        ElectricitySurplusSold:Facility, !- Output Meter Name
        kWh, !- Conversion Factor Choice
        , !- Energy Conversion Factor
        , !- Demand Conversion Factor
        , !- Time of Use Period Schedule Name
        , !- Season Schedule Name
        , !- Month Schedule Name
        , !- Demand Window Length
        , !- Monthly Charge or Variable Name
        , !- Minimum Monthly Charge or Variable Name
        , !- Real Time Pricing Charge Schedule Name
        , !- Customer Baseline Load Schedule Name
        , !- Group Name
        sellToUtility; !- Buy Or Sell

!UtilityCost:Charge:Simple,
!       SummerOnPeak, ! Charge Variable Name
!       ElectricitySold, ! Tariff Name
```

```
!		peakEnergy, ! Source Variable
!		Summer, ! Season
!		EnergyCharges, ! Category Variable Name
!		-0.17151; ! Cost per Unit Value or Variable Name

!UtilityCost:Charge:Simple,
!		SummerOffPeak, ! Charge Variable Name
!		ElectricitySold, ! Tariff Name
!		offPeakEnergy, ! Source Variable
!		Summer, ! Season
!		EnergyCharges, ! Category Variable Name
!		-0.05554; ! Cost per Unit Value or Variable Name

!UtilityCost:Charge:Simple,
!		WinterOnPeak, ! Charge Variable Name
!		ElectricitySold, ! Tariff Name
!		peakEnergy, ! Source Variable
!		Winter, ! Season
!		EnergyCharges, ! Category Variable Name
!		-0.17151; ! Cost per Unit Value or Variable Name

!UtilityCost:Charge:Simple,
!		WinterOffPeak, ! Charge Variable Name
!		ElectricitySold, ! Tariff Name
!		offPeakEnergy, ! Source Variable
!		Winter, ! Season
!		EnergyCharges, ! Category Variable Name
!		-0.05554; ! Cost per Unit Value or Variable Name


!-   ===========  ALL OBJECTS IN CLASS: ENVRIONMENTAL IMPACT FACTORS ===========

EnvironmentalImpactFactors, ! 100-Year GWP (IPCC 2000)
0.3, !- Disctrict Heating Efficiency
3.0, !- District Cooling COP
0.25, !- Steam Conversion Efficiency
298, !- Total CO2 Equivalent Emission Factor From NOx
25, !- Total CO2 Equivalent Emission Factor From CH4
1; !- Total CO2 Equivalent Emission Factor From CO2

!-   ===========  ALL OBJECTS IN CLASS: FUEL FACTORS ===========

FuelFactors, ! BC Ministry of Environment
		Electricity, !- Existing Fuel Resource Name
		kg, !- Units of Measure (kg or m3)
		, !- Energy per Unit Factor
		1, !- Source Energy Factor {J/J}
		, !- Source Energy Schedule Name
		6.9, !- CO2 Emission Factor {g/MJ}
		, !- CO2 Emission Factor Schedule Name
		0, !- CO Emission Factor {g/MJ}
		, !- CO Emission Factor Schedule Name
		0, !- CH4 Emission Factor {g/MJ}
		, !- CH4 Emission Factor Schedule Name
		0, !- NOx Emission Factor {g/MJ}
		, !- NOx Emission Factor Schedule Name
		0, !- N2O Emission Factor {g/MJ}
		, !- N2O Emission Factor Schedule Name
		0, !- SO2 Emission Factor {g/MJ}
		, !- SO2 Emission Factor Schedule Name
		0, !- PM Emission Factor {g/MJ}
		, !- PM Emission Factor Schedule Name
		0, !- PM10 Emission Factor {g/MJ}
		, !- PM10 Emission Factor Schedule Name
		0, !- PM2.5 Emission Factor {g/MJ}
		, !- PM2.5 Emission Factor Schedule Name
		0, !- NH3 Emission Factor {g/MJ}
		, !- NH3 Emission Factor Schedule Name
		0, !- NMVOC Emission Factor {g/MJ}
		, !- NMVOC Emission Factor Schedule Name
		0, !- Hg Emission Factor {g/MJ}
		, !- Hg Emission Factor Schedule Name
```

```
        0, !- Pb Emission Factor {g/MJ}
        , !- Pb Emission Factor Schedule Name
        0, !- Water Emission Factor {L/MJ}
        , !- Water Emission Factor Schedule Name
        0, !- Nuclear High Level Emission Factor {g/MJ}
        , !- Nuclear High Level Emission Factor Schedule Name
        0; !- Nuclear Low Level Emission Factor {m3/MJ}

FuelFactors, ! BC Ministry of Environment
        Natural Gas, !- Existing Fuel Resource Name
        m3, !- Units of Measure (kg or m3)
        , !- Energy per Unit Factor
        1, !- Source Energy Factor {J/J}
        , !- Source Energy Schedule Name
        49.86, !- CO2 Emission Factor {g/MJ}
        , !- CO2 Emission Factor Schedule Name
        0, !- CO Emission Factor {g/MJ}
        , !- CO Emission Factor Schedule Name
        0.0010, !- CH4 Emission Factor {g/MJ}
        , !- CH4 Emission Factor Schedule Name
        0.0009, !- NOx Emission Factor {g/MJ}
        , !- NOx Emission Factor Schedule Name
        0.0009, !- N2O Emission Factor {g/MJ}
        , !- N2O Emission Factor Schedule Name
        0, !- SO2 Emission Factor {g/MJ}
        , !- SO2 Emission Factor Schedule Name
        0, !- PM Emission Factor {g/MJ}
        , !- PM Emission Factor Schedule Name
        0, !- PM10 Emission Factor {g/MJ}
        , !- PM10 Emission Factor Schedule Name
        0, !- PM2.5 Emission Factor {g/MJ}
        , !- PM2.5 Emission Factor Schedule Name
        0, !- NH3 Emission Factor {g/MJ}
        , !- NH3 Emission Factor Schedule Name
        0, !- NMVOC Emission Factor {g/MJ}
        , !- NMVOC Emission Factor Schedule Name
        0, !- Hg Emission Factor {g/MJ}
        , !- Hg Emission Factor Schedule Name
        0, !- Pb Emission Factor {g/MJ}
        , !- Pb Emission Factor Schedule Name
        0, !- Water Emission Factor {L/MJ}
        , !- Water Emission Factor Schedule Name
        0, !- Nuclear High Level Emission Factor {g/MJ}
        , !- Nuclear High Level Emission Factor Schedule Name
        0; !- Nuclear Low Level Emission Factor {m3/MJ}
!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:ENVIRONMENTAL IMPACT FACTORS ===========
Output:EnvironmentalImpactFactors,
RunPeriod; !- Reporting_Frequency

!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:SQLITE ===========

Output:SQLite,
   SimpleAndTabular;        !- Option Type

Output:Diagnostics,DisplayExtraWarnings;
```

# Appendix O Harmony House Case Optimization Results

**Table O1 Optimization results for standard wall with standard roof Pareto solutions.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Stud Insulation | Ceiling Drywall | LCC ($) | LCGWP (kgCO2eq) | PPD (%) | Initial Cost ($) | Initial GWP (kqCO2eq) | Operational Cost ($) | Operational GWP (kgCO2eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 204552 | 76935 | 20 | 77443 | 43793 | 127109 | 33142 |
| 2 | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 221037 | 69484 | 20 | 94725 | 36545 | 126312 | 32939 |
| 3 | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 205201 | 76477 | 20 | 77517 | 43189 | 127684 | 33289 |
| 4 | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 210270 | 72470 | 20 | 84380 | 39639 | 125890 | 32831 |
| 5 | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 215393 | 71222 | 20 | 81042 | 36233 | 134351 | 34989 |
| 6 | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 221688 | 69027 | 20 | 94799 | 35941 | 126889 | 33086 |
| 7 | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 210921 | 72013 | 20 | 84454 | 39035 | 126467 | 32978 |
| 8 | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 235761 | 67326 | 20 | 106809 | 33714 | 128952 | 33612 |
| 9 | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 226531 | 68328 | 20 | 91397 | 33139 | 135134 | 35189 |
| 10 | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 218377 | 70465 | 20 | 83285 | 35286 | 135093 | 35178 |
| 11 | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 209277 | 75588 | 20 | 74094 | 40387 | 135184 | 35202 |
| 12 | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 216084 | 70774 | 20 | 81119 | 35628 | 134965 | 35146 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **13** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 229513 | 67570 | 20 | 93640 | 32192 | 135873 | 35377 |
| **14** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 16 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 214633 | 71735 | 20 | 81110 | 36958 | 133523 | 34778 |
| **15** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 16 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 215275 | 71683 | 19 | 81789 | 36915 | 133486 | 34768 |
| **16** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 209966 | 75140 | 19 | 74171 | 39782 | 135795 | 35357 |
| **17** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 227219 | 67879 | 19 | 91474 | 32535 | 135745 | 35345 |
| **18** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 224777 | 68681 | 19 | 90660 | 33751 | 134117 | 34929 |
| **19** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 207524 | 75941 | 19 | 73357 | 40999 | 134167 | 34942 |
| **20** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 16 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 209200 | 75652 | 19 | 74238 | 40507 | 134962 | 35145 |
| **21** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 16 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 226453 | 68392 | 19 | 91542 | 33260 | 134911 | 35132 |
| **22** | Stucco on Mesh (White), 1 in. | Softwood Plywood, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 238787 | 66740 | 19 | 102046 | 31141 | 136741 | 35599 |
| **23** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 236754 | 67100 | 19 | 100123 | 31529 | 136631 | 35571 |
| **24** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 234988 | 67450 | 19 | 99385 | 32142 | 135602 | 35308 |

**Table O2 Optimization results for standard wall with high-performance roof.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Exterior Insulation | Roof Stud Insulation | Ceiling Drywall | LCC | LCGWP | PPD | Initial Cost | Initial GWP | Operational Cost | Operational GWP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **25** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 207457 | 76230 | 20 | 79877 | 42968 | 127580 | 33262 |
| **26** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 223666 | 68669 | 20 | 96767 | 35581 | 126899 | 33089 |
| **27** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 207823 | 75661 | 20 | 79558 | 42224 | 128265 | 33437 |
| **28** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x8 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 213179 | 71766 | 20 | 86814 | 38814 | 126365 | 32952 |
| **29** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 224314 | 68212 | 20 | 96840 | 34976 | 127474 | 33235 |
| **30** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 213549 | 71198 | 20 | 86496 | 38070 | 127053 | 33128 |
| **31** | Stucco on Mesh (White), 1 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 235773 | 65809 | 20 | 106816 | 32195 | 128957 | 33613 |
| **32** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 232604 | 66334 | 20 | 103895 | 32784 | 128709 | 33550 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **33** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 221841 | 69321 | 20 | 93551 | 35877 | 128290 | 33443 |

**Table O3 Optimization results for double-stud wall with standard roof Pareto solutions.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Stud Insulation | Ceiling Drywall | LCC | LCGWP | PPD | Initial Cost | Initial GWP | Operational Cost | Operational GWP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 205850 | 77965 | 20 | 79372 | 44984 | 126478 | 32981 |
| **2** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 222333 | 70514 | 20 | 96653 | 37736 | 125679 | 32778 |
| **3** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 211565 | 73500 | 20 | 86309 | 40830 | 125256 | 32670 |
| **4** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 206375 | 77477 | 20 | 79442 | 44380 | 126933 | 33097 |
| **5** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 216668 | 72246 | 20 | 82971 | 37424 | 133697 | 34822 |
| **6** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 208397 | 77114 | 20 | 81366 | 43992 | 127031 | 33122 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **7** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 224881 | 69663 | 20 | 98648 | 36744 | 126233 | 32919 |
| **8** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 212092 | 73012 | 20 | 86379 | 40226 | 125713 | 32786 |
| **9** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 214113 | 72649 | 20 | 88303 | 39838 | 125810 | 32811 |
| **10** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 219518 | 71456 | 20 | 85210 | 36478 | 134308 | 34978 |
| **11** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 227808 | 69353 | 20 | 93326 | 34330 | 134482 | 35023 |
| **12** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 210838 | 76670 | 19 | 76266 | 41624 | 134573 | 35046 |
| **13** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 217219 | 71764 | 19 | 83044 | 36820 | 134175 | 34944 |
| **14** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Gypsum-Fiber Board (Ceiling), 0.5 in. | 230656 | 68562 | 19 | 95565 | 33384 | 135091 | 35178 |
| **15** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 228358 | 68870 | 19 | 93399 | 33726 | 134959 | 35144 |

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| **16** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 211105 | 76131 | 19 | 76095 | 40974 | 135010 | 35157 |

**Table O4 Optimization results for double-stud wall with high-performance roof.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Continuous Insulation | Roof Stud Insulation | Ceiling Drywall | LCC | LCGWP | PPD | Initial Cost | Initial GWP | Operational Cost | Operational GWP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **17** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 210701 | 76337 | 20 | 82604 | 42942 | 128097 | 33394 |
| **18** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 208478 | 77151 | 20 | 81413 | 44020 | 127065 | 33131 |
| **19** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 227191 | 68887 | 20 | 99886 | 35695 | 127305 | 33192 |
| **20** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 224965 | 69700 | 20 | 98695 | 36772 | 126270 | 32928 |
| **21** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Gypsum-Fiber Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 216426 | 71873 | 20 | 89542 | 38788 | 126884 | 33085 |
| **22** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 209002 | 76662 | 20 | 81484 | 43416 | 127518 | 33247 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Filled) | | | | | | | | | | | |
| **23** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 212119 | 76125 | 20 | 84402 | 42827 | 127717 | 33297 |
| **24** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 214199 | 72686 | 20 | 88351 | 39866 | 125848 | 32821 |
| **25** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 225490 | 69212 | 20 | 98766 | 36168 | 126724 | 33044 |
| **26** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 228607 | 68674 | 20 | 101684 | 35580 | 126922 | 33095 |
| **27** | Vinyl Siding, 0.048 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 217840 | 71660 | 20 | 91340 | 38673 | 126501 | 32987 |
| **28** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 214724 | 72198 | 20 | 88421 | 39262 | 126303 | 32937 |
| **29** | Stucco on Mesh (White), 1 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 236810 | 66774 | 20 | 108741 | 33387 | 128069 | 33387 |
| **30** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 233658 | 67303 | 20 | 105820 | 33975 | 127838 | 33328 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Filled) | | | | | | | | | | | |
| **31** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 222894 | 70290 | 20 | 95476 | 37069 | 127418 | 33221 |

**Table O5 Optimization results for EIFS wall with standard roof Pareto solutions.**

| ID | Exterior Cladding | Sheathing | Wall Drywall | Wall Continuous Insulation | Wall Stud Insulation | Window Frame | Glazing Type | Roofing Type | Roof Stud Insulation | Ceiling Drywall | LCC | LCGWP | PPD | Initial Cost | Initial GWP | Operational Cost | Operational GWP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 205507 | 76841 | 20 | 78137 | 43632 | 127370 | 33209 |
| **2** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 211228 | 72377 | 20 | 85074 | 39478 | 126154 | 32899 |
| **3** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 222677 | 68942 | 20 | 95492 | 35780 | 127184 | 33161 |
| **4** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 211911 | 71928 | 20 | 85148 | 38874 | 126763 | 33054 |
| **5** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 203746 | 78455 | 20 | 77353 | 45495 | 126392 | 32959 |
| **6** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 209462 | 73989 | 20 | 84291 | 41341 | 125171 | 32648 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **7** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 204199 | 77949 | 20 | 77420 | 44891 | 126779 | 33058 |
| **8** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x12 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 209917 | 73484 | 20 | 84357 | 40737 | 125560 | 32747 |
| **9** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Isocyanurate, 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 236092 | 66162 | 19 | 98340 | 30306 | 137752 | 35856 |

**Table O6 Optimization results for EIFS wall with high-performance roof.**

| **ID** | **Exterior Cladding** | **Sheathing** | **Wall Drywall** | **Wall Continuous Insulation** | **Wall Stud Insulation** | **Window Frame** | **Glazing Type** | **Roofing Type** | **Roof Continuous Insulation** | **Roof Stud Insulation** | **Ceiling Drywall** | **LCC** | **LCGWP** | **PPD** | **Initial Cost** | **Initial GWP** | **Operational Cost** | **Operational GWP** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **10** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 207628 | 75832 | 20 | n/a | n/a | n/a | n/a |
| **11** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 2 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 209074 | 75241 | 20 | n/a | n/a | n/a | n/a |
| **12** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 205383 | 76602 | 20 | n/a | n/a | n/a | n/a |
| **13** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 224117 | 68382 | 20 | 97250 | 35302 | 126868 | 33081 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **14** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 208122 | 75337 | 20 | 80036 | 41945 | 128086 | 33391 |
| **15** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 213352 | 71369 | 20 | 86905 | 38396 | 126447 | 32973 |
| **16** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 221872 | 69152 | 20 | 95100 | 36096 | 126772 | 33056 |
| **17** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 2 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 225566 | 67791 | 20 | 98017 | 34537 | 127549 | 33254 |
| **18** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 224612 | 67887 | 20 | 97318 | 34698 | 127294 | 33189 |
| **19** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 205835 | 76096 | 20 | 77885 | 42740 | 127950 | 33357 |
| **20** | Fiber Cement Siding, 0.3125 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 211106 | 72139 | 20 | 84755 | 39190 | 126351 | 32949 |
| **21** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 2 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 214801 | 70778 | 20 | 87672 | 37631 | 127128 | 33147 |
| **22** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. | Vinyl Clad Wood Core | Double Glazed Low-E Coating | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. | Regular Gypsum Board (Ceiling), | 222325 | 68646 | 20 | 95167 | 35492 | 127158 | 33155 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.5 in. | | Framing | | (Argon Filled) | | | Framing | 0.5 in. | | | | | | | |
| **23** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x6 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 213847 | 70873 | 20 | 86974 | 37791 | 126873 | 33082 |
| **24** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Isocyanurate, 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 234540 | 66086 | 20 | 104805 | 32275 | 129735 | 33812 |
| **25** | Stucco on Mesh (White), 1 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Isocyanurate, 0.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 237754 | 65572 | 20 | 107728 | 31686 | 130025 | 33886 |
| **26** | Vinyl Siding, 0.048 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 211559 | 71633 | 20 | 84822 | 38586 | 126737 | 33047 |
| **27** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 233674 | 66269 | 20 | 104590 | 32623 | 129084 | 33646 |
| **28** | Stucco on Mesh (White), 1 in. | Softwood Plywood, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Spray Polyurethane Foam (Closed Cell), 1 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 236882 | 65753 | 20 | 107513 | 32035 | 129369 | 33718 |
| **29** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Vinyl Clad Wood Core | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 231491 | 67777 | 20 | 103800 | 34486 | 127691 | 33291 |
| **30** | Stucco on Mesh (White), 1 in. | OSB, 0.5 in. | Regular Gypsum Board (Wall), 0.5 in. | Mineral Wool, 3.5 in. | Blown Cell 2x4 24 in. o.c. Framing | Solid Wood | Double Glazed Low-E Coating (Argon Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 220726 | 70764 | 20 | 93455 | 37580 | 127271 | 33183 |

**Table O7 Optimization results for ICF wall with high-performance roof.**

| ID | Exterior Cladding | Wall Drywall | ICF Type | Window Frame | Glazing Type | Roofing Type | Roof Continuous Insulation | Roof Stud Insulation | Roof Drywall | LCC | LCGWP | PPD | Initial Cost | Initial GWP | Operational Cost | Operational GWP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **7** | Residential 30 ga. Steel Siding, 0.016 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 218753 | 92679 | 20 | 92320 | 59710 | 126433 | 32970 |
| **8** | Stucco on Mesh (White), 1 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 246624 | 77959 | 20 | 117410 | 44280 | 129214 | 33679 |
| **9** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 225377 | 82104 | 20 | 98354 | 48984 | 127023 | 33120 |
| **10** | Vinyl Siding, 0.048 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 219867 | 86004 | 20 | 91471 | 52533 | 128396 | 33470 |
| **11** | Vinyl Siding, 0.048 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 226073 | 81659 | 20 | 98424 | 48379 | 127649 | 33280 |
| **12** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 219179 | 86450 | 20 | 91402 | 53138 | 127777 | 33313 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **13** | Fiber Cement Siding, 0.3125 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Vinyl Clad Wood Core | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 236437 | 79191 | 20 | 108706 | 45890 | 127731 | 33301 |
| **15** | Stucco on Mesh (White), 1 in. | Regular Gypsum Board (Wall), 0.5 in. | Insulated Concrete Forms (2 in. EPS Foam Shell), 6 in. Concrete Core | Solid Wood | Double Glazed No Coating (Air Filled) | Asphalt Roof Shingles, 0.125 in. | Isocyanurate, 0.5 in. | Blown Cell 2x6 24 in. o.c. Framing | Regular Gypsum Board (Ceiling), 0.5 in. | 235585 | 80877 | 19 | 107060 | 47374 | 128525 | 33503 |

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