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Performance assessment of innovative framing systems through building information modeling based energy simulation

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PERFORMANCE ASSESSMENT OF INNOVATIVE FRAMING SYSTEMS THROUGH BUILDING INFORMATION MODELING BASED ENERGY SIMULATION

A Thesis

Submitted to Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Industrial Engineering

in

The Department of Construction Management and Industrial Engineering

By
Santhosh Reddy Chinnayeluka
B.E, Osmania University, India, 2008
August 2011

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ABSTRACT

While many residential contractors, architects, and home-buyers today are concerned about the environment and interested in sustainable construction technologies, the perceived higher initial costs of innovative materials and methodologies and a lack of life-cycle cost and performance data present significant barriers in the implementation of such techniques. Research regarding an integrated design process has suggested that performance based decision making is key to the successful implementation of sustainable building practices. Therefore, a need exists for the development of whole building design and evaluation models to allow decision making in all phases of a building project.

This research seeks information regarding residential framing systems and the corresponding expected energy performance, as well as to present a case-study utilizing the integration of building information modeling and energy simulation. The primary goals of this research are 1) assess the ability of BIM integrated energy simulation modeling to accurately predict the energy performance of a building and 2) compare the predicted energy performance for four different residential framing systems through the integration of BIM, energy simulation and performance monitoring. These research goals will be accomplished through a case-study approach utilizing the Louisiana State University Agricultural Center's showcase home, known as the LaHouse, which serves as a display of sustainable construction materials and technologies. This research focuses on the integration of design software Autodesk® Revit Architecture with energy simulation modeling. Models based on the LaHouse were created in Autodesk® Revit Architecture and will be used to simulate the energy utilization of four different framing systems: insulated concrete forms, structural insulated panels, advanced framing and standard framing, all

of which were used in the construction of LaHouse. The energy utilization obtained by the performance monitoring systems installed in the LaHouse Garage will be compared with simulation results.

CHAPTER 1: INTRODUCTION

Sustainable construction is an increasingly relevant topic for the United States residential construction industry. Concerns about natural disasters, global warming, energy supply and demand, and the environmental impacts of construction are driving forces in the development and implementation of innovative building materials and techniques. However, limited information is available to enable decision making for optimal integration of these technologies. While many residential contractors, architects, and home-buyers today are concerned about the environment and interested in sustainable construction technologies, the perceived higher initial costs of innovative materials and methodologies and a lack of life-cycle cost and performance data present significant barriers in the implementation of such techniques. The most common homebuilding technology used in the U.S. is site build wood frame construction. However, innovative building systems exist and offer significant advantages over conventional construction techniques. These advantages include such things as energy efficiency, reduced material wastes, increased productivity, and compression of the construction schedule. While the innovative building systems offer significant benefits to both the residential contractor and the potential homeowner, acceptance and implementation of these methods have not increased despite increased availability and rising interest in sustainable construction. The data from the U.S. Census bureau shown in Figure 1 illustrates that there has not been a significant increase in implementation of these methods over the past 15 years. Therefore, a need exists for the development of whole building design and evaluation models to allow decision making in all phases of a building project, including pre-design, design, construction, operation and maintenance, and retirement.

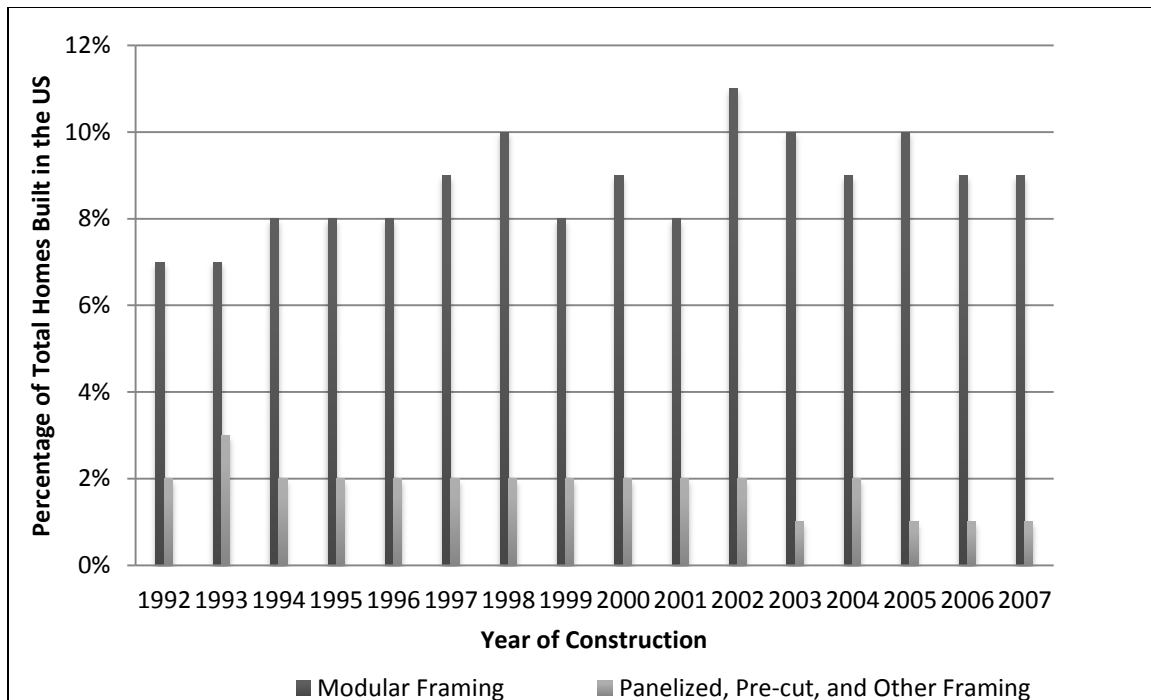


Figure 1: Percentage of single family homes in the U.S by framing method (Bureau 2008)

Agencies such as the U.S. Green Building Council and the Environmental Protection Agency have developed standards and rating systems that provide guidelines to support contractors and prospective owners and developers in the implementation of sustainable technologies, and the National Association of Home Builders (NAHB) recently unveiled a residential green building rating system known as the NAHB Nation Green Building Program. In addition, the National Science and Technology Council (NSTC) recently released a report entitled “Federal Research and Development Agenda for Net-Zero Energy, High-Performance Green Building” that outlines specific goals and focus areas for future research needed to achieve significant improvements in energy efficiency and resource sustainability in construction. One important focus area included in the report is the need for an integrated design approach to building construction and the development of practical tools and processes to address the complex interactions of building components and systems throughout the building life cycle (NSTC 2008). Much of the recent research regarding an integrated design process has suggested

that performance based decision making is key to the successful implementation of sustainable building practices (Hitchcock 2002; Deru and Torcellini 2004; Fischer 2006; Utzinger and Bradley 2009).

The performance based building approach establishes explicit, performance based procedures during all phases of the building process and replaces traditional, prescriptive provisions with performance requirements (Becker 2008). The established performance goals developed during the initial design phase serve to guide key decisions during the life of the building concerning material selection, building design, and system operation and maintenance. Performance monitoring during the operations and maintenance phase of the building provide feedback on whether the established performance goals are being met through the use of performance metrics. Performance based building, as defined by the International Council for Building (CIB), refers to “computational procedures and/or computer programs that can be used in developing quantitative performance criteria for building codes and standards, designing a building to a target performance, or evaluating a given design (or product) for each level in the building performance hierarchy (from the whole building to individual elements or materials)” (Foliente and Becker 2001).

While there are significant benefits associated with moving from the traditional, prescriptive and/or code compliant building approach to a performance based approach, it is well accepted that the performance based approach is more complex and demanding to implement (Becker 2008). The development of integrated design models and performance based building can be enhanced and facilitated through the use of building information modeling (BIM) and simulation tools for optimizing the design and operation of a building (NSTC 2008). BIM is a technology that allows the coupling of descriptive and performance characteristics of building

components and processes with a 3D representation of a project. BIM also provides the ability to include building-specific information for a wide variety of building components and system (Ho and Matta 2009). Assembling building components and associated information within a BIM framework enables the generation of design and construction alternatives with accompanying quantitative and qualitative predictions about the performance of each alternative. Building performance monitoring provides necessary feedback, information necessary for decision makers to assess both the long and short term performance and environmental consequences of a design, operational, and/or maintenance decision (Morrissey, O'Donnell et al. 2004). Figure 2 is an illustration of how a BIM model can be integrated with the design and energy simulation process.

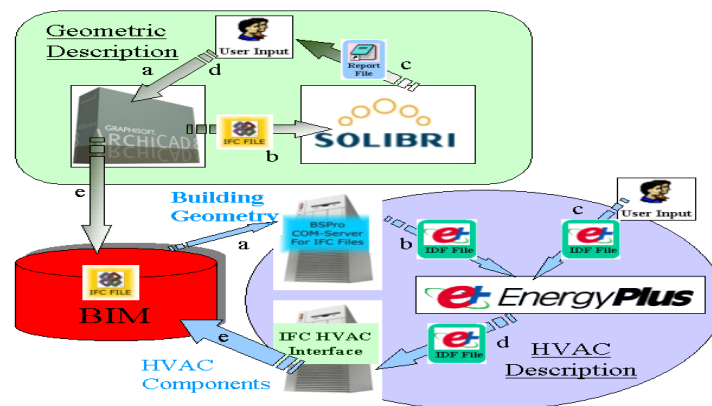


Figure 2: Instantiating the BIM (Morrissey, O'Donnell et al. 2004)

1.1 Research Goals and Objectives

The primary goals of this research are 1) assess the ability of BIM integrated energy simulation modeling to accurately predict the energy performance of a building and 2) compare the predicted energy performance for four different residential framing systems through the integration of building information modeling, energy simulation and performance monitoring. These research goals will be accomplished through a case study approach utilizing the Louisiana

State University Agricultural Center's showcase home, known as the LaHouse Home and Landscape Resource Center, which serves as a display of sustainable construction materials and technologies. In order to achieve the aforementioned goals, the following research objectives are identified.

- Develop an as-built building information model of LaHouse and separate building information models of the LaHouse garage for each of the four different framing systems.
- Conduct energy simulation modeling based on the as-built BIM utilizing EnergyPlus, Autodesk® Ecotect Analysis, and Integrated Environmental Solutions (IES VE-Pro) and compare simulation results with actual performance data. Results will also be compared with standard benchmark models set by Department of Energy.
- Utilize BIM models of the LaHouse garage and energy simulation results to determine energy performance and energy cost savings for each of the framing systems.

CHAPTER 2 LITERATURE REVIEW

Simulating the building energy and its performance is called energy simulation. Energy simulation of a building involves analysis of the actual or predicted energy performance of buildings (Zixiang Cong 2009). Comparison between actual or predicted energy performances of the building energy can be done with the help of simulation. Architects and engineers must use energy simulation software to calculate the complex energy of buildings. The complex nature of energy flow paths in a building is illustrated in the following diagram (Clarke, 2001).

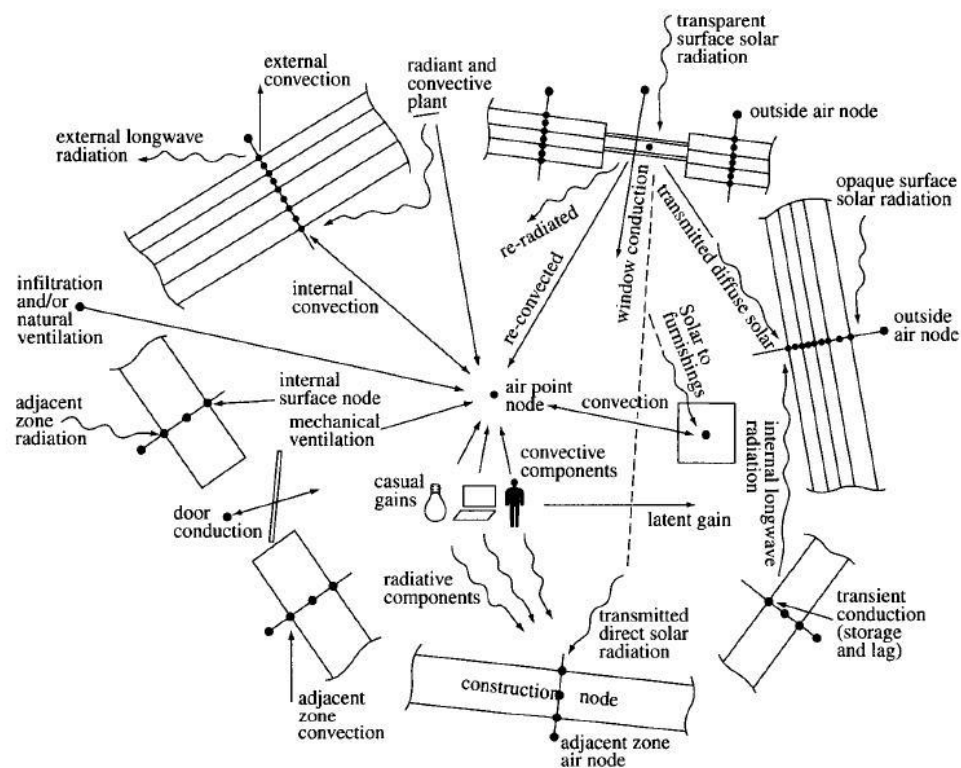


Figure 3: Building Energy Flow paths (Clarke 2001)

Over the past 50 years, a variety of building energy simulation tools have been developed including BLAST, DOE 2.1, BSim, EnergyPlus, EQuest, and Autodesk® Ecotect Analysis.

Such energy simulation tools have been available for utilization by the construction industry since the 1970s. The Building Load Analysis and System Thermodynamics (BLAST) program was developed by the U.S. Army Construction Engineering Research Laboratory (USA CERL) and the University of Illinois (Drury B. Crawley July 2005). BLAST analyses the energy performance of new or retrofit buildings. The 3 main features of BLAST are Space loads Prediction, Air System Simulation and Central Plant. In addition to those features, BLAST calculates the annual energy reports. Since 1998, no new versions have been released for the BLAST program (Drury B. Crawley July 2005). DOE-2 software was developed by James J. Hirsch & Associates (JJH) in collaboration with Lawrence Berkeley National Laboratory (LBNL), with funding from the United States Department of Energy (USDOE) (Ham 2008) and is suitable for both building design studies and for developing building standards. DOE 2.1 predicts the hourly energy usage of a building with provided weather data. DOE 2.1 didn't support all interfaces and was later released as DOE 2.2 in the year 1994. The new capabilities of DOE-2.2 can provide accurate and flexible simulation of window, lighting, and HVAC systems, and will allow integration with interactive user interfaces (Ham 2008). After DOE-2 and BLAST simulation tools, the most advanced tool developed by the Department of Energy is EnergyPlus. EnergyPlus is a tool used for energy simulation, load calculations, and building performance.

Energy simulation of a building is used to examine the energy performance of a building and can lead to energy conservation methods. Due to climate change and awareness of energy consumption, designers have to consider the life cycle performance of the building. Currently, thermal performances of the buildings are typically calculated after the construction or design stage. According to Laine, "Energy tools are still used by the researchers, but not widely used by

the practitioners in building projects”(Laine, Hänninen et al. 2007). The reasons for this situation are steep learning curves and huge data requirements for analysis. The current design process does not effectively support life cycle energy analysis since energy-related decisions are often made during the “conceptual” phases of the project. During the conceptual design phase, a practitioner doesn’t always have sufficient data for detailed energy analysis. Another reason is the cost barrier. For a small residential home with a limited budget, building designers do not embrace energy analysis (P. Jacobs 2002). Building information modeling and building automation are new technologies that support the application of life cycle energy analysis during the design phase of a project. BIM enabled energy simulation tools allow energy analysis to be completed prior to construction which helps in the decision making process. Despite the multitude of tools available, research and case studies are needed to determine the accuracy of such tools in comparison to actual performance data.

2.1 Factors That Impact Energy Performance of a Building

According to (Ramesh, Prakash et al. 2010) life cycle energy depends on the operating (80-90%) and embodied (10-20%) energy of the buildings. The effective usage of embodied energy during the manufacturing phase will significantly decrease the operating energy. A study done by Lam and Hui explains that energy consumption and design loads are sensitive to the operating energy including the temperature set point, window systems, HVAC system and building envelope (Lam and Hui 1996). Data was collected by Lindberg (2004) for 5 years on six identical test buildings having exterior walls made up of different materials. The data includes indoor–outdoor temperatures; indoor–outdoors relative humidity, wind speed and direction; air tightness, infiltration, heating energy, and horizontal global solar radiation. Approximately 520 sensors in each test building were fixed for the data collection. Data loggers were used to monitor, integrate

and calculate the data. Lindberg found that the thermal performance of walls is influenced by the heat capacity of the wall materials as well as their thermal conductivity. A proper selection of thermal mass in the building envelope can be an efficient way of reducing building's heating and cooling energy loads (Lindberg, Binamu et al. 2004). Thermal mass is the storage material present in the outer envelope of the building. It is typically contained in the walls, ceilings, floors etc. in the form of concrete, bricks, wood etc. with high heat absorbing capacity to reduce air temperature and cooling load peaks. The thermal mass stores heat energy in the material and transfer heat in the later times in the day, thus reduces the energy consumption by 20% (Azhar 2008). The factors affecting the thermal mass are material properties, thermal mass location and distribution, ventilation, occupancy and insulation (Azhar 2008).

The building envelope separates the exterior of the building from the interior, and is designed by the architects with regard to climate, ventilation and energy consumption. The building envelope is made up of several exterior components including walls, roofs, foundations, doors and windows. The building envelope is constructed in two ways: tight envelope and loose envelope. A tight envelope restricts the air flow from interior to exterior and vice versa whereas loose envelopes allow the air to flow more freely from the exterior to interior spaces. Construction of the tight envelope should be done precisely by the contractors to allow relatively few air leaks. A tightly designed envelope will allow more control over indoor air temperature, humidity level and energy consumption for a comfortable living environment. The loose envelope allows natural air flow from outside to the interior for better indoor air quality; but at the same time, these buildings will have little or no control over the humidity level and temperature level which can lead to higher energy bills. Due to the moisture presence in the open

envelope, the building components easily gets mold and its lifetime performance is reduced (Turner 09 September 2010).

Material types and their properties play a major role in exterior wall energy performance. Regions with greater variation in their daily temperature should adopt more thermal mass in their wall structure. The thermal mass in exterior walls has a significant effect on the heating and cooling loads (Asan, et. al, 2005). The exterior walls and their material configuration play a major role in stabilizing the inside temperature and can significantly affect the annual thermal performance of the whole building. Kossecka and Kosny analyzed the effect of mass and insulation location on heating and cooling loads for a one story residential building with various wall configurations (Kossecka and Kosny 2002). Their study utilized DOE 2.1 for energy analysis for the whole building and simulations were run for 6 different U.S. climates. Kossecka recommended that the best thermal performance is obtained when massive material layers are located at the inner side and directly exposed to the interior space (Kossecka and Kosny 2002). According to Kossecka, the total energy difference between the insulation does outside to the insulation does inside may exceed 11%.

Nelson Fumo introduced a simple methodology to estimate the energy consumption from monthly utility bills of a building by applying the fixed coefficients from the EnergyPlus Benchmark Model simulations (Fumo, Mago et al. 2010). Commercial building Benchmark Models for new construction were developed by Department of Energy's Building Technologies Program, working with the Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, and National Renewable Energy Laboratory (Community 2008). These benchmark models include 16 commercial buildings in 16 different U.S climatic zones. "EnergyPlus weather data is available for more than 1042 locations in the USA, 71 locations in Canada, and

more than 1000 locations in 100 other countries throughout the world” (Fumo, Mago et al. 2010). The developed benchmark models act as standard buildings for comparison, and these benchmark models “will form the basis for research on specific building technologies, energy code development, appliance standards, and measurement of progress toward the DOE energy goals” (Demchak 2008). Fumo et al, 2010 compared the example building with the benchmark model buildings and proposed a new method to generate normalized energy profiles to estimate hourly energy consumption from monthly utility bills. According to Fumo, simulation software requires a significant amount of time, experience and effort to enter detailed simulation. So, a series of predetermined coefficients obtained from EnergyPlus benchmark models were applied in the study. Fumo expressed that “detailed building simulations will not represent exact energy consumption profile, there is an accepted degree of uncertainty in the estimated energy demands in order to make a conclusion” (Fumo, Mago et al. 2010). A normalized energy use index (NEUI) based on a temperature function (reference) has also been proposed(Papa 2007). In their report, temperature was found to be the most important factor in energy consumption because the equipment consumption for daily use was always the same due to no significant change in their daily scheduled work except for the HVAC system cooling loads. EnergyPlus was used as a simulation tool to obtain the temperature function to compute the NEUI (Chuck Eastman 2008). One comparison study between the conventional wood frame systems and insulated concrete walls observed that the internal temperature changes more slowly and steadily in thermal walls (ICF) than the conventional wood frame type. By taking heat flux into account, insulated concrete walls have the ability to store heat in daytime and deliver it at night, resulting in lower energy consumption (Zhu, Hurt et al. 2009).

2.2 BIM and Energy Simulation

The construction industry spends millions of dollars in building systems every year. Errors while constructing a building can cause huge loss to contractors and builders. It is necessary and cheaper to create a replica of the building (3D model) and test alternative options to construct an efficient building (Crawley 2008). For thousands of years, architect and engineers used hand drawn models of a building. Architects implemented their vision of a building on paper and tried to explain the design of building to builders and clients using various views of the building. During the past decades, architects upgraded to the use of two dimensional CAD, and 2D drawings generated by CAD technology have been standard since 1982. AutoCAD with 3D modeling techniques and integration of other software into the 3D modeling laid a foundation for BIM. BIM is not just a 3D model of a building, but it also provides descriptive information about building components including costs, specifications, quantities, and expected performance data. BIM also facilitates construction scheduling and updating, as well as life cycle assessment.

Why do we need BIM? BIM improves the design process and transfers the information from the architects to every project participant in a single database without information loss. This tool provides the necessary information for project participants to eliminate data loss, miscommunication and errors. BIM can retrieve any parameter in the information provided by the user. BIM provides not only the shape of the building (thickness, walls, doors) but also can store information regarding the material used for walls, its physical properties, and technical specifications. For example, the walls used in a project vary when considering interior compared to exterior walls. One difference between the CAD system and BIM is that CAD uses many 2D drawings to explain the model, whereas BIM can explain the model in a single drawing page. CAD systems cannot store the information related to building, but it just projects the visual

model of the building. The BIM has a capability to store the related information of the building by integrating various tools available with BIM software.

The energy simulation models, through the implementation of BIM, will help the AEC industry in the decision making process of choosing energy conservation products and evaluating the energy systems operating in a building. For example, the case study building utilized in this research, LaHouse, is constructed with the energy efficient components. The performance of this resource efficient building should be analyzed to determine if the components installed are actually performing as designed in regards to energy consumption. For future buildings, lifecycle costs, utility bills, energy performance should be calculated with the help of energy simulation. A need exists for the integration of BIM and energy simulation for successful implementation of sustainable construction. A replica of a building (3D model) is not sufficient for simulating the building energy usage. Additional information such as, type of insulation, windows installed and their material type, foundation type, walls and their material, HVAC load, occupancy data, and environmental weather files, are required for simulation. The weather data file contains climatic conditions including humidity, wind speed, and temperature throughout the year. The geometry of a building in a 3D model and in an energy simulation engine is the same but representation of the geometry is different. In an energy simulation engine, the walls of a structure are shown as a line that represents the thermal values associated with the wall properties. Another input data for energy simulation is HVAC systems. Estimating the HVAC system energy is a challenging task in energy simulation. A proper operating schedule of HVAC systems and occupancy data are key inputs for the simulation. Weather data is another important data set that must be included in the simulation model. Similarly the internal loads like occupancy data, lighting load, should be

added to the model. For unavailable data, proper assumptions should be made about the internal loads in a given zones within the building (Tarabieh 2007).

2.3 Simulation Tools

Previous research compared the simulation tools Autodesk® Ecotect Analysis, EnergyPlus, and NEN2916 with the same input data and weather conditions on a typical building and concluded that for any simulation process, the data integrity, expert level, and assumptions play a pivotal role in obtaining successful results (Tarabieh 2007). The simulation results from each of the tools were compared with the metered data and the results indicated that Autodesk® Ecotect Analysis was the closest to the metered data at 21% below the metered data, while NEN2916 and EnergyPlus results were lower than the metered data by 55% and 31%. Final recommendations were that the selection of tools depends on the level of analysis and accuracy requirements, and EnergyPlus was recommended when high precision results are required (Tarabieh 2007). The general data input for the simulation engine is shown in Figure 4.

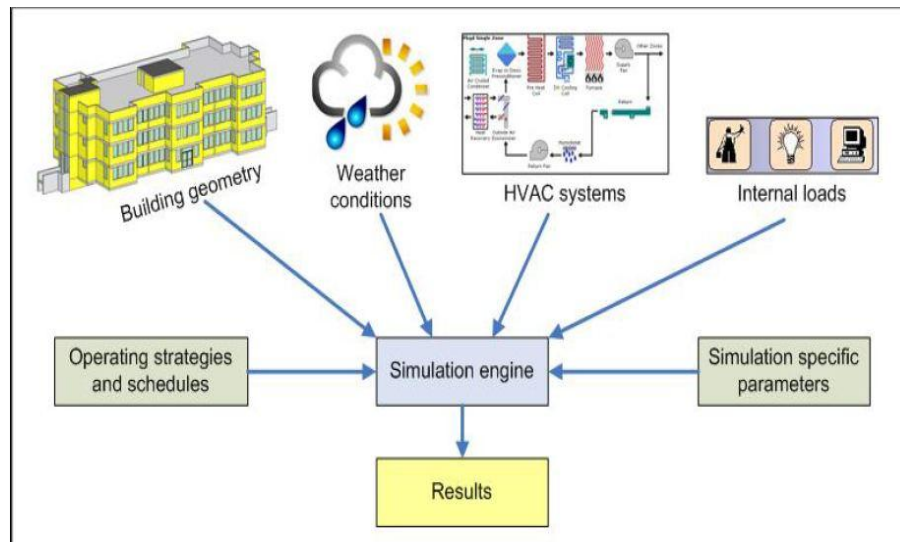


Figure 4: General data flow of Simulation Engine (Maile, Fischer et al. 2007)

By utilizing BIM as a source for energy analysis, the input data will be more efficient and reusable (Laine, Karola et al. 2007). Building geometry, loads, air conditioning system and lighting system are imported as input data and other inputs like HVAC, weather, and schedules are defined in their respected simulation software user interfaces. Limitations may apply to every simulation tool. Thermal analysis is complex and not fully understood even today, and energy simulation programs are approximated with qualified equations and methods to satisfy the actual data. If assumptions are not satisfied in the simulation, results can be arbitrarily incorrect (Maile, Fischer et al. 2007). The selection of simulation tools or implementation is entirely different for every condition, climate or building type. Each simulation tool has its own uncertainty levels based on the load calculation method. To reduce uncertainty between the tools, the operator should use the same model in each tool (Marsh and Al-Oraier 2005).

In research comparing roof and wall properties, three different wall and roof material types were used in an energy simulation model. However, the three models showed no detectable differences in the results, so the average values of material properties of wall and roof were used in his study. The results of the research concluded that internal gains and ventilation rates have effect on both temperature and space loads and insulation type and external surface treatments have a smaller effect (Marsh and Al-Oraier 2005). Two simulation tools, IES and LEA, were compared by changing the material properties of the walls, roofs and floors in each model and the uncertainty between the two tools was calculated. Conclusions indicated that a change in the material properties including wall thickness, conductivity, absorptance, and conductivity, causes uncertainty in annual energy demand for heating/cooling and peak heating/cooling loads between the simulation tools IES and LEA (Struck, Kotek et al. 2007). Previous studies mentioned that innovative framing types are more efficient than the conventional wood framing but few

comparison studies using energy simulation tools are available. No other study has compared these four types of wall framing performance by using energy simulation tools.

In one study, building performance was simulated using three different simulation methods, TS 825(static), CIBSE Admittance, and ASHRAE Heat Balance method. It was determined that ASHRAE Heat Balance method was the most accurate method when compared with the measured data (Yaman 2009). In this study, comparison between Autodesk® Ecotect Analysis and EnergyPlus was selected to compare CIBSE with ASHRAE calculation methods. Yaman (2009) compared the characteristics of Autodesk® Ecotect Analysis and EnergyPlus calculation methods. The following table provides the capabilities between the three software tools which are used in the present study.

Table 1. Characteristics of Three Simulation Tools

Software	Autodesk® Ecotect Analysis (CIBSE Admittance method)	EnergyPlus (ASHRAE's Heat Balance method)	IES VE-Pro (Both CIBSE and ASHRAE)
Time step	Daily and hourly	Hourly	Daily and hourly
Zoning	Multi-zone	Multi-zone	Multi-zone
Heating regime	Intermittent or continuous	Intermittent or continuous	Both types
Heating set point temp	Optional	Optional	Optional
Cooling calculation	Simple dynamic	Detailed dynamic	Dynamic
Internal gains	Daily + hourly values	Hourly	Sensible heat supplied by equipment, lights, people and other heat sources (Hourly)
Outside conditions	Local meteorological data can be implemented	Local meteorological data can be implemented	Only zonal data will be implemented. EX: South eastern part of US

(Table 1 Continued...)

HVAC equipment	Only efficiency of equipment is included	Heating type (radiant, convective or both), pump and fan consumptions are included.	HVAC, heat pump, boilers load, fan consumption are included.
Thermal mass	Included	Included	Included
Thermal bridging	Not included	Included	Included
Surface temperatures	Average surface temperature	Each surface treated differently	N/A
Natural ventilation and infiltration	User defined air change rate	Natural ventilation can be calculated from buoyancy and pressure difference	User defined and latent heat gain calculation

Yaman (2009)

Previous research included a comparison of three simulation engine types, TS 825, CIBSE Admittance method and ASHRAE's Heat Balance method (Yaman 2009). The present study extends the previous research by adding the IES VE-Pro which is comprised of both the CIBSE Admittance and ASHRAE's Heat Balance method.

CHAPTER 3: METHODOLOGY

The primary goals of this research are 1) assess the ability of BIM integrated energy simulation modeling to accurately predict the energy performance of a building and 2) compare the predicted energy performance for four different residential framing systems through the integration of building information modeling, energy simulation and performance monitoring. This research goal will be accomplished through a case study approach utilizing the Louisiana State University Agricultural Center's showcase home, known as the LaHouse Home and Landscape Resource Center, which serves as a display of sustainable construction materials and technologies. Figure 4 on the next page illustrates the methodology that will be utilized for this research.

3.1 Case Study Description

The proposed methodology is applied to a case study LaHouse-Home and Landscape Resource Center situated at LSU Baton Rouge. LaHouse, a partial two-story building, is a property of the LSU Agricultural Center with 3000 square foot living area. LaHouse is used as a showcase home and serves as a display of sustainable construction materials and technologies for people who want to know about high performance sustainable buildings. LaHouse has four high performance building framing systems: Structured Insulated Panels (SIPS), Insulated Concrete forms (ICF), OVE/Advanced Framing and Standard Framing. LaHouse focuses on five sustainability factors: Resource Efficient, Durable, Healthy, Convenient, and Practical. LaHouse is constructed with different framings for different areas. The living room walls are framed with 2x4, 16" o.c. treated timber strand LSL studs and sills, the east wing with SIPS framing, the west wing with advanced framing, and the garage with ICF. A description of each of these framing methods is provided in the following sections.

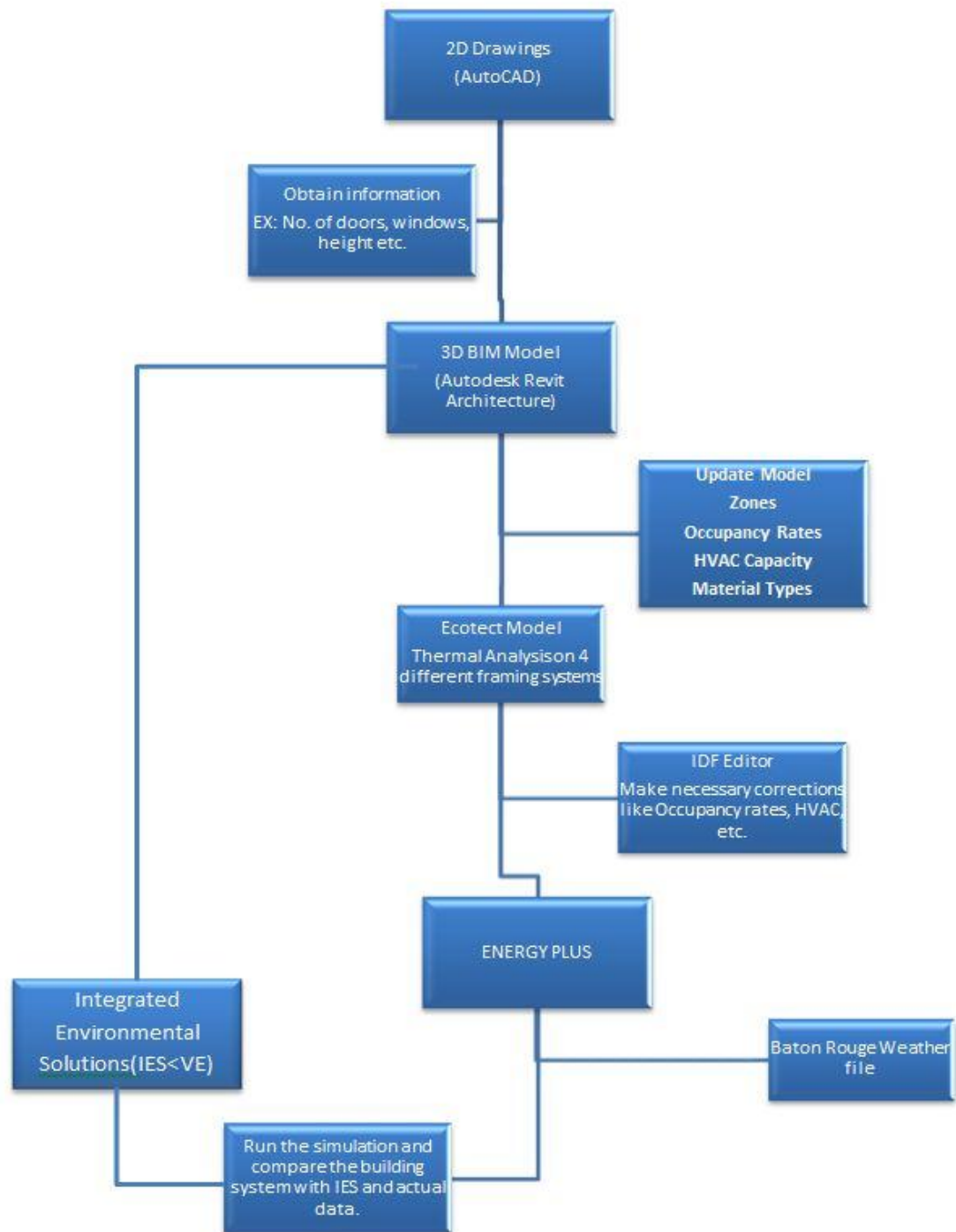


Figure 4: Methodology Overview

3.1.1 Advanced Framing

Advanced Framing, also known as Optimum Value Engineering (OVE), is a framing approach that uses lumber layout and usage techniques that minimize the amount of lumber used to construct a house without compromising its structural integrity.

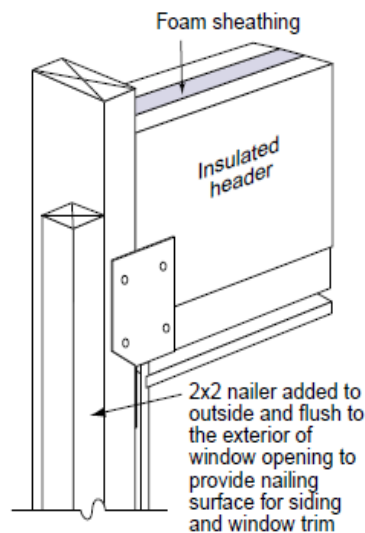


Figure 5: Example of Advanced Framing Techniques (U.S. Department of Energy; NAHB 2009)

Advanced framing also maximizes the exterior wall cavity available for insulation installation, creating a more energy-efficient building envelope. Advanced framing was developed by the National Home Builders Association (NAHB) Research Center in the early 1970s. Published benefits of this technique include lower material and labor costs, improved energy efficiency, improved resource efficiency, reduced waste, increased comfort due to more consistent room temperature, and reduced drywall cracking. Barriers to implementation of this framing method include training requirements for contractors and skilled trades; design implications for built-in furnishings and external elements, such as siding, that may require attachment on studs spaced 16" o.c. rather than the wider spacing (24" o.c.) utilized in OVE; and buyer acceptance of this method (Pease July 2006).

3.1.2 Panelized Wall Systems

Panelized Wall Systems consist of prefabricated or factory-manufactured panels that form a structural envelope. This type of system has become the homebuilding technology of choice for a number of large production builders, aiming to reduce their construction cycle time and improving the building's energy performance. Typically, the panels will arrive at the site as prefabricated wall, floor, and ceiling assemblies that workers erect and join. Similar to conventional homebuilding, all electrical, plumbing and code inspections are completed on site. Published benefits include reduced on-site construction time and reduced labor costs, increased product consistency, improved energy efficiency, increased soundproofing, resistance to natural disasters, moisture, and rodent/insect infestation, and decreased noise pollution.



Figure 6: Factory-Produced wooden wall

Potential drawbacks include higher initial costs, which can vary based on the panel type; amount of customization needed, site proximity to a manufacturing plant, code acceptance, and increased design and engineering costs.

3.1.3 Structural Insulated Panel System (SIPS)

Structural Insulated Panels (SIPS) are high performance building panels used in homebuilding as floors, walls, and roofs components. The panels are typically made by sandwiching a core of rigid foam plastic insulation between two structural skins of oriented strand board (OSB) or other



Figure 7: LaHouse framed with OSB Structural Insulated Panel

materials. This technology has existed for over 50 years, but has experienced rapid growth in the past five years, due mainly to utilization in Europe. In the U.S, however, SIPS made up only 0.5% of the building market in 2005 (Mullens and Arif 2006). Driving forces that encourage the use of SIPS technology include increasing global skilled labor shortages, recent research dedicated to hurricane-resistant materials, and the movement towards sustainability. However, high uncertainties in costs, schedule, labor productivity, quality, safety, possible benefits, and waste involved in the implementation of SIPS is believed to have discouraged its growth rate (Mullens and Arif 2006).

3.1.4 Insulated Concrete Forms

Insulated Concrete Forms (ICF) are rigid plastic foam forms that hold concrete in place during curing and remain in place afterwards to serve as thermal insulation for concrete walls. ICF with its innovative design meet all installation requirements without gaps and voids. The foam

sections are lightweight and result in energy-efficient, durable construction. Potential benefits include increased energy efficiency, reduced construction durations, ease of implementation, and high wind and seismic resistance. Potential drawbacks include higher initial construction costs, retraining requirements for contractors and skilled labor, moisture protection, termite protection, fire resistance provisions, and differing methods of attachment for interfacing materials. The following figure shows the ICF construction at LaHouse.



Figure 8: Insulated Concrete Form Construction at LaHouse

ToolBase.org is the home building industry's technical information resource provided by National Association of Home Builders (NAHB) resource center. The performance characteristics provided by the Tool Base for innovative framing methods are shown in Table 2.

Table 2. Framing Types and Benefits

Benefit	SIPS	ICF	Advanced	Standard
Energy Efficiency	48% more with standard	Increased insulation and reduced air infiltration	Reduces no. of studs, improve insulation and lower energy costs	Baseline
Environmental Performance	Reduction in use of lumbar	Slag waste is recycled	Reduces landfill waste	Baseline
Safety and comfort	Sound insulation	Resist fire, wind and earthquakes		
Durability	High wind resistance	Resist decay	May not be suitable for high winds	

(Table 2 Continued...)

Affordability	Additional construction costs, changes are costly	Higher costs than standard	Reduces lumbar cost	Baseline
Remodeling	Requires service design professional	Changes are costly and require special tools to cut through concrete walls		
Initial Cost	More expensive	More Expensive	Initial cost may high but later decreases the energy costs	Baseline
Operational Cost	Lower than stick built homes	Typically lower than light frame wood	Reduces the energy use of a home	Baseline
Fire Resistance	2X			Baseline
R value	24- 47	20-25	14-20	14-19
Strength	20-30% stronger			Baseline
Indoor Air Quality	Healthier			Baseline
Labor Costs	55% labor savings			Baseline
Insulation Type		Polystyrene		Fiberglass
Air Leakage		Near zero, 0.09 air change / hour		High, 0.35 air change /hour
Heating / Cooling Cost per 1500 Sq. Foot		\$240/ year		\$820/year
Framing Factor		Polystyrene		Fiberglass
Life Expectancy		200+ years		80-85 years

(http://www.toolbase.org)

3.2 Develop an as-built Building Information Model of LaHouse and Separate Building Information Models of the LaHouse Garage for Each of the Four Different Framing Systems

3.2.1 Develop the Model from 2D CAD Drawings into as-built BIM Model

The BIM software used in this research for designing the 3D model is Autodesk® Revit Architecture. Software interoperability is the ability to exchange data between two programs. Generally, it's a file format which supports both the programs. Revit imports the .dwg interoperability file which is the 2D file. Information such as height of the walls, door types, window specifications, roof type, and floor type should be collected before the conversion into the 3D model. Revit enables one to access, manage and update data very quickly with ease along

with controlling visibility, graphics and reporting based on that data. The Autodesk® Revit Architecture database has standard wall framing systems for building a model. The innovative framing systems used in this research can be updated in the Autodesk® Revit Architecture model in two ways:

- **Creating in-place Families:** These are custom families that are unique to the current project. Custom families can be created as a .rfa file according to the required specifications.
- **Standard Component Families:** These families are standard files used in the building design. Geometry and size of the family is user defined, and the family can be saved as an .rfa file and loaded it into a project. The element properties of the family can be changed from the standard walls to the required innovative material properties. There are many templates to create different families.

In this study, the first method is utilized to create the innovative framings. After creating the user defined family (.rfa), the standard walls are replaced by the innovative wall framing methods.

3.2.2 Develop Different BIM Models for LaHouse Garage

After creating the LaHouse model in Autodesk® Revit Architecture, the exterior walls are replaced with innovative wall framings. LaHouse was constructed with different framings for different areas of the building. The living room walls are framed with 2x4, 16” o.c. treated timber strand LSL studs and sills, the east wing with SIPS framing, the west wing with advanced framing, and the garage with ICF. All framing types except ICF falls under one zone and cannot be easily divided into different zones for simulation and comparison to actual measurements. Inaccurate results will be obtained if the simulation is run on different framings that fall under the same zone. Moreover, there is no performance monitoring energy collecting equipment in

any zone except the garage portion of the building. For better and accurate energy analysis, only the LaHouse garage was taken into account, as it represents one zone with a single framing method. The LaHouse garage was constructed with ICF framing and a BIM model was created for the ICF framing type. The BIM models for the different framing types were developed by changing the wall type and properties and keeping all other objects the same.

3.3 Conduct Energy Simulation Modeling Based on the as-built BIM Utilizing EnergyPlus, Autodesk® Ecotect Analysis, and Integrated Environmental Solutions (IES VE-Pro) and Compare Simulation Results with Actual Performance Data

For the detailed energy simulation, all the information regarding the wall frame, including R value, U value, emissivity, transmittance, roughness, solar absorption is needed. Autodesk® Ecotect Analysis has been utilized as a medium for inputting this thermal information. After developing the 3D model, Revit can export the model into different output formats including DWG, DXF, gbXML, and IFC file formats. Energy analysis tools are generally used after the design process. It's a time consuming process to recreate the building model in the energy analysis program. The interoperability files between the BIM design software's and energy analysis software makes the work easier. The models can be directly exported to these programs and need not be created from scratch. Interoperability file formats such as gbXML, DXF, and dwg files can be directly exported and imported via software such as Autodesk® Revit Architecture, Autodesk® Ecotect Analysis, and other energy analysis programs. The 3D Revit model is exported into the gbXML file which is an input file to energy simulation tools like Autodesk® Ecotect Analysis and IES VE-Pro. The material properties of the innovative wall frames are updated in the Autodesk® Ecotect Analysis software and exported via interoperable IDF file into the EnergyPlus simulation engine. The software's EnergyPlus and Integrated

Environmental Solutions (IES VE-Pro) will be utilized for the building energy simulations for each of the models.

3.3.1 Export the Model from Revit to Autodesk® Ecotect Analysis

The BIM model created in Revit can be exported to DXF, gbXML file formats, which are input for the Autodesk® Ecotect Analysis program. Energy analysis on different framings was done on the LaHouse garage. The methodology used in this research is to customize the wall properties for the different framing systems in Autodesk® Ecotect Analysis.

Autodesk® Ecotect Analysis's database (interface) is comprised of 3D design, visualization, performance analysis, and simulation functions. The primary capabilities of Autodesk® Ecotect Analysis include thermal analysis, energy analysis, lighting analysis and solar access analysis. In the Autodesk® Ecotect Analysis model, the whole building system can be separated with the help of zones. Zonal types is a sub-tool used in the Autodesk® Ecotect Analysis model to minimize the inaccuracies occurred by using a larger space. With the help of zonal types, the interior rooms of a building can be divided into different zones. Architect and designers can design a building model before the preconstruction phase and can run a detailed energy analysis to calculate the potential effectiveness of the building. Optimization use of solar, light and wind resources can be accomplished by making changes in the model and updating the model until the final design appears. Autodesk® Ecotect Analysis uses the Chartered Institute of Building Services Engineers (CIBSE) Admittance Method to calculate the internal temperatures and heat loads. In the CIBSE admittance method, load calculations and temperature are two separate processes. After knowing the detailed hourly temperatures, a second calculation is performed to determine the absolute heating and cooling loads. The LaHouse Garage model built in Autodesk® Ecotect Analysis is shown in Figure 9.

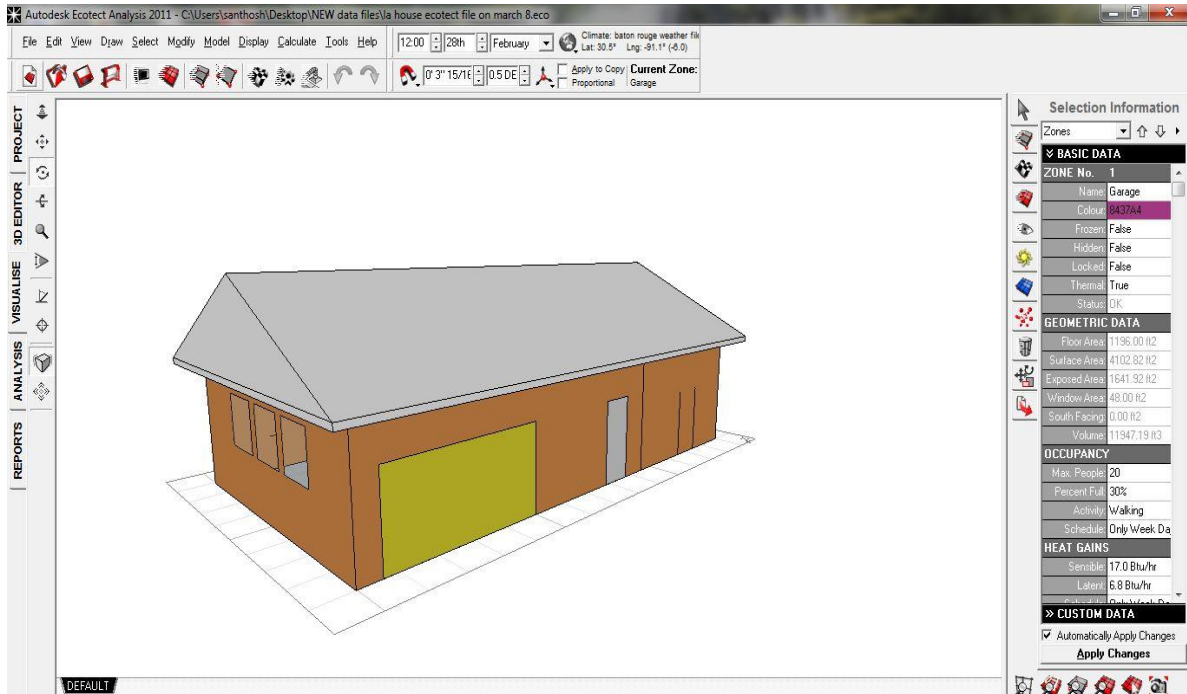


Figure 9: LaHouse Garage in Autodesk® Ecotect Analysis

3.3.2 Export Model from Autodesk® Ecotect Analysis to EnergyPlus

EnergyPlus is a simulation engine which has the previous capabilities of DOE 2.1 and Blast software's (Zixiang Cong 2009). EnergyPlus calculations are based on ASHRAE's preferred heat balanced based approach (Strand et al. 2001). EnergyPlus can accept text files for both input and output. It was launched in the year 2001 and has become the most commonly used simulation tool. EnergyPlus can calculate the heating, cooling, electrical system loads with a variable time step. Figure 10 illustrates the EnergyPlus simulation software launch. It requires two input files for the simulation. They are supported IDF files (which contain all the thermal information of the building) and weather files. The EnergyPlus simulation will run in the MS DOS background. The results can be viewed in four different formats. EnergyPlus has the capability to export the simulation results via text file, drawing file, spreadsheet format and html files. Autodesk® Ecotect Analysis can model the building and has the capability to export the

information directly into an IDF file. Autodesk® Ecotect Analysis has the capability to model any complex building shape with few simple modeling rules and can shape into an IDF description. The use of Autodesk® Ecotect Analysis vastly accelerates and simplifies the generation of EnergyPlus analysis. The IDF file includes customizable material and construction information as well as an operational schedule for the working IDF file.

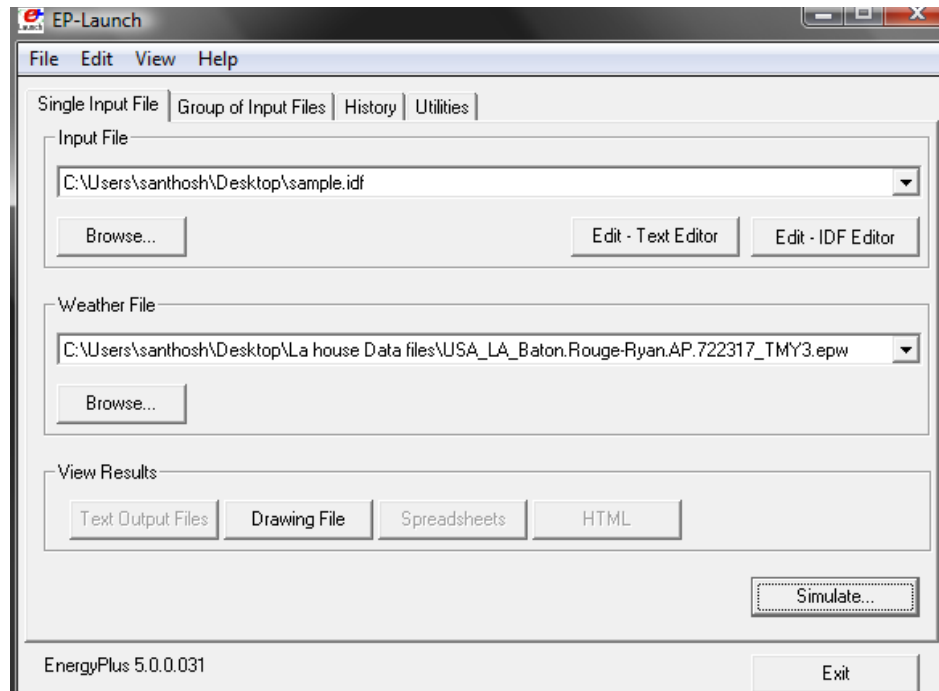


Figure 10: EnergyPlus Launch

3.3.3 Export Model from Revit into Integrated Environmental Solutions (IES VE-Pro)

The IES VE-Pro energy analysis software tool offers high accuracy and interoperability with BIM tools. Integrated Environment Solutions is a software system for integrated building performance analysis, providing tools for thermal analysis, value engineering, cost planning, lifecycle analysis, airflow analysis, lighting, and occupant safety, in one unified system (Khemlani 2006). IES VE-Pro has the capability to store the thermal information about the building. The 3D geometry can be imported straight from CAD or BIM packages using gbXML. IES VE-Pro calculates the heat gain calculations and cooling load calculations for a selected

design day of the week, and for a range of design months. IES VE-Pro includes thermal, solar, lighting, energy costs, heating/cooling load calculations. The value /cost analysis function in IES VE-Pro assess the life cycle costs. Previous research concluded that IES VE- Pro is a better tool for performance analysis when compared with Green Building Simulation and Autodesk® Ecotect Analysis tools (Azhar 2008).

IES VE-Pro is a project oriented system. In IES VE-Pro, thermal applications fall into three main groups (Helpdesk):.

- **Virtual Environment Compliance Checks:** This is used to test compliance with UK building regulations.
- **Industry Standard Thermal Calculations:** CIBSE heat loss/ gain calculation and ASHRAE heating /cooling loads calculation.
- **Dynamic Simulation:** Building dynamic thermal simulation (Apache Sim), Natural Ventilation Simulation. and HVAC system simulation (Apache HVAC) (Helpdesk)

The material properties of the construction components can be edited using the program's Apache construction database manager (APCDB). The IES VE-pro is an integrated suite of applications linked by a Common User Interface (CUI) and a single integrated data model (IDM). This means that all the applications have a consistent “look and feel” and that data input for one application can be used by the others (IES VE-Pro Helpdesk). The present study extends previous research by adding the IES VE-Pro which is comprised of both the simulation engines CIBSE Admittance and ASHRAE's Heat Balance method. Industry standard thermal ASHRAE calculations results were taken into account in this study.

3.3.4 Performance Monitoring System in LaHouse Garage

The performance monitoring system installed in the LaHouse Garage to collect energy consumption data is TED 1001 (<http://www.theenergydetective.com>). TED (The Energy Detective) is used to collect the real time data of home energy usage. Ted will accurately measure the electricity consumption with less than 2% difference to make you aware of energy usage. The TED 1001 energy detective is used to collect the data from the LaHouse Garage. Data was collected for six months from October, 2010 through March, 2011.

3.4 Utilize BIM Models of the LaHouse Garage and Energy Simulation Results to Determine Energy Performance and Energy Cost Savings for Each of the Framing Systems

The results from three energy simulation tools, Autodesk® Ecotect Analysis, EnergyPlus, and IES VE-Pro are obtained. The results are compared with the actual data collected from the performance monitoring system installed in the LaHouse Garage. Based on these results, utilization of energy for each different framing system and energy cost savings for each of the designs can be produced. A simple payback period is estimated through the total construction costs and energy savings for different framing systems with respect to standard framing. Details about the energy performance of the four framing systems and analysis are shown in the next chapter.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Develop as-built Building Information Model of LaHouse and Separate Building Information Models of the LaHouse Garage for Each of the Four Different Framing Systems

With the available 2D drawings, an as-built 3D BIM model was created in Autodesk® Revit Architecture. The top view of the case study LaHouse is shown in Figure 11. The floor plan of LaHouse is imported into Revit through the supported interoperable file between AutoCAD and Revit (.dwg) and a 3D BIM model was created with available data and information.

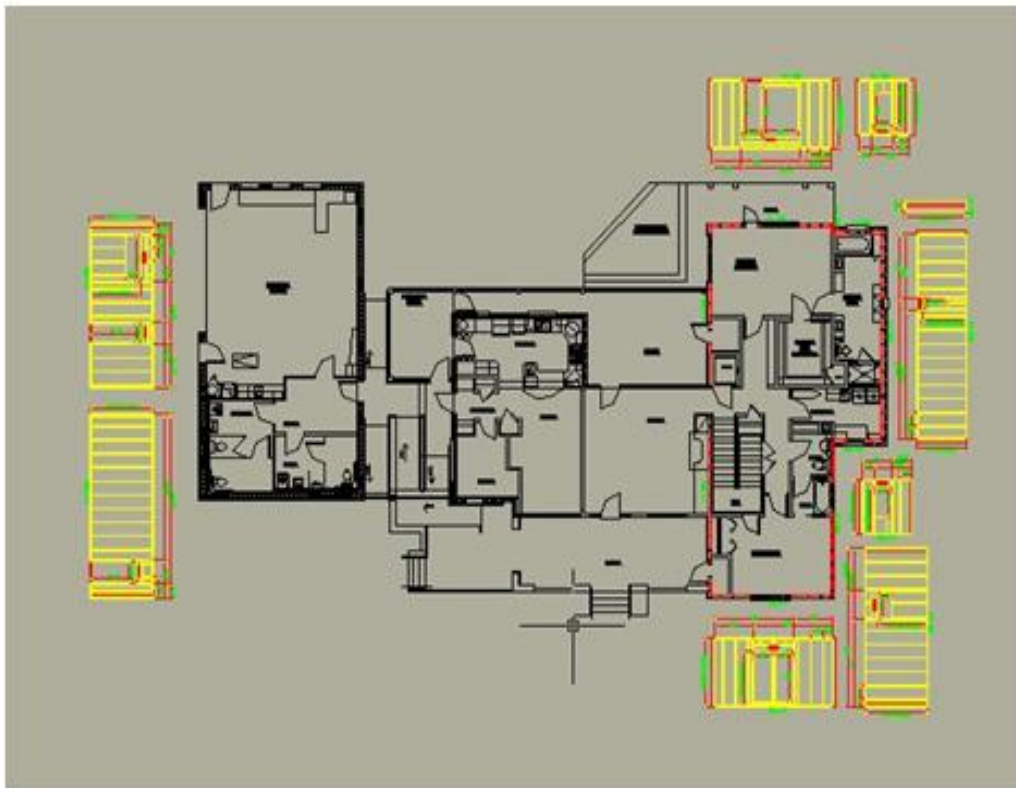


Figure 11: 2D Drawing of a LaHouse-Home and Landscape Resource Center

Information was gathered from the LaHouse plans and specification, including type of doors, walls, and material properties, and incorporated into the BIM model. The as-built 2D drawings were verified through visible inspection and photographs to create a BIM model. The 3D BIM

model created in Autodesk® Revit Architecture is shown in Figure 12. Autodesk® Revit Architecture has wide import and export capabilities. After developing the 3D model, Revit can export the model into different output formats including DWG, DXF, gbXML, and IFC.



Figure 12: 3D BIM model of a LaHouse drawn in Revit Architecture

The BIM model of the garage portion of LaHouse was exported into Autodesk® Ecotect Analysis and the model was updated with data, including occupancy data, HVAC system, weather file, and material properties for energy analysis. The weather data utilized in the simulations can be obtained from the Department of Energy's website at the following web address:

(http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=4_north_and_central_america_wmo_region_4/country=1_usa/cname=USA#LA). Figure 13 shows the La House Garage model used for the thermal analysis of the building in Autodesk® Ecotect Analysis.

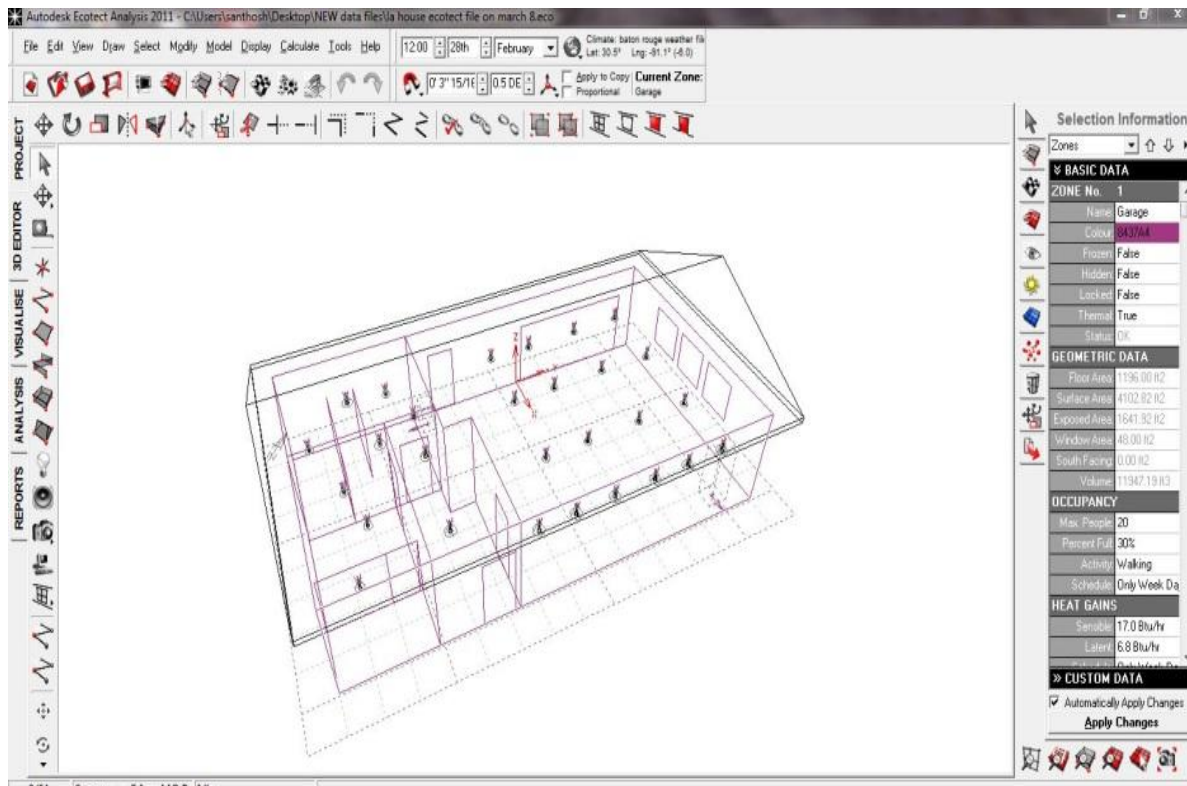


Figure 13: LaHouse Autodesk® Ecotect Analysis Model

Creating the different walls in the Autodesk® Ecotect Analysis model for the different framing systems was done changing the material properties to match the specification for each framing system. Different framings have their own technical specifications, cross sectional areas, layers and material properties. This information was gathered from the LaHouse building specifications. A model of the LaHouse Garage for each of the four different framing systems was created in Autodesk® Ecotect Analysis for use in generating the thermal simulation results for all framing types. The material properties for different wall framings used in Autodesk® Ecotect Analysis are shown below in the following figures. These figures are the screenshots for the material properties of the four different framing types. The first figure in each framing type is the wall cross sectional layers used in the analysis and the second figure in each framing type shows the material properties of the wall.

Material Properties for ICF

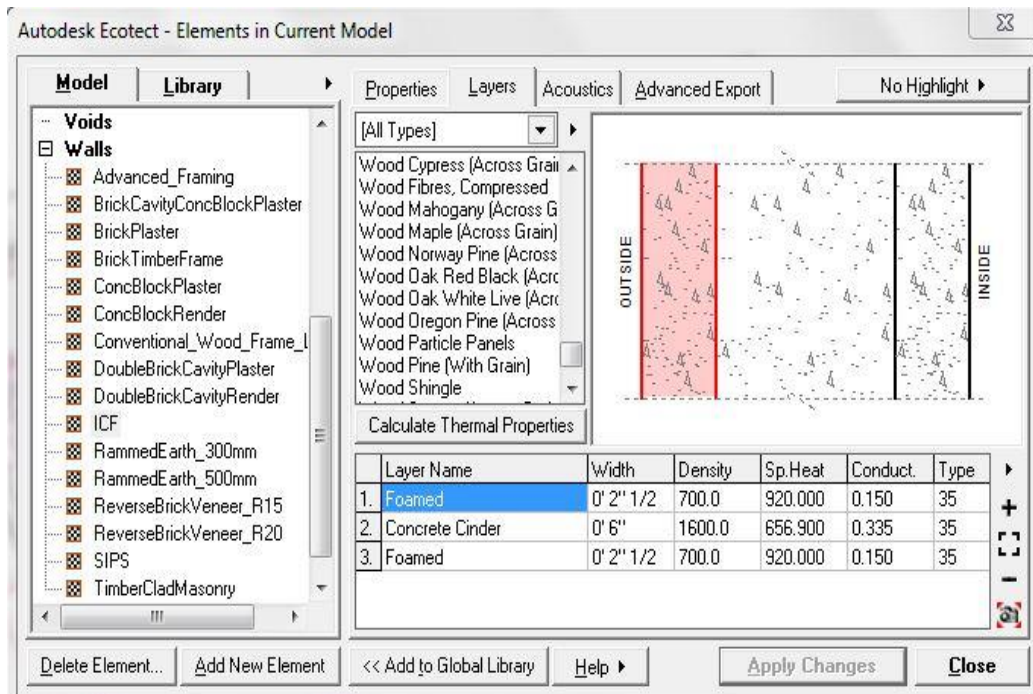


Figure 14: Cross section of the ICF wall framing

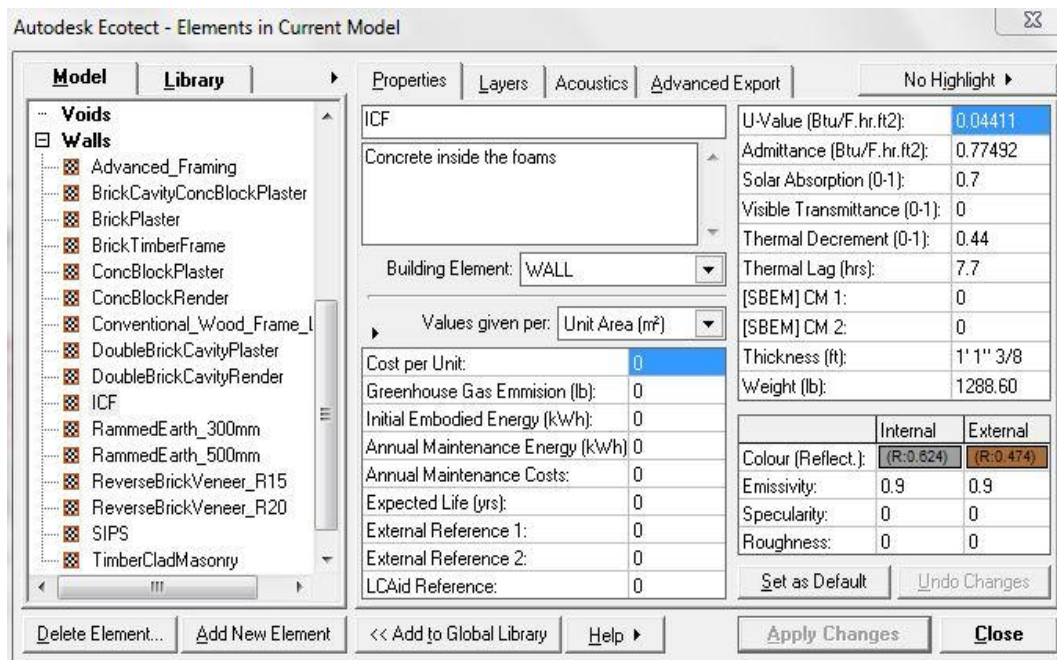


Figure 15: Material Properties of the ICF wall framing

Material Properties for SIPS:

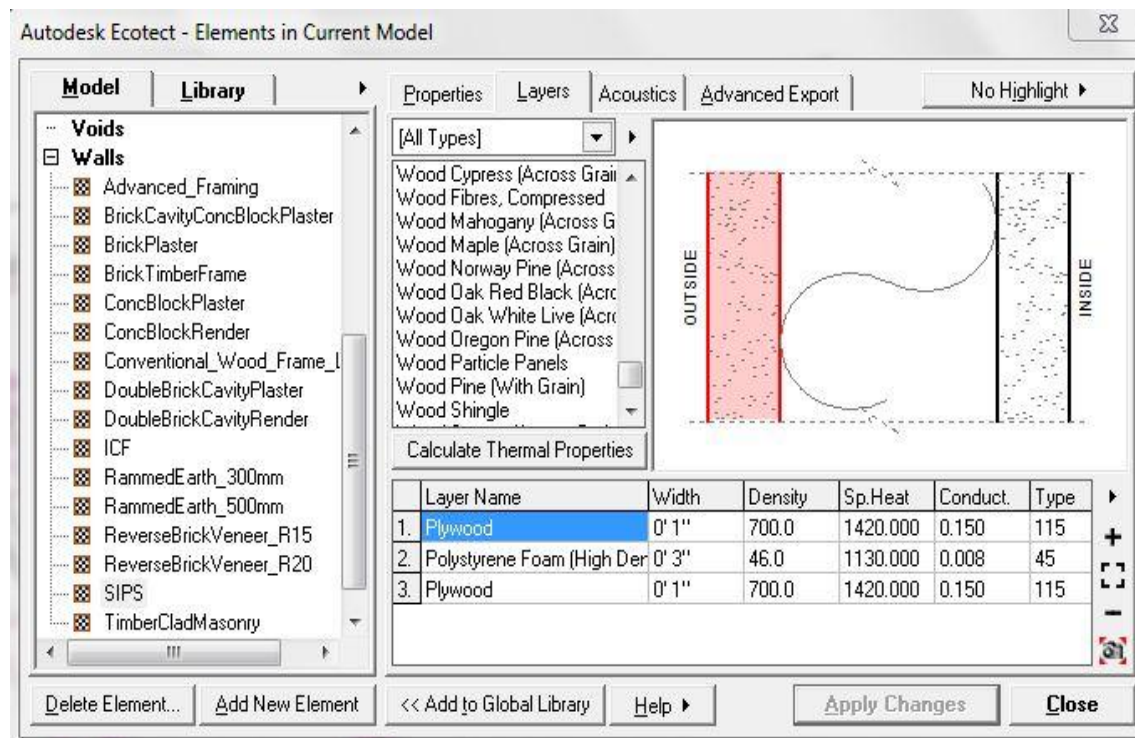


Figure 16: Cross section wall layers of the SIPS

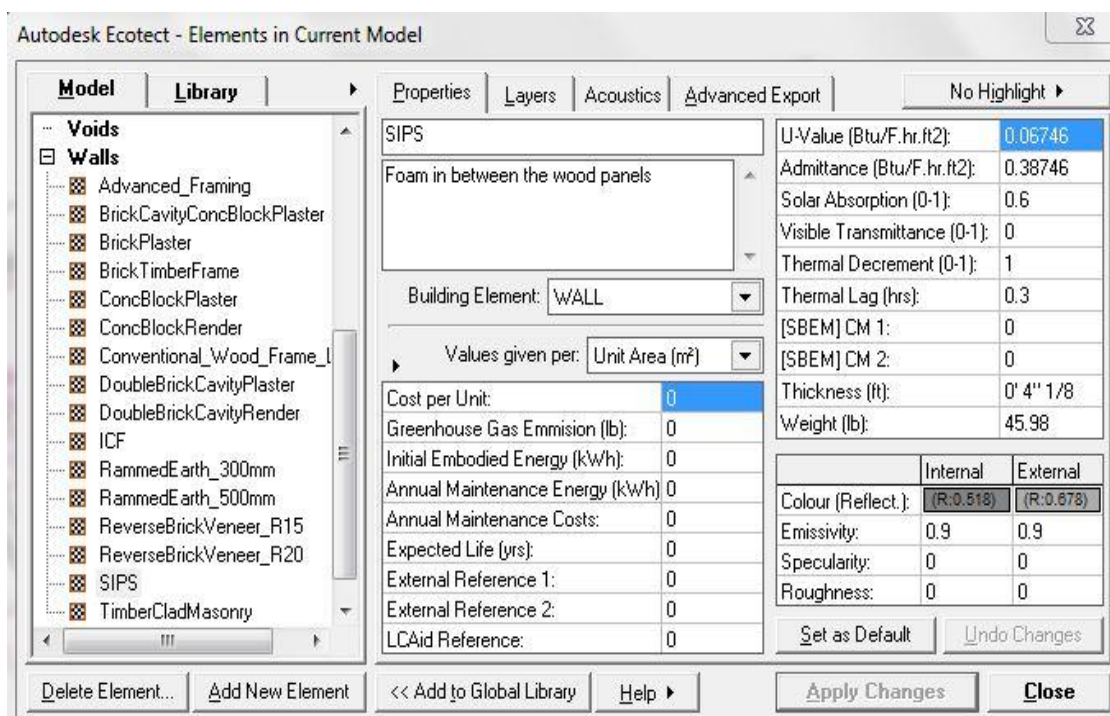


Figure 17: Material Properties of SIPS

Material Properties for Advanced Framing:

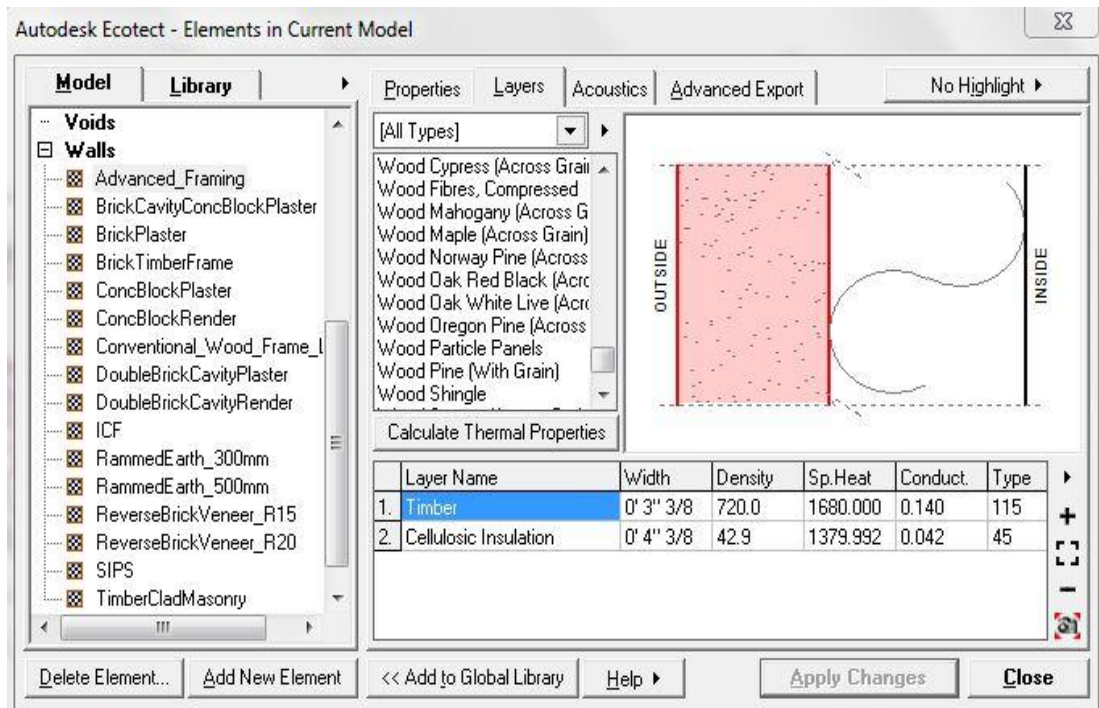


Figure 18: Cross section wall layers of the advanced framing

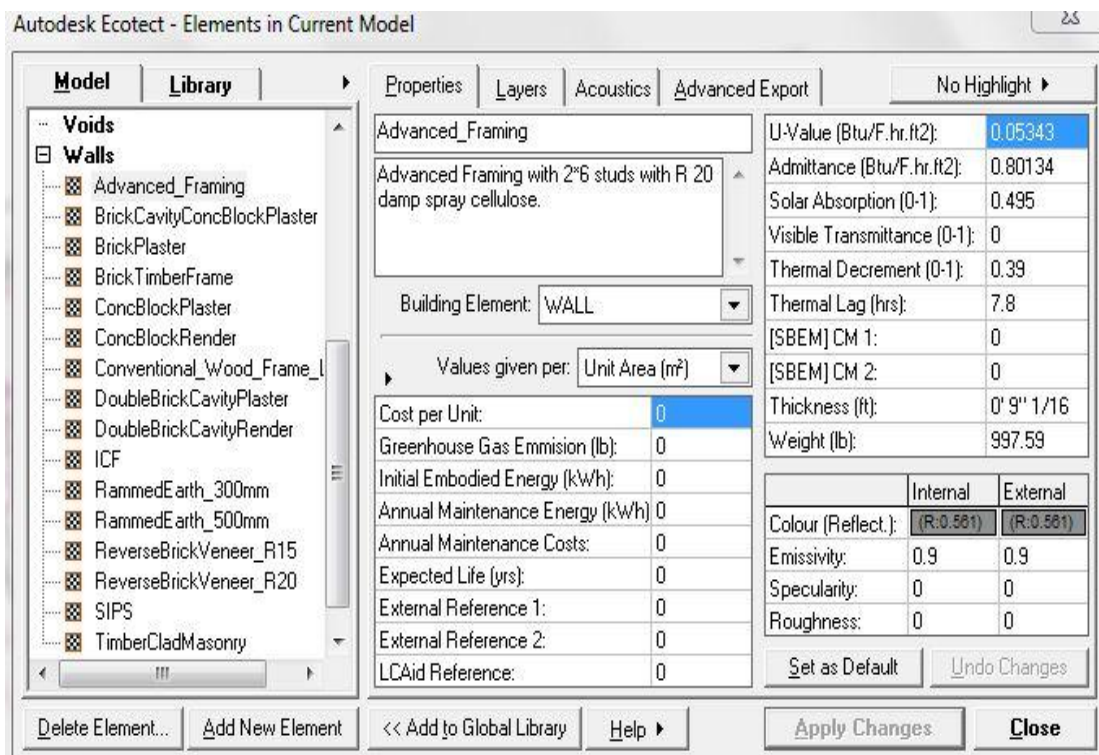


Figure 19: Material properties for advanced framing

Material Properties for Standard Framing:

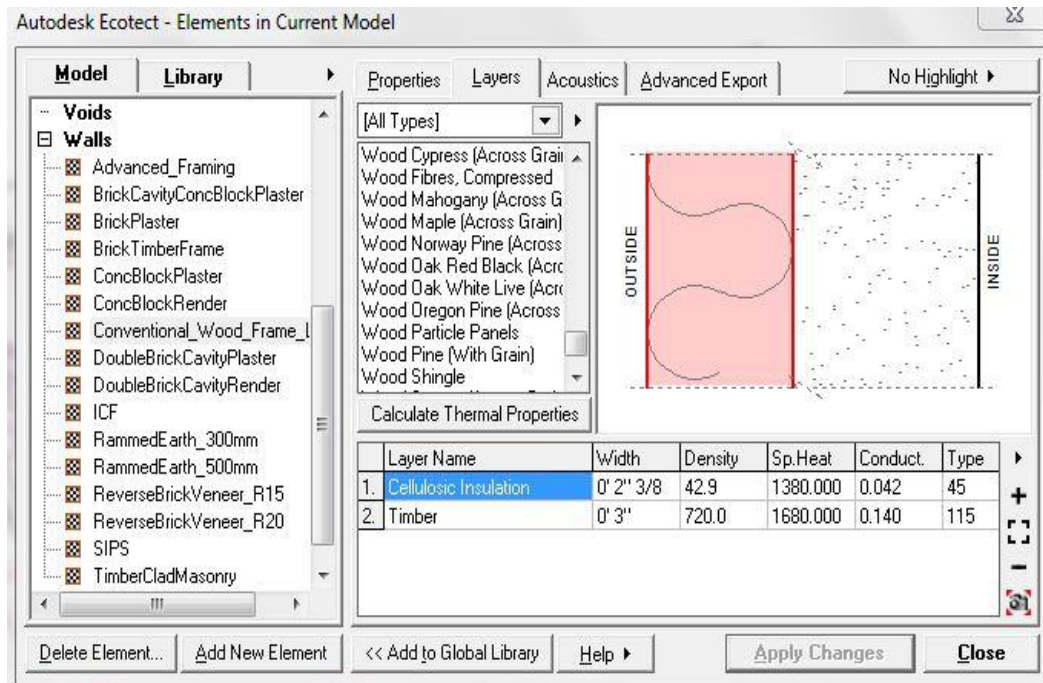


Figure 20: Cross section wall layers of the Standard Framing

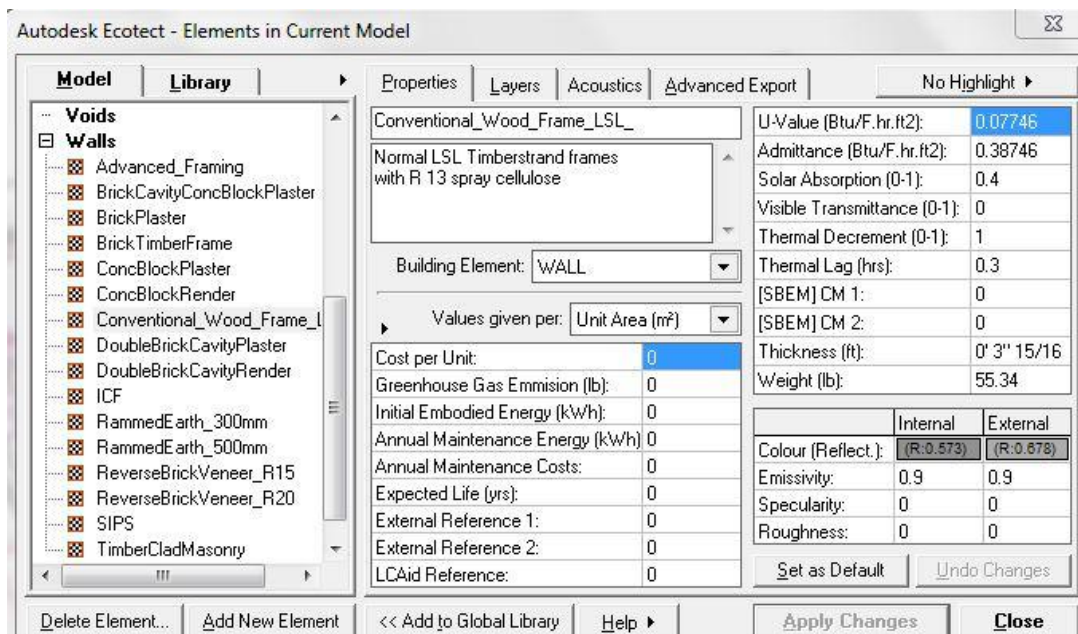


Figure 21: Material Properties for Standard Framing

4.2 Conduct Energy Simulation Modeling Based on the as-built BIM Utilizing EnergyPlus, Autodesk® Ecotect Analysis, and Integrated Environmental Solutions (IES VE-Pro) and Compare Simulation Results with Actual Performance Data and Standard Benchmark Models Set by Department of Energy

To compare the different software tools with actual results, only ICF framing was taken into account because the LaHouse Garage is built with ICF framing. This study used the same input model data to find the uncertainty between simulation tools. Using the same base model, there is no requirement to manually edit the files for each tool. Here, in this study our model is simply exported and new analysis is done in each simulation tool.

Assumptions

The following assumptions are used in the energy simulation modeling for the LaHouse garage:

1. Heating (72°F) and cooling (73°F) set point temperatures are the average temperatures of heated and cooled zones.
2. Occupancy density was taken as 0.09 person / m² for all the simulation tools.
3. Lights Intensity assumed as 13.76 W.
4. Assuming the weather files contain the same meteorological data in both Department of Energy's weather file and IES-VE-Pro software included weather file for one particular region. The IES VE-Pro doesn't support the Department of Energy's weather file. It has its own weather file divided with specific zones. In this study, the southeast region of the US weather zone was utilized.

The basic information of the site and weather of the LaHouse Garage obtained from the Department of Energy is provided in the Table 3.

Table 3. Site Information

Zone	Garage
Location	Baton Rouge
Operation	Weekdays 8AM-6PM
Area of the garage	111.1m ² or 1196 ft ²
Daily temperature range	5-16 ⁰ C
Wind Speed	0- 15.7 m/s
Annual average outdoor air temperature	20 ⁰ C
Thermostat Settings	21.1 – 22.2 ⁰ C
Maximum Dry Bulb Temp	6.1 to 40 ⁰ C
Barometric Pressure	101085 Pa
Wind Direction	180 W 270 S
Site Location	20 m above sea level

The weather data used in this study is the Baton Rouge, LA weather file, obtained from the Department of Energy website at the following web address:

(http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=4_north_and_central_america_wmo_region_4/country=1_usa/cname=USA#LA). The case study LaHouse is

located near Louisiana State University in Baton Rouge, LA. So, this weather file is an appropriate choice for the case study.

4.2.1 EnergyPlus Results

The IDF file exported from Autodesk® Ecotect Analysis and the Baton Rouge weather file is used for the Energy simulation in EnergyPlus. IDF editor is utilized for inputting the information, including output results type, energy units, monthly summaries, window loads, etc.

The energy simulation results for ICF framing in EnergyPlus are shown in Table 4.

Table 4. LaHouse Garage Resource Consumption for ICF obtained by EnergyPlus

Month	Heating (Kwh)	Cooling (Kwh)	Electric (Kwh)	Total Electricity (Kwh)
January	868.51	146.61	656.59	1671.71
February	627.82	120.62	601.98	1350.42
March	90.04	309.67	672.17	1071.88
April	10.43	595.66	643.32	1249.41
May	0	1020.67	641.42	1662.09
June	0	1104.78	637.97	1742.75
July	0	1018.9	663.24	1682.14
August	0	1116.48	643.42	1759.9
September	0	966.93	645.67	1612.6
October	18.01	573.67	651.82	1243.5
November	125.45	277.68	653.54	1056.67
December	936.8	198.57	680.5	1815.87
Total	2677.06	7450.24	7791.64	17918.94

4.2.2 IES VE-Pro data for ICF: Energy Analysis Results for ICF

Figure 22 shows the LaHouse Garage model in IES VE-Pro, and the simulation results from the IES VE-Pro are tabulated in Table 5. The weather file used in IES VE-Pro is the weather file for the southeast region of the United States and is included in the simulation software. IES VE-Pro has both CIBSE and ASHRAE heat gain/loss calculation methods. In IES VE-Pro, the calculation method chosen in this research is ASHRAE heat balance method due to the comparison with the EnergyPlus simulation results which are based on the ASHRAE's heat balance approach.

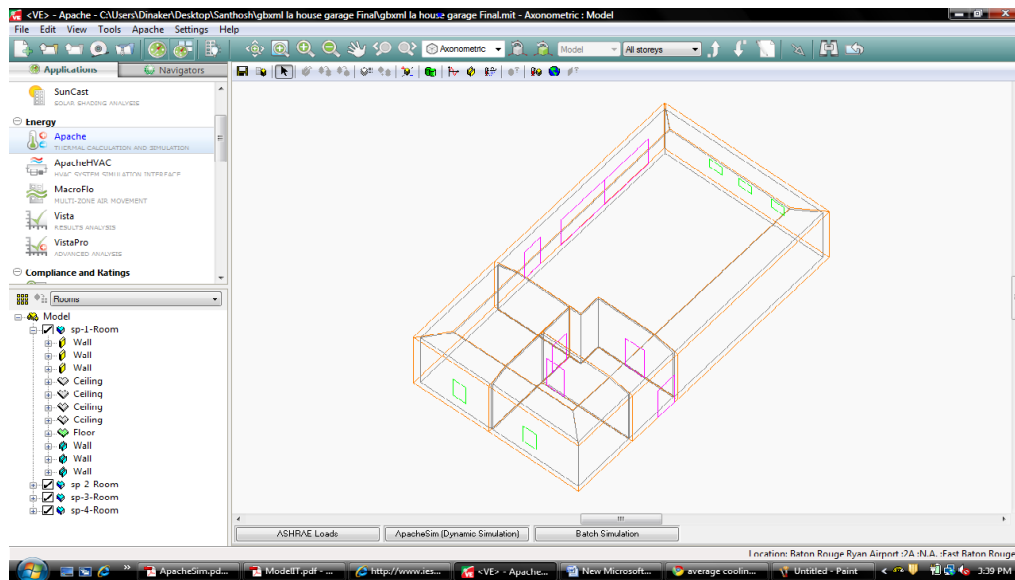


Figure 22: LaHouse Model in IES VE-Pro software exported by Revit via gbXML

Table 5. Simulation Results for ICF framing from IES VE- Pro

Month	Heating (Kwh)	Cooling (Kwh)	Electric (Kwh)	Total Electricity (Kwh)
January	573.61	94.76	359.01	1027.38
February	488.2	67.45	324.13	879.78
March	45.3	408.56	359.01	812.87
April	53.69	634.92	347.28	1035.89
May	0	900.38	359.01	1259.47
June	0	1028.03	347.28	1375.31
July	0	1068.16	359.01	1427.17
August	0	1006.88	359.01	1365.89
September	0	909.04	347.28	1256.32
October	0	649.33	359.01	1008.34
November	268.48	306.21	347.28	921.97
December	415.1	49.65	359.01	823.76
Total	1844.38	7123.37	4226.32	13194.15

4.2.3 Autodesk® Ecotect Analysis Values for ICF

The energy simulation results for the LaHouse Garage using ICF framing from the Autodesk® Ecotect Analysis is shown in Table 6.

Table 6. Energy results for ICF Framing from the Autodesk® Ecotect Analysis

Monthly	Heating (Kwh)	Cooling (Kwh)	Electric (Kwh)	Total (Kwh)
Jan	791.6	101.894	311.321	1204.816
Feb	656.149	33.273	280.23	969.652
Mar	86.218	313.165	310.077	709.46
Apr	79.067	716.695	299.714	1095.476
May	0	1087.78	311.321	1399.097
Jun	0	1358.8	299.714	1658.513
Jul	0	1484.84	310.077	1794.912
Aug	0	1398.67	311.321	1709.994
Sep	0	1094.62	298.47	1393.089
Oct	36.99	759.263	311.321	1107.574
Nov	129.578	208.879	300.957	639.414
Dec	735.387	11.444	307.59	1054.421
Total	2514.99	8569.3	3652.05	14736.34

4.2.4 Actual Values collected from TED 1001 at LaHouse Garage

The Energy Detective (TED) is a measurement unit used to collect the real time power consumption. The TED transmits the energy data from main electric panel to the LCD display. The unit is installed in the LaHouse Garage and the data collected from TED gives only the total energy consumption on a monthly basis. Table 7 shows the energy values that were collected from the performance monitoring equipment TED 1001 for six months from October 2010 to March 2011.

Table 7. LaHouse Garage ICF Framing Actual Data Collected by TED 1001

Month	Energy(Kwh)
Oct	1431
Nov	1687
Dec	1292
Jan	1296
Feb	1201
Mar	1192

4.2.5 Comparison of Energy Results for ICF Framing

Actual values include the data from a six month period beginning October, 2010 and ending March, 2011. The following Table 8 compares the three simulation results with the actual data as well as with benchmark model data.

Table 8. Comparison between EnergyPlus, IES VE-Pro, Autodesk® Ecotect Analysis and Actual data for ICF

Type	Heating& Cooling Loads(Kwh) (Oct-March)	Electric Loads(Kwh) (Oct-March)	Total(Kwh) (Oct-March)	Total Energy percentage difference when compared to actual data (Oct-March)
EnergyPlus	4293.45	3916.60	8210.05	+1.37%
IES VE-Pro	3366.65	2107.45	5474.10	-32.41%
Autodesk® Ecotect Analysis	3863.84	1821.50	5685.38	-29.80%
Actual Data			8099	0%
Benchmark model	1349.24	7031.80	8381.10	+3.48%

The results conclude that EnergyPlus shows very less deviation, + 1.37%, from the actual results. These results show that the EnergyPlus (ASHRAE) simulation calculation method provided the closest results to the measured data. The energy consumption for each of the simulations, the

benchmark model and the actual results are clearly shown with the help of the graph in Figure 23. The benchmark model used in this comparison is explained in Section 4.2.7, and the simulation values for this model are shown in Appendix.

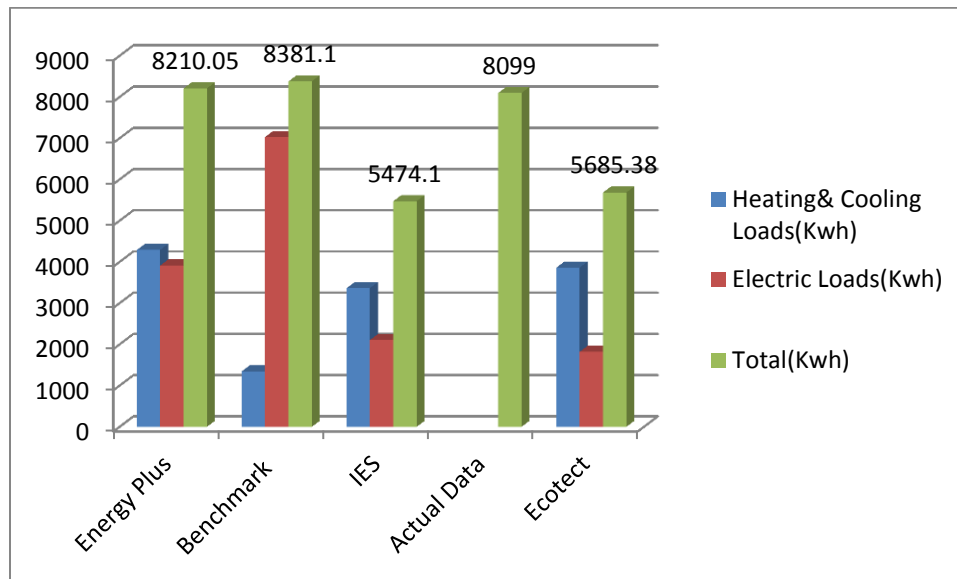


Figure 23: Comparison of Energy Simulation Results for ICF framing

4.2.6 Statistical Analysis of Simulation Results

Statistical analysis of the simulation results was performed using Sigma Plot[®]. A description of the results of the statistical analysis is provided in the following paragraphs.

The heating results data failed the normality test but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the heating values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of the performed test (0.049) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

The cooling results data failed the normality test but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in

the mean values for each simulation results. In the case of the cooling values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of the performed test (0.049) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

The electric results data failed the normality test but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the electric values, the analysis concluded that there was a statistically significant difference in the mean values among the treatment groups greater than would be expected by chance; the Holm-Sidak method was then used to isolate the groups that differed from one another. In the case of the electric results, the results from all three simulation packages differed significantly from one another.

The total results data passed the normality test, so the one way analysis of variance was used to determine if there was a significant difference in the mean values for each simulation results. In the case of the total values, the analysis concluded that there was a statistically significant difference in the mean values among the treatment groups greater than would be expected by chance; the Holm-Sidak method was then used to isolate the groups that differed from one another. In the case of the total energy usage, only the EnergyPlus and IES VE-Pro results differed significantly from one another.

The actual data collected from the LaHouse was then compared to the results from the three simulation software's. The actual data collected was for total energy usage, so the total energy usage data from each simulation was used in the comparison. The data passed the normality tests, so the One Way Analysis of Variance was used to determine if there was a significant difference in the mean values. In this case, the analysis concluded that there was a

statistically significant difference in the mean values among the treatment groups greater than would be expected by chance; the Holm-Sidak method was then used to isolate the groups that differed from one another. The actual data was used as a control group, and each of the simulation results were compared to the control group. The EnergyPlus results were found to not be statistically different from the actual results. However, both the IES VE-Pro results and the Autodesk® Ecotect Analysis results differed significantly from the actual results.

4.2.7 Comparison between the LaHouse Garage Model and Benchmark Model

The Department of Energy set 16 different building types for 16 different U.S. climatic zones as benchmark models. The developed benchmark models act as standard buildings for comparison, and these benchmark models “will form the basis for research on specific building technologies, energy code development, appliance standards, and measurement of progress toward the DOE energy goals” (Demchak 2008). Thus, LaHouse Garage needs to be tested to determine if it met the standard benchmark model in construction and performance goals.

The LaHouse Garage is a single zone model with 1195.87 square feet which is five times smaller than the benchmark model. The window area / wall area in LaHouse Garage is nearly six times smaller than the benchmark model. The standard benchmark model energy data are compared with the LaHouse Garage model EnergyPlus results. The differences between the standard office building benchmark model provided by the Department Of Energy and LaHouse Garage is shown in Table 9. To satisfy a comparison with the standard benchmark model, the window area to the wall area for LaHouse Garage should be increased. Overall, the total energy consumption per square foot for benchmark model and the LaHouse Garage model are almost equal.

Table 9. Differences between the Standard Benchmark Model and LaHouse Garage

Type	Benchmark Model	LaHouse Garage
Area(Sq.ft)	5502.08	1195.87
Shape	Rectangular	Rectangular
Zones	5	1
Height (m)	3.12	3.048
People /100 m ²	5.38	9
Electrical Intensity(MJ/m ²)	525.78	580.57
Window Area/Wall Area	21.20	3.3
Lights Intensity (W)	10.76	13.76
Exterior Walls	1 in Stucco , 8 inch concrete, Hw Wall Insulation, 4.5 inch gypsum	Eco block ICF walls
Cooling COP	4	5
Water Heater	Yes	No
Interior Lights Intensity (W)	4950.048	1528.902
Carbon Dioxide Emission(kg)	5320.68	1249.83
Total Site Energy (kwh)	81919.4	17919.4
Total Energy/ft ²	14.89	14.98
Gross Roof Area (m ²)	598.76	153.25

4.3. Utilize BIM Models of the LaHouse Garage and Energy Simulation Results to Determine Energy Performance and Energy Cost Savings for Each of the Framing Systems

Thermal analysis was done on four different framing types ICF, SIPS, advanced and standard framing in EnergyPlus, Autodesk® Ecotect Analysis and IES VE-Pro. In this study, we analyzed the effect of exterior walls on heating, cooling and electric loads by running simulation for single region. In addition, the expected energy cost for each of the different framing systems was computed for each of the simulation results. The results from EnergyPlus, Autodesk® Ecotect Analysis and IES VE-Pro for different framings are discussed in the following sections.

4.3.1 EnergyPlus Values for Different Framings

Tables 10-13 include the simulation results from EnergyPlus for ICF, SIPS, Advanced framing and Conventional framing systems. The heating, cooling, and total energy loads from the EnergyPlus simulation results for the different framing systems are shown in Figures 24-26.

Table 10. LaHouse Garage Energy Consumption for ICF per EnergyPlus

Month	Heating (H _L)(Kwh)	Cooling (C _L) (Kwh)	Electric (E _L)(Kwh)	Total Energy(TE _U) (Kwh)
January	868.51	146.61	656.59	1671.71
February	627.82	120.62	601.98	1350.42
March	90.04	309.67	672.17	1071.88
April	10.43	595.66	643.32	1249.41
May	0	1020.67	641.42	1662.09
June	0	1104.78	637.97	1742.75
July	0	1018.9	663.24	1682.14
August	0	1116.48	643.42	1759.9
September	0	966.93	645.67	1612.6
October	18.01	573.67	651.82	1243.5
November	125.45	277.68	653.54	1056.67
December	936.8	198.57	680.5	1815.87
Total	2677.06	7450.24	7791.64	17918.94

Table 11. LaHouse Energy Consumption for SIPS as per EnergyPlus

Month	Heating (H _L)(Kwh)	Cooling (C _L) (Kwh)	Electric (E _L) (Kwh)	Total Energy (TE _U) (Kwh)
January	1279.4	218.72	656.59	2154.71
February	1055.03	189.46	601.98	1846.47
March	258.03	290.12	672.17	1220.32
April	48.89	872.64	643.32	1564.85
May	0	1077.37	641.42	1718.79

(Table 11 Continued....)

June	0	1159.17	637.97	1797.14
July	0	1174.94	663.24	1838.18
August	0	1171.63	643.42	1815.05
September	0	1027.18	645.67	1672.85
October	93.1	644.54	651.82	1389.46
November	443.98	253.1	653.54	1350.62
December	1463.62	176.08	680.5	2320.2
Total	4642.05	8254.95	7791.64	20688.64

Table 12. LaHouse Garage Energy Consumption for Advanced Framing by EnergyPlus

Month	Heating (H_L) (Kwh)	Cooling (C_L) (Kwh)	Electric (E_L) (Kwh)	Total Energy (TE_U) (Kwh)
January	1669.28	279.94	656.59	2605.81
February	1445.19	247.54	601.98	2294.71
March	545.85	258.3	672.17	1476.32
April	151.53	739.25	643.32	1534.1
May	0	1134.35	641.42	1775.77
June	0	1207.49	637.97	1845.46
July	0	1318.98	663.24	1982.22
August	0	1317.09	643.42	1960.51
September	0	1184.21	645.67	1829.88
October	248.51	707.36	651.82	1607.69
November	870.07	317.78	653.54	1841.39
December	1906.66	242.09	680.5	2829.25
Total	6837.09	8954.38	7791.64	23583.11

Table 13. LaHouse Garage Energy Consumption for Standard Framing by EnergyPlus

Month	Heating (H _L)(Kwh)	Cooling (C _L) (Kwh)	Electric (E _L) (Kwh)	Total Energy(TE _U) (Kwh)
January	1848.13	314.7	656.59	2819.42
February	1628.06	279.71	601.98	2509.75
March	704.82	297.19	672.17	1674.18
April	215.01	776.3	643.32	1634.63
May	0	1169.21	641.42	1810.63
June	0	1239.41	637.97	1877.38
July	0	1348.91	663.24	2012.15
August	0	1346.45	643.42	1989.87
September	0.85	1219.66	645.67	1866.18
October	344.29	744.13	651.82	1740.24
November	1068.19	354.98	653.54	2076.71
December	2121.68	280	680.5	3082.18
Total	7931.03	9370.65	7791.64	25093.32

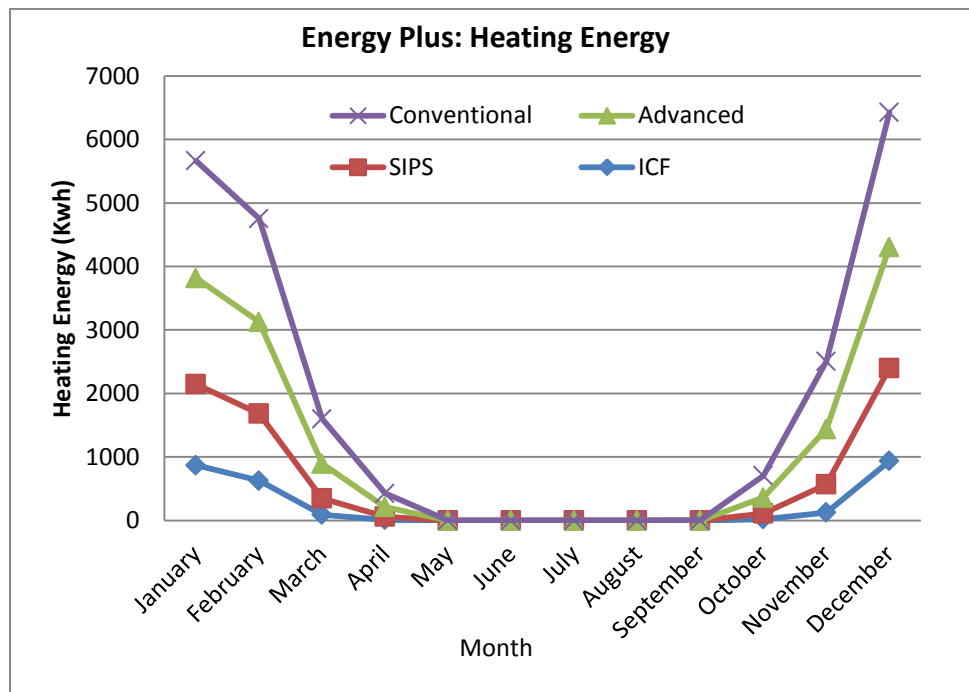


Figure 24: Energy Utilization for heating for different framing systems by EnergyPlus

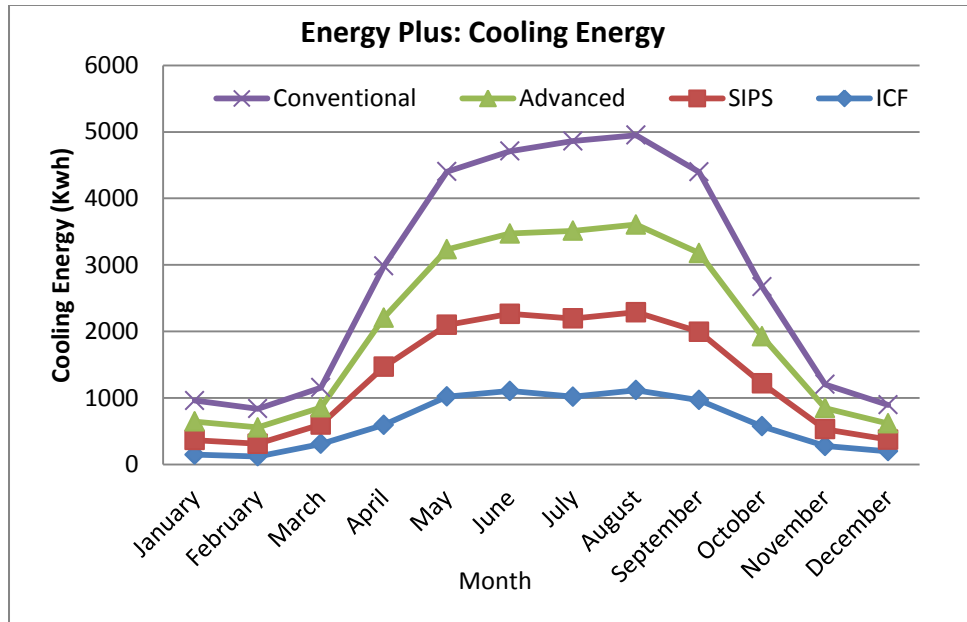


Figure 25: Energy Utilization for cooling for different framing systems by EnergyPlus

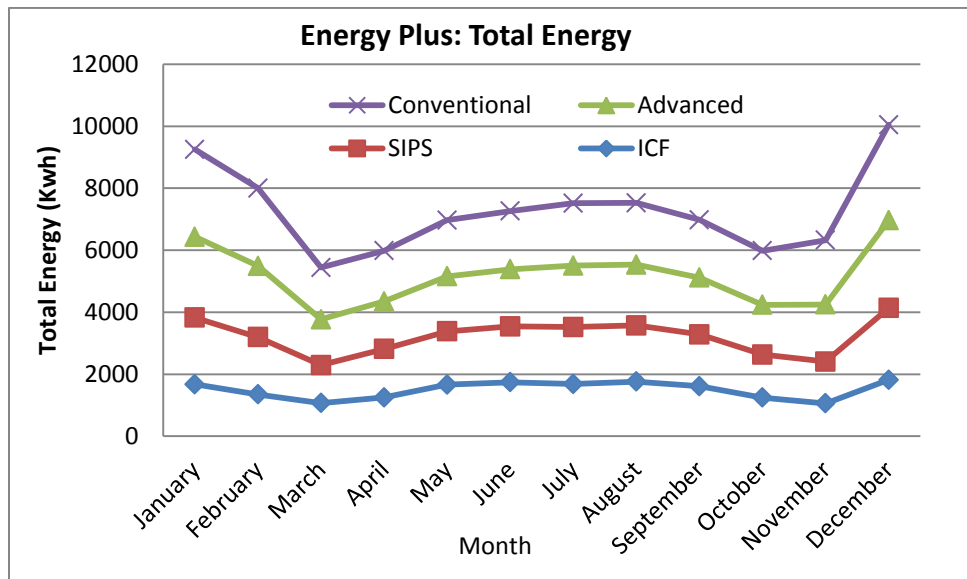


Figure 26: Total Energy Utilization for different framing systems by EnergyPlus

4.3.1(A) Statistical Analysis of EnergyPlus Simulation Results

Statistical analysis of the simulation results was performed using Sigma Plot[®]. The results from this statistical analysis are discussed in the following paragraphs.

The heating results data failed the normality test but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the heating values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of the performed test (0.071) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

The cooling results data for the four framing types failed the normality test but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the cooling values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of the performed test (0.049) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

The electric results data for the four framing types using EnergyPlus are identical due to the inputs, so no statistical analysis was performed.

The total results data for the four framing types passed the normality test, so the one way analysis of variance was used to determine if there was a significant difference in the mean values for each simulation results. In the case of the total values, the analysis concluded that there was a statistically significant difference in the mean values among the treatment groups greater than would be expected by chance; the Holm-Sidak method was then used to isolate the groups that differed from one another. In the case of the total energy usage, the ICF results were significantly different from the conventional framing results, and the ICF results were significantly different from the advanced framing results. There were no statistically significant differences in any of the other results.

4.3.1(B) Economic Analysis

An economic analysis was performed using the results of the energy simulation results from EnergyPlus for the four different framing types. The following equations and notations were used in the analysis:

Notations:

Heating Loads = H_L

Cooling Loads = C_L

Electric Loads = E_L

Total Energy Utilization = TE_U

Total Energy Utilization (TE_U) = Heating Loads+ Cooling Loads+ Lighting/ Equipment Loads

Total energy consumption is computed as shown in Equation

$$TE_U = H_L + C_L + E_L \quad \text{----- Equation 1}$$

To determine energy usage per square foot, the calculated total energy consumption was divided by the total area of the LaHouse garage as shown below:

Energy Usage per Square foot = $TE_U / 1196$

According to the Department of Energy, the average retail price (cents/Kwh) for Louisiana is approximated as 9 cents/Kwh (U.S. Department of Energy and Building Technology Program)

Using this information, total energy costs were computed as shown below:

$E_C = 0.09$ cents/Kwh

Total Energy Costs = Total Energy (Kwh) * Energy Cost per Kwh

$$TE_C = TE_U * E_C \quad \text{-----Equation 2}$$

Using Equations 1 and 2 the total energy consumption and the corresponding energy costs for each framing type are calculated and tabulated in Table 14.

Table 14. Energy Utilization and Energy Costs for Each Framing System

Type	Total Energy Utilization(TE _U)	Annual Energy Usage per Sq. foot	Annual Energy Costs(TE _C)
ICF	17918.94	14.98	1612.7
SIPS	20688.64	17.29	1861.97
Advanced Framing	23583.11	19.71	2122.47
Standard Framing	25093.32	20.98	2258.39

The construction cost estimates for each framing system were then computed using estimates provided by LaHouse personnel. Only the construction costs related to the framing was included in this calculation. Table 15 details the construction components and associated costs that were used in determining the construction cost estimate.

Table 15. Total Construction Cost Estimate for Framing Types for LaHouse Garage

Type	ICF	SIPS	Advanced	Standard
Slab	5683	5683	5683	5683
Exterior Wall Framing	5944.96	4784	4979.76	4339
Interior Wall Framing	1980.3	1980.3	1980.3	1980.3
Roof Framing	6567.4	6567.4	6567.4	6567.4
Roof	4441.32	2965.12	2443.48	2443.48
Insulation	ICF walls are R22: Unfaced fiberglass insulation	R 15 Sips Walls, R 30 SIPS roof panels; Unfaced fiberglass insulation	R 19 spray borate cellulose in walls; Unfaced fiberglass Insulation	R 13 Kraft faced fiberglass
Total Insulation Costs	1183.05	1183.05	1183.05	1183.05
Total Costs	25800.03	23162.87	22836.23	22152.53
Variation from Standard	3647.5	1010.34	683.7	0

* All insulation costs based on \$0.99/ft², except for R13 Kraft Faced Fiberglass insulation which is based on \$0.65/ft².

Simple Payback Period:

The simple payback period for each of the innovative framing methods was computed as shown in Equation 3 below:

$$\sum_{t=1}^{n_{min}} R_t \geq C_0 \quad \text{-----Equation 3}$$

R = Annual Savings (Energy) which is deviation from standard framing energy cost

C₀= Additional Cost (Deviation from standard framing cost)

n = service life = 30 years

Garage Area= 1196 square foot

As shown in Table 16, the SIPS framing system has the shortest payback period. Although the ICF framing system results in the greatest energy savings according to the energy simulation results, the additional construction costs are significantly higher than those for standard framing. This results in the longest payback period for the ICF framing system.

Table 16. Simple Payback Period with respect to Standard Framing by EnergyPlus Results

TYPE	Annual Energy Usage (Kwh)	Variation of Energy with standard (Kwh)	Total Electricity Cost (\$)	Annual Energy Savings (\$)	Construction Costs (\$)	Variation in Construction Costs with standard (\$)	Simple Payback Period (years)
ICF	17918.94	7174.38	1612.7	645.69	25800.03	3647.5	5.65
SIPS	20688.64	4404.68	1861.9	396.42	23162.87	1010.34	2.55
Advanced	23583.11	1510.21	2122.47	135.92	22836.23	683.7	5.03
Standard	25093.32	0	2258.39	0	22152.53	0	0

4.3.2 Energy Consumption for Different Framings by Autodesk® Ecotect Analysis

Thermal analysis was done on four different framing types ICF, SIPS, advanced and standard framing in Autodesk® Ecotect Analysis. For each framing type, the model was updated and thermal analysis was done. The first figure in each type of framing shows the daily energy usage

annually and the second figure in each type of framing shows the heating/cooling loads for each month individually, followed by their values in table form.

ICF:

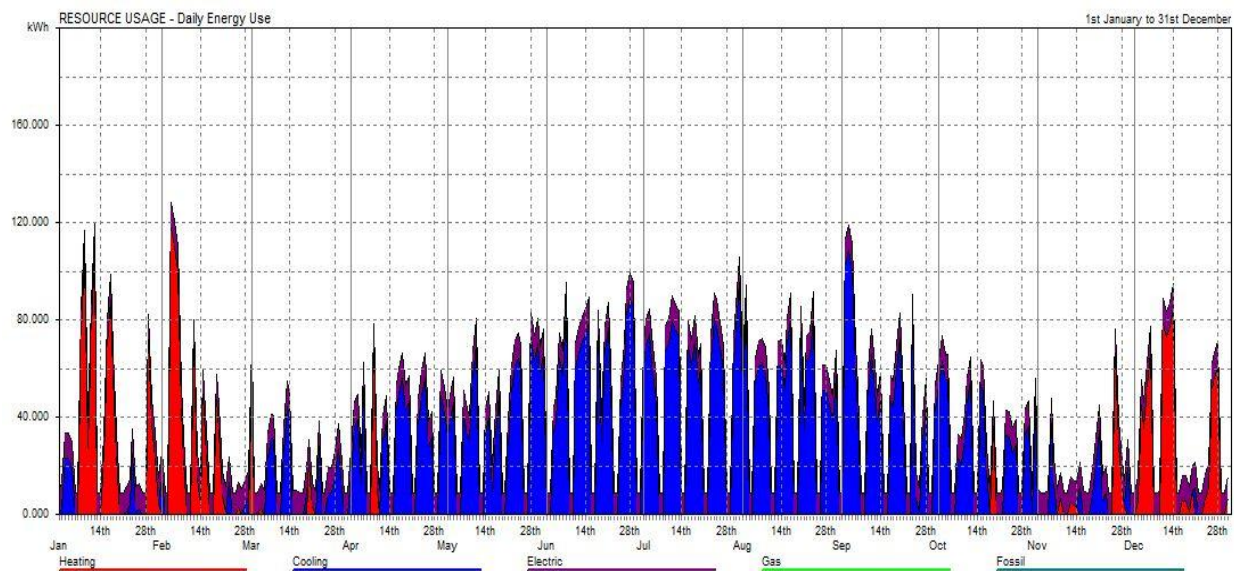


Figure 27: Resources Usage for ICF- Daily Energy Usage

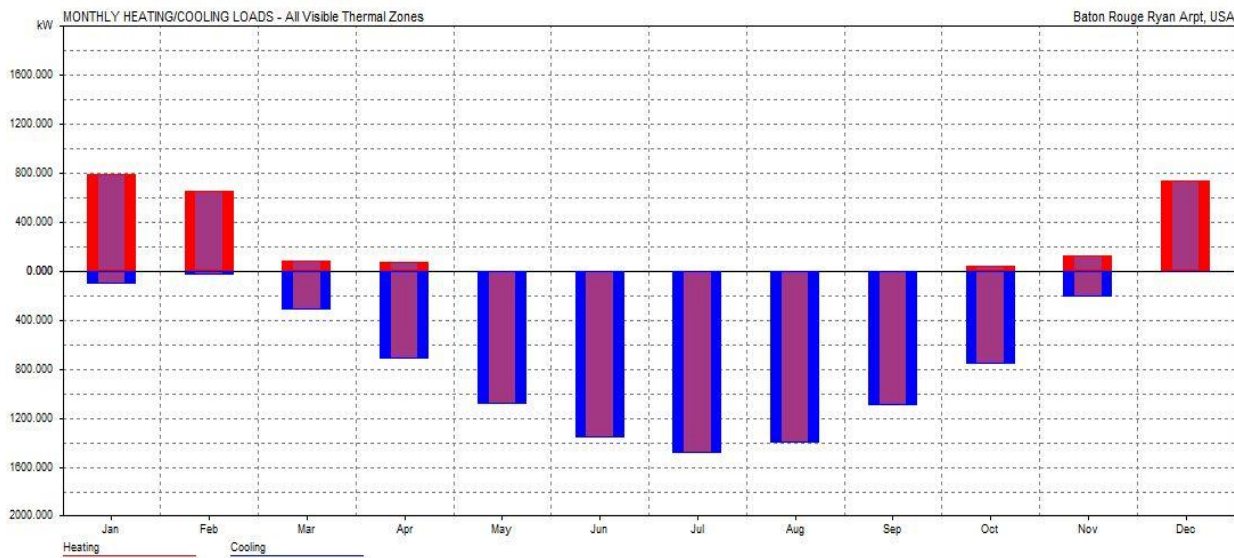


Figure 28: Monthly Heating/Cooling Loads for ICF

Table 17. ICF Framing Energy Consumption for LaHouse Garage

Month	Heating (H _L) (Kwh)	Cooling (C _L) (Kwh)	Electric (E _L) (Kwh)	Total Energy (TE _U) (Kwh)
January	791.6	101.894	311.321	1204.816
February	656.149	33.273	280.230	969.652
March	86.218	313.165	310.077	709.46
April	79.067	716.695	299.714	1095.476
May	0.000	1087.776	311.321	1399.097
June	0.000	1358.799	299.714	1658.513
July	0.000	1484.835	310.077	1794.912
August	0.000	1398.673	311.321	1709.994
September	0.000	1094.619	298.470	1393.089
October	36.990	759.263	311.321	1107.574
November	129.578	208.879	300.957	639.414
December	735.387	11.444	307.590	1054.421
Total	2514.99	8569.3	3652.05	14736.34

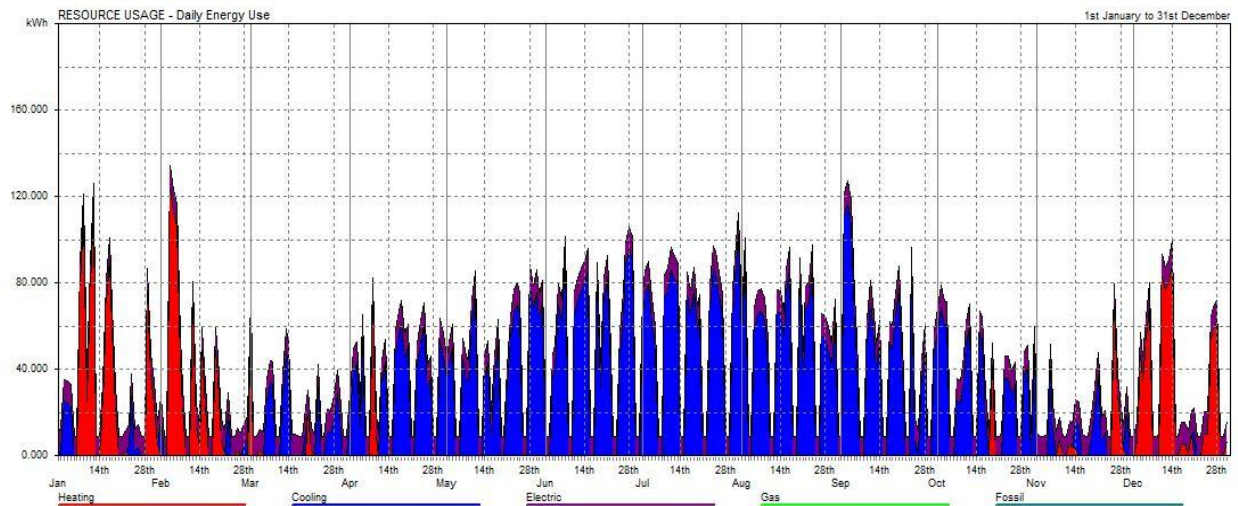


Figure 29: SIPS Framing Resource Usage- Daily Energy Use

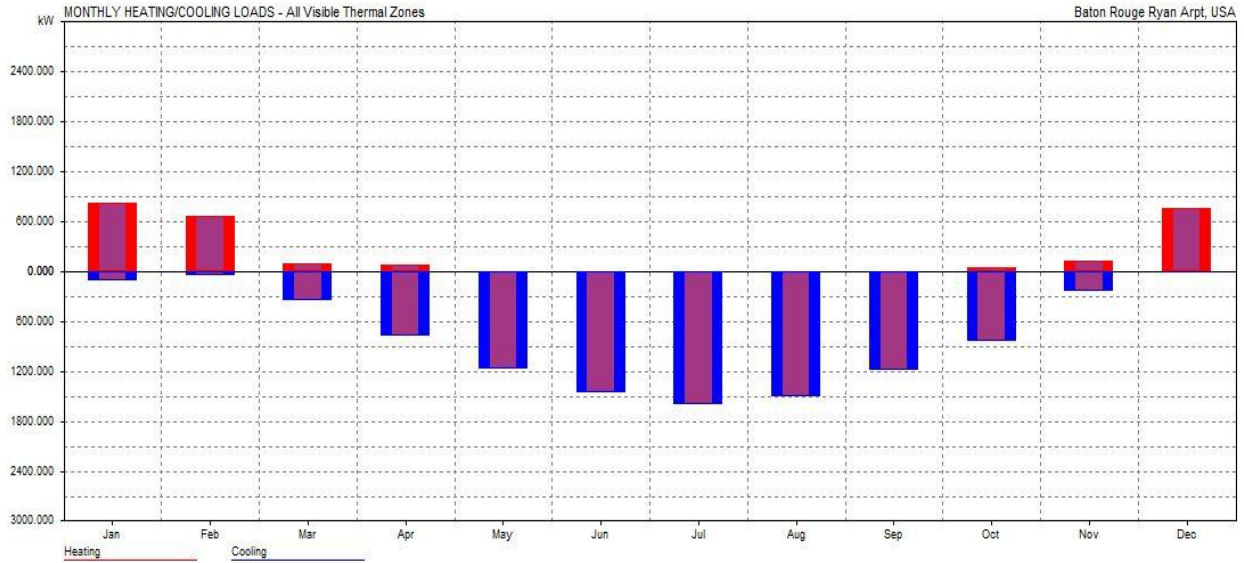


Figure 30: Monthly Heating/ Cooling Loads for SIPS

Table18. SIPS Energy Consumption for LaHouse Garage

Month	Heating (H _L) (Kwh)	Cooling (C _L) (Kwh)	Electric (E _L) (Kwh)	Total Energy (TE _U) (Kwh)
January	816.314	114.157	311.321	1241.792
February	672.234	40.464	280.230	992.928
March	88.108	345.009	310.077	743.194
April	80.916	783.078	299.714	1163.708
May	0.000	1178.945	311.321	1490.266
June	0.000	1463.266	299.714	1762.98
July	0.000	1600.849	310.077	1910.926
August	0.000	1508.136	311.321	1819.457
September	0.000	1183.771	298.470	1482.241
October	42.399	838.181	311.321	1191.901
November	134.340	241.983	300.957	677.28
December	766.350	12.015	307.590	1085.955
Total	2600.661	9309.855	3652.058	15562.56

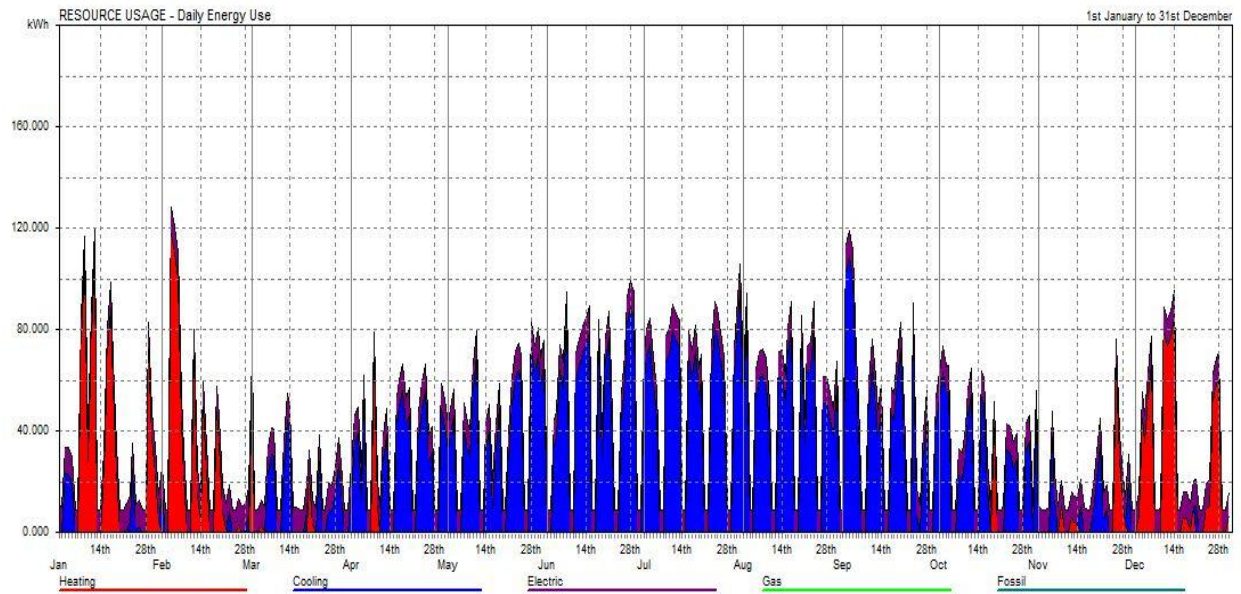


Figure 31: Resources Usage (Daily) for Advanced Framing

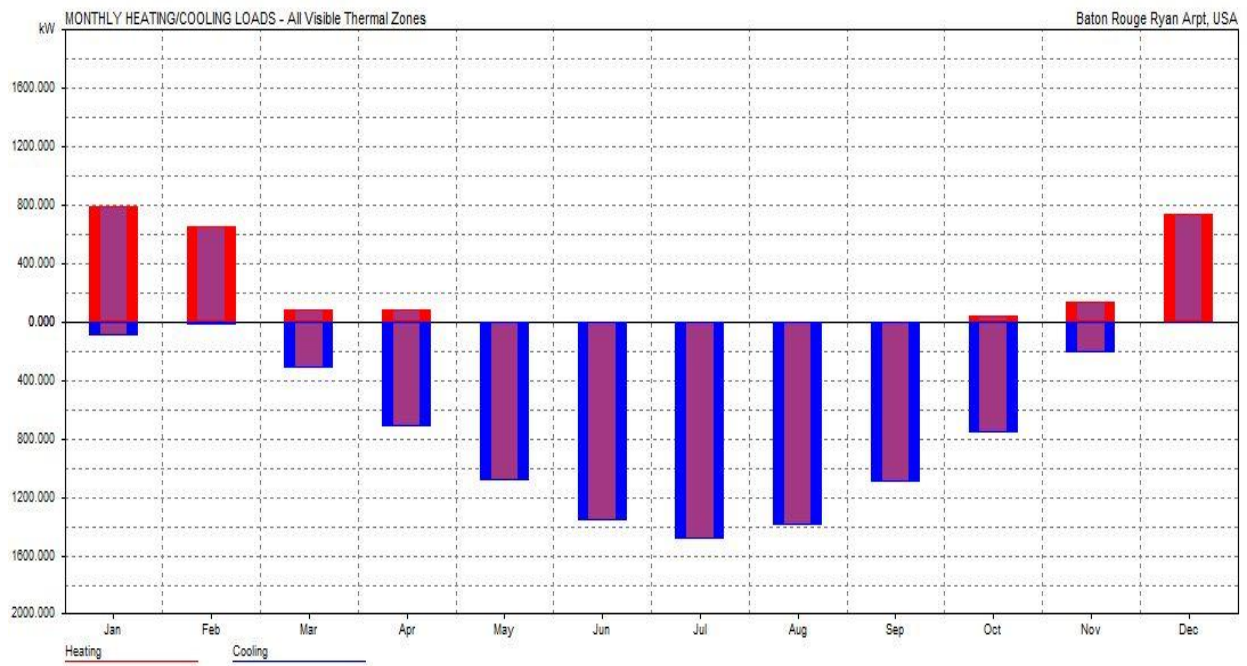


Figure 32: Monthly Heating /Cooling Loads for Advanced Framing

Table 19. Advanced Framing Energy Consumption for LaHouse garage

Month	Heating (H _L) (Kwh)	Cooling (C _L) (Kwh)	Electric (E _L) (Kwh)	Total Energy (TE _U) (Kwh)
January	794.630	98.597	311.321	1204.548
February	659.008	24.739	280.230	963.977
March	88.506	312.054	310.077	710.637
April	79.447	712.785	299.714	1091.946
May	0.000	1085.897	311.321	1397.218
June	0.000	1357.080	299.714	1656.794
July	0.000	1483.381	310.077	1793.458
August	0.000	1397.052	311.321	1708.373
September	0.000	1093.194	298.470	1391.664
October	41.716	756.881	311.321	1109.918
November	134.247	207.591	300.957	642.795
December	741.425	10.682	307.590	1059.697
Total	2538.98	8539.93	3652.05	14730.96

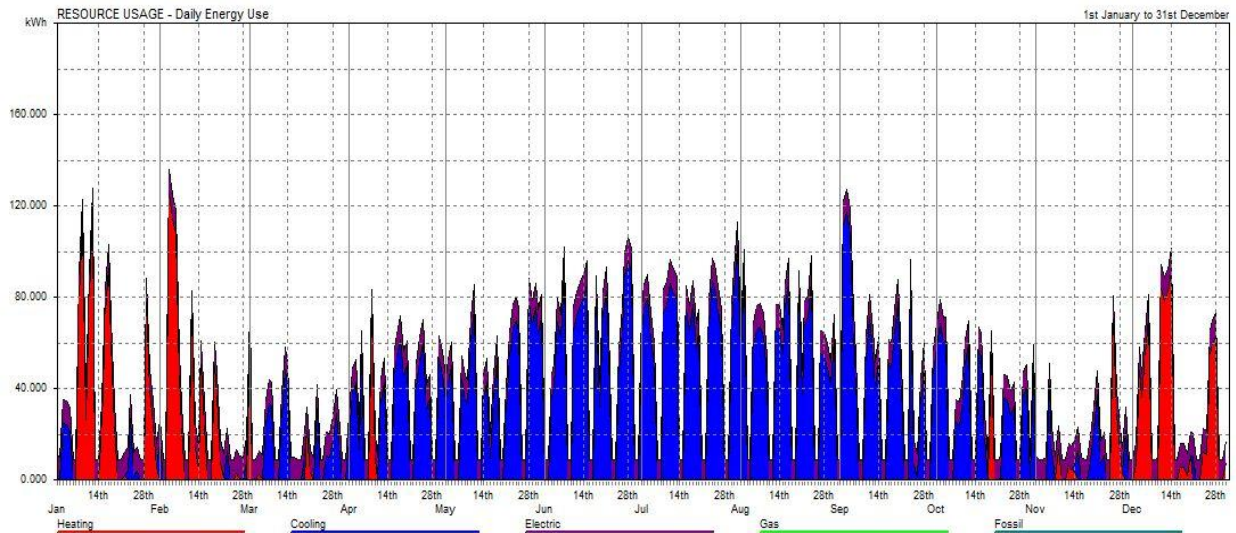


Figure 33: Resources Usage (Daily) for Standard Framing



Figure 34: Monthly Heating/ Cooling Loads for Standard Framing

Table 20. Standard Wood Framing Energy Consumption for LaHouse Garage

Month	Heating (H _L) (Kwh)	Cooling (C _L) (Kwh)	Electric (E _L) (Kwh)	Total Energy (TE _U) (Kwh)
January	934.685	108.375	311.321	1354.381
February	688.721	29.091	280.230	998.042
March	91.607	340.497	310.077	742.181
April	82.789	777.642	299.714	1160.145
May	0.000	1174.942	311.321	1486.263
June	0.000	1563.531	299.714	1863.245
July	0.000	1702.091	310.077	2012.168
August	0.000	1607.455	311.321	1918.776
September	0.000	1282.879	298.470	1581.349
October	155.560	931.465	311.321	1398.346
November	244.335	328.844	300.957	874.136
December	986.319	110.284	307.590	1404.193
Total	3184.015	9957.098	3652.058	16793.17

Figures 35, 36 and 37 show the graphs for heating, cooling and total energy loads for different framing systems according to the Autodesk® Ecotect Analysis results.

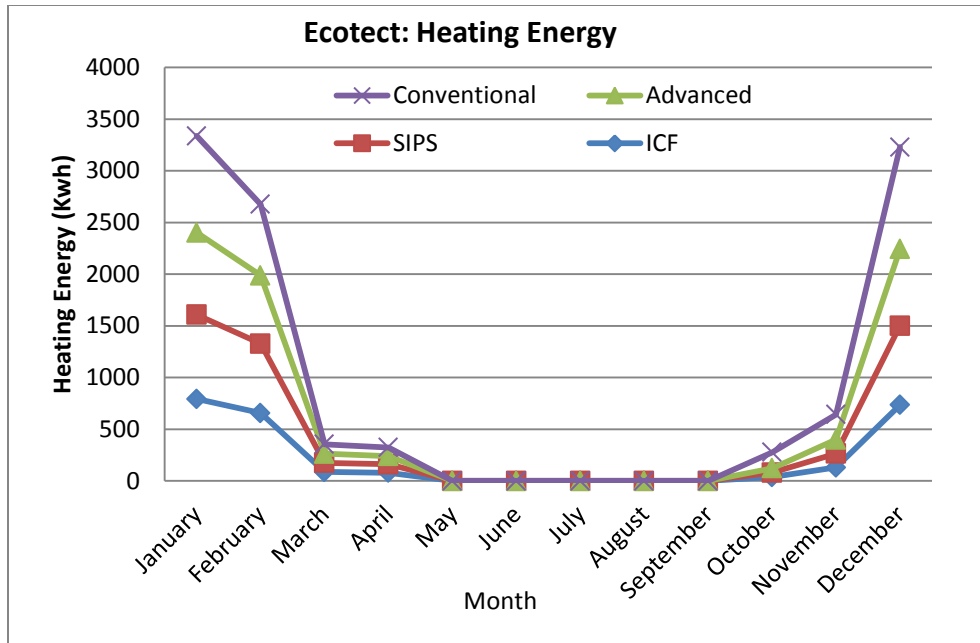


Figure 35: Heating loads for different framing systems from Autodesk® Ecotect Analysis

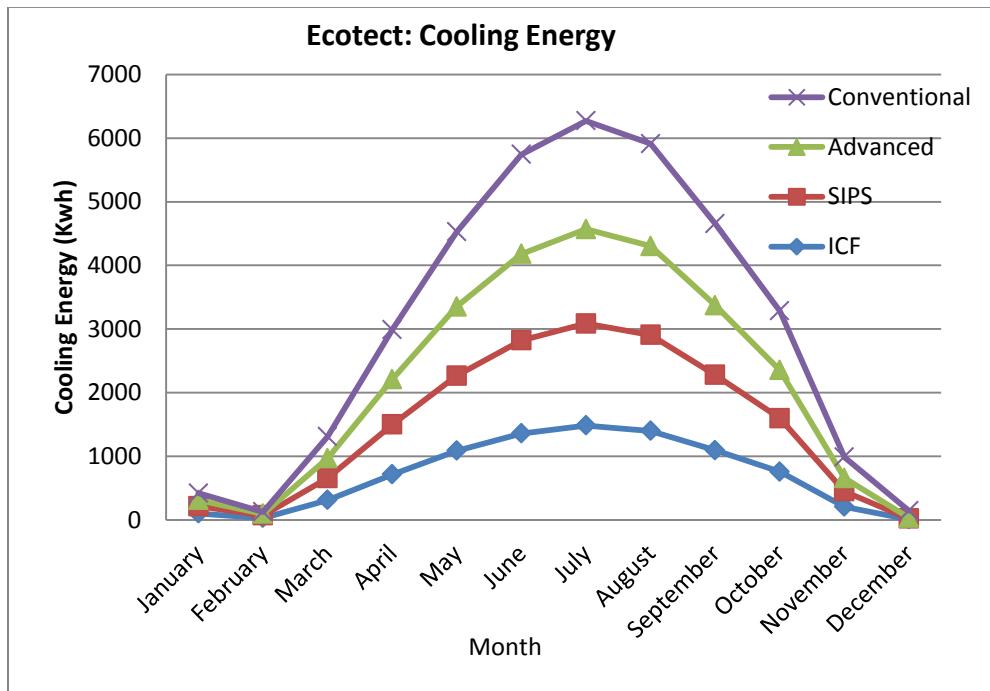


Figure 36: Cooling Loads for different framing systems from Autodesk® Ecotect Analysis

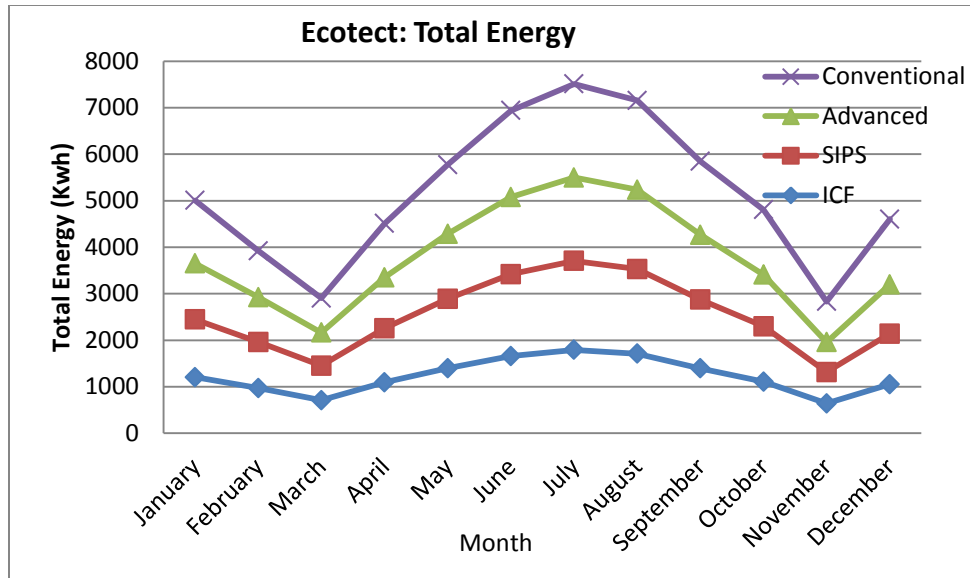


Figure 37: Total Energy for different framing systems from Autodesk® Ecotect Analysis

4.3.2(A) Statistical Analysis of Autodesk® Ecotect Analysis Results

Statistical analysis of the simulation results for the four different framing types was performed using Sigma Plot®. Results from the statistical analysis are described in the following paragraphs.

The heating results data failed the normality test but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the heating values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of the performed test (0.049) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

The cooling results data for the four framing types failed the normality test but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the cooling values, the analysis concluded that there was no statistically significant difference in the mean

values. However, the power of the performed test (0.049) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

The electric results data for the four framing types using Autodesk® Ecotect Analysis are identical due to the inputs, so no statistical analysis was performed.

The total results data failed the normality test, but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the total energy values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of the performed test (0.049) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

4.3.2 (B) Economic Analysis for Autodesk® Ecotect Analysis Results

Using Equations 1 and 2 the total energy consumption and its energy costs are calculated and tabulated in Table 21.

Table 21. Energy Utilization and Energy Costs for each Framing Types by Autodesk® Ecotect Analysis

Type	Total Energy Utilization(TE_U)	Annual Energy Usage/ ft^2	Total Energy Costs (TE_C)($\\$)
ICF	14736.34	12.32	1326.27
SIPS	15562.56	13.01	1400.63
Advanced Framing	14730.96	12.32	1325.79
Standard Framing	16793.16	14.04	1511.38

Construction costs for the innovative framing systems are higher when compared to standard framing. Using Equation 3, the simple payback period is computed and shown in Table 22.

In Autodesk® Ecotect Analysis, the annual consumption rate is lower than the actual consumption. In the same way, the annual savings are less than the EnergyPlus results. The

simple payback period for ICF is 19.7 years due to its higher initial costs. According to the Autodesk® Ecotect Analysis results, the advanced framing has the shortest payback period of 3.6 years, while the SIPS framing system has a payback period of 9.12 years.

Table 22. Simple Payback Period with respect to Standard Framing

TYPE	Annual Energy Usage (Kwh)	Variation of Energy to standard (Kwh)	Total Electricity Cost (\$)	Annual Energy Savings (\$)	Construction Costs (\$)	Variation of Construction Costs with standard (\$)	Simple Payback Period (years)
ICF	14736.34	2056.82	1326.27	185.1	25800.1	3647.5	19.7
SIPS	15562.56	1230.60	1400.63	110.7	23162.8	1010.34	9.12
Advanced	14730.96	2062.2	1325.79	185.5	22836.2	683.7	3.68
Standard	16793.16	0	1511.38	0	22152.5	0	0

4.3.3 Energy Consumption for Different Framings by IES VE-Pro Energy Results

Tables 23-26 show the simulation results from IES VE-Pro for ICF, SIPS, Advanced framing and Conventional framing types. Figures 38-40 provide the energy utilization for heating, cooling and total loads for different framing systems as per IES VE-Pro simulation results. Model was updated for each of the different framing systems and the results are as follows:

Table 23. ICF Framing Energy Consumption for LaHouse Garage per IES VE-Pro

Month	Heating, Kwh	Cooling, Kwh	Electric, Kwh	Total Electricity, Kwh
January	573.61	94.76	359.01	1027.38
February	488.20	67.45	324.13	879.78
March	45.30	408.56	359.01	812.87
April	53.69	634.92	347.28	1035.89
May	0	900.38	359.01	1259.47
June	0	1028.03	347.28	1375.31
July	0	1068.16	359.01	1427.17
August	0	1006.88	359.01	1365.89
September	0	909.04	347.28	1256.32

(Table 23 Continued...)

October	0	649.33	359.01	1008.34
November	268.48	306.21	347.28	921.97
December	415.10	49.65	359.01	823.76
Total	1844.38	7123.37	4226.32	13194.15

Table 24. SIPS Energy Consumption for LaHouse Garage per IES VE-Pro

Month	Heating, Kwh	Cooling, Kwh	Electric, Kwh	Total Electricity, Kwh
January	743.89	195.63	359.01	1298.53
February	539.66	296.64	324.13	1160.43
March	39.57	596.44	359.01	995.02
April	53.69	866.36	347.28	1267.33
May	0	1009.57	359.01	1368.58
June	0	1268.85	347.28	1616.13
July	0	1475.83	359.01	1834.84
August	0	1479.57	359.01	1838.58
September	0	1064.74	347.28	1412.02
October	196.64	847.36	359.01	1403.01
November	196.57	479.876	347.28	1023.726
December	419.7	56.75	359.01	835.46
Total	2189.72	9637.616	4226.32	16053.66

Table 25. Advanced Framing Energy Consumption for LaHouse Garage by IES VE-Pro

Month	Heating, Kwh	Cooling, Kwh	Electric, Kwh	Total Electricity, Kwh
January	679.67	106.84	359.01	1145.52
February	576.62	94.83	324.13	995.58
March	73.86	585.92	359.01	1018.79
April	84.41	736.42	347.28	1168.11
May	0	1006.73	359.01	1365.74
June	0	1184.63	347.28	1531.91

(Table 25 Continued...)

July	0	1285.84	359.01	1644.85
August	0	1375.84	359.01	1734.85
September	0	1073.53	347.28	1420.81
October	0	739.75	359.01	1098.76
November	312.95	286.95	347.28	947.18
December	396.86	38.53	359.01	794.4
Total	2124.37	8515.81	4226.32	14866.5

Table 26. Standard Framing Energy Consumption for LaHouse Garage as per IES VE-Pro

Month	Heating, Kwh	Cooling, Kwh	Electric, Kwh	Total Electricity, Kwh
January	765.93	179.9	359.01	1304.84
February	543.56	232.86	324.13	1100.55
March	106.34	498.09	359.01	963.44
April	34.56	842.95	347.28	1224.79
May	0	1278.45	359.01	1637.46
June	0	1297.69	347.28	1644.97
July	0	1529.54	359.01	1888.55
August	0	1538.39	359.01	1897.4
September	0	1385.54	347.28	1732.82
October	156.76	837.94	359.01	1353.71
November	483.67	531.94	347.28	1362.89
December	623.95	69.23	359.01	1052.19
Total	2714.77	10222.52	4226.32	17163.61

The heating, cooling, electric and total loads provided in the above tables are shown in the form of figures. The electric loads are equal in all types of framing systems because it depends on the internal equipment loads and doesn't depend on the framing type. The heating, cooling and total energy of all framing types are shown in following figures.

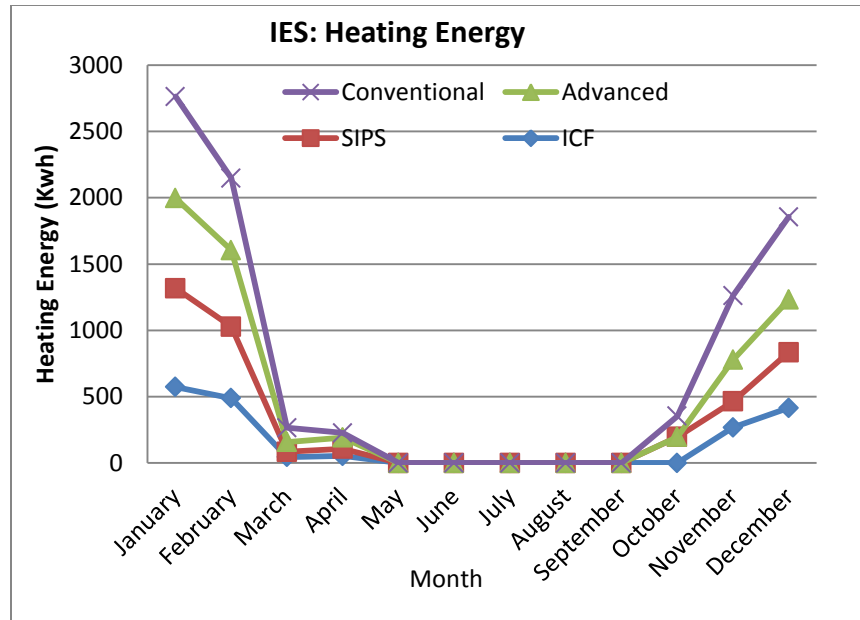


Figure 38: Heating Loads for different framing types from IES VE-Pro

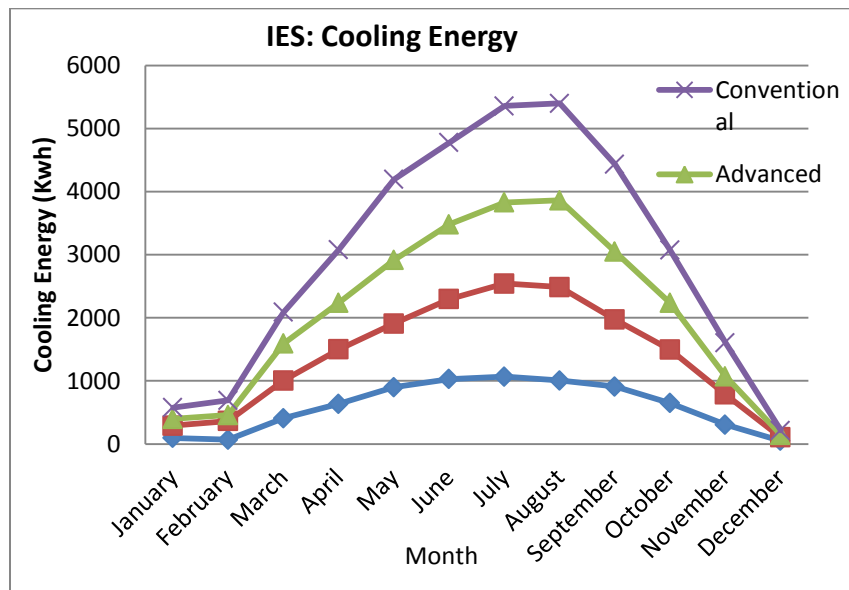


Figure 39: Cooling Loads for different framing types from IES VE-Pro

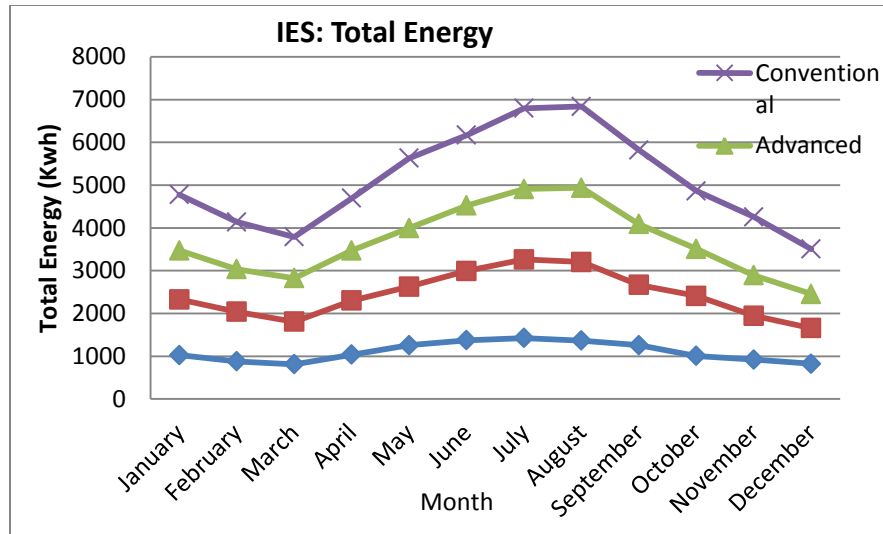


Figure 40: Total Energy utilized for different framing types from IES VE-Pro

4.3.3 (A) Statistical Analysis for IES VE-Pro

Statistical analysis of the simulation results for the four different framing types was performed using Sigma Plot[®]. The results of the statistical analysis are discussed in the following paragraphs.

The heating results data failed the normality test but passed the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the heating values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of the performed test (0.049) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

The cooling results data passed both the normality test and the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the cooling values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of

the performed test (0.049) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

The electric results data for the four framing types using IES VE-Pro are identical due to the inputs, so no statistical analysis was performed.

The total results data passed both the normality test and the equal variance test. A one way analysis of variance was performed to determine if there was a significant difference in the mean values for each simulation results. In the case of the total energy values, the analysis concluded that there was no statistically significant difference in the mean values. However, the power of the performed test (0.429) was below the desired power of 0.8, which indicates less likelihood of detecting a difference when one actually exists.

4.3.3 (B) Economic Analysis

Using Equations 1 and 2 the total energy consumption and the corresponding energy costs for each framing system are calculated and tabulated in Table 27.

Table 27. Energy Utilization and Energy Costs for Each Framing Types as per IES VE-Pro

Type	Total Energy Utilization(TE_U) Kwh	Energy Usage per Sq. foot annually(Kwh)	Total Energy Costs(TE_C)in \$
ICF	13194.15	11.03	1187.47
SIPS	16053.66	13.42	1444.82
Advanced Framing	14866.5	12.43	1337.98
Standard Framing	17163.61	14.35	1544.72

The construction cost estimates for each framing type were then computed using estimates provided by LaHouse personnel. Only the construction costs related to the framing was included in this calculation. Table 15 details the construction components and associated costs that were used in determining the construction cost estimate.

Table 28.Simple Payback period with respect to Standard Framing according to IES VE-Pro Results

TYPE	Annual Energy Usage (Kwh)	Variation of Energy Usage with standard (Kwh)	Total Electricity Cost (\$)	Annual Energy Savings (\$)	Construction Costs (\$)	Variation of Construction Costs to standard (\$)	Simple Payback Period (years)
ICF	13194.15	3969.46	1187.47	357.25	25800.1	3647.5	10.2
SIPS	16053.66	1109.95	1444.82	99.9	23162.8	1010.34	10.1
Advanced	14866.5	2297.11	1337.98	206.74	22836.2	683.7	3.3
Standard	17163.61	0	1544.72	0	22152.5	0	0

From IES VE-Pro energy analysis, the annual consumption simulation results are lower than the actual consumption. The simple payback period for ICF is 10.2 years due to its higher initial costs. According to the IES VE-Pro simulation results, advanced framing has the lowest payback period of 3.3 years, while ICF and SIPS has almost same payback period of 10 years.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

The first goal of this research was to assess the ability of BIM integrated energy simulation modeling to accurately predict the energy performance of a building. Three different simulation software tools, EnergyPlus, IES VE-Pro and Autodesk® Ecotect Analysis, were used in a case study based comparison. The input model for all the simulation tools used was the as built BIM of the garage portion of LaHouse. The annual energy consumption values from each of these software's were compared with the actual data collected by the performance monitoring system installed in the garage. EnergyPlus produced the smallest deviation (+ 1.37%) from the actual results, while Autodesk® Ecotect Analysis and IES VE-Pro both underestimated the energy consumption with deviations from the actual of – 29.8% and -32.41% respectively. Statistical analysis of the results indicated that there is a significant difference between both the Autodesk® Ecotect Analysis and IES VE-Pro results when compared to the actual monitoring energy usage, while there was no significant difference between the EnergyPlus results and the actual values. Hence EnergyPlus proved to be the most accurate analysis simulation tool utilized in this case study.

The second goal of this research was to compare the predicted energy performance for four different residential framing systems through the integration of building information modeling, energy simulation and performance monitoring. Building information models of the LaHouse garage were created for each of the four framing systems. By changing the material properties of the exterior walls, different simulations were run using EnergyPlus, Autodesk® Ecotect Analysis, and IES-VE Pro. Statistical analysis was performed to determine if there were significant different among the simulation results for each framing system. In the case of EnergyPlus, the ICF total energy usage was significantly different from both the conventional

framing results and the advanced framing results. There were no statistically significant differences in any of the other results. Statistical analysis of both the Autodesk® Ecotect Analysis results and the IES-VE Pro results for the four framing systems found no significant differences in the energy consumption predicted for the four framing systems.

A simple payback method was utilized with estimated initial construction costs and predicted energy cost savings from each of the three simulation engines to compare the three innovation framing systems with respect to standard framing. Each of the three simulation tools predicted different payback periods for the innovative framing systems. Using the EnergyPlus predicted energy consumption and corresponding energy cost savings, SIPS resulted in the shortest payback period at 2.55 years, followed by advanced framing with a payback period of 5.03 years and ICF with a payback period of 5.67 years. Results from Autodesk® Ecotect Analysis energy consumption and corresponding energy cost savings indicated that advanced framing would result in the shortest payback period at 3.58 years, followed by SIPS at 9.12 years and ICF at 19.7 years. Finally, IES-VE Pro energy consumption results with the corresponding energy cost savings found that advanced framing produced the shortest payback period at 3.3 years, followed by SIPS at 10.1 years and ICF at 10.2 years. Given that EnergyPlus generated results closer to the actual energy consumption data from the LaHouse garage, it is assumed that the ranking of the three innovative framing systems based on the EnergyPlus results more accurately reflects reality. However, the different results and corresponding rankings by the three different simulation engines highlights the need for further research into assessing simulation tools and their ability to accurately predict energy consumption.

5.1 Recommendations

The present study is limited in that actual performance results were only available for the case of ICF framing. This study can be extended to assessment of other framing systems and simulation tools with actual performance data. In addition, this study only included six months of actual performance data. Further data collection and analysis is recommended for future research.

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APPENDIX: BENCHMARK MODEL ENERGY DETAILS

The values shown here is the benchmark model results as established by the Department of Energy. The area of the benchmark model is 5502 square ft. and the case study LaHouse is 1196 square foot. Therefore, the values for comparison of energy consumption are Kwh per square foot for each type of energy.

	INTERIOR LIGHTS[Kwh]	EXTERIOR LIGHTS [Kwh]	EQUIPMENT [Kwh]	FANS [Kwh]	COOLING [Kwh]	HEATING [Kwh]	COGENERATION :GAS [Kwh]	TOTAL [Kwh]
Jan	1313.96	979.16	2052.07	914.45	141.44	1845.64	260.19	7506.91
Feb	1191.86	840.59	1857.37	825.38	81.21	859.39	235.01	5890.81
Mar	1416.26	868.23	2127.97	957.62	436.31	71.49	260.19	6138.07
Apr	1265.01	775.34	1981.39	880.69	846.68	34.13	243	6026.24
May	1365.11	746.17	2090.02	1008.14	1624.54	0.22	247	7081.2
Jun	1358.51	693.2	2050.42	1044.22	2115.81	0.47	234.65	7497.28
July	1271.61	731.2	2020.99	1092.2	2316.34	0.59	236.88	7669.81
Aug	1416.26	776.88	2127.97	1136.99	2358.03	0.5	239.96	8056.59
Sep	1265.01	811.42	1981.39	1026.14	1710.87	2.87	233.77	7031.47
Oct	1313.96	905.85	2052.07	892.16	977.85	29.59	247	6418.48
Nov	1298.56	932.33	2005.59	856.33	329.53	165.2	245.2	5832.74
Dec	1271.61	996.05	2020.99	875.01	33.48	1316.52	256.67	6770.33
Annual Sum	15747.75	10056.43	24368.26	11509.33	12972.09	4326.61	2939.53	81919.93

VITA

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