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Roof Design Efficiency for Energy Consumption in Residential Units

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This project investigates roof efficiency designs in the southeastern United States homes by creating a workflow for efficient roofing design. For this purpose, multiple 3D models are generated with different floorplan sizes and lower roof heights from the original pitch. This is done to find the most effective pitch in cost and performance, while still satisfying codes and local regulations. A Building Information Modeling (BIM) software package from Autodesk (Revit) is employed in this process along with an add-on, Metal-Wood-Framer (MWF), to create detailed models of the involved structures. Then, due to its compatibility with Revit and its parametric energy analysis, the Autodesk Insight platform was selected to further analyze the models. Results from Autodesk Insight provided information on Energy Use Intensity (EUI) and cost mean while comparing against Architecture 2030 and ASHRAE 90.1 standards. The RS Means catalog was employed to estimate the cost of roof construction. In the modified models, the cost of roof construction is lower than in the original models because less material is needed. However, findings indicate that, in the modified models, the EUI and cost mean is higher than in the original models, which may be due to heat gain/losses and lack of ventilation.

Key Words: design, roof, geometry, energy efficiency, cost analysis

Introduction, Objective and Literature Review

Roof design is an important factor to consider when designing residential structures. With the cost of construction rising, there is a new demand for cost-effective design/construction assemblies. The use of 3D BIM can assist with this task. Varying the roof pitch could lower its costs and also modify the energy performance of the associated building (Roof Replacement Cost, 2018). The purpose of this study was to analyze ten different residential buildings with different square footages, in order to see if lowering the roof pitch of their roofs would increase energy performance. This study focuses on homes in the southeast region of the USA. It analyzes their upfront costs and their solar efficiency versus more common roof designs. The way roofs are designed and constructed has not changed much overtime. So, it is conceivable that the current popular roof geometry may not be the most affordable or energy efficient. The selected roofs were geometrically similar because most roofs in the Southeast region have an average roof pitch of 9”/12”, or higher. This causes the quantity and cost of the involved materials to be relatively high. The average cost of a new roof, in the southeast region, is increasing (Roof Replacement Cost, 2018). Modern roofs, regardless of their geometrical shape, consist of five components which include structural framing, sheathing, underlayment, gutters, and finished surfaces (Vandervort, 2014). However, with some modifications applied to roof components, the price of a new roof construction can be lowered. This can be done by lowering the pitch of the roof in order to meet minimum code requirements and local regulations. High roof pitches are not required in most areas in the Southeast region. Another alternative to lower roof prices is to reconsider the materials used in new roof construction. Some of these materials may include different framing lumber sizes, different kinds of thermal protection, and/or different kinds of surface finishes. BIM software can be used to efficiently create new roof designs, t. Using BIM will facilitate a collaborative process in which multiple trades can be involved in planning, design, and construction (Lorek, 2018). Designers and contractors may use BIM services to generate 3D models that could assist owners in making informed decisions (Hergunsel, 2011). Some of the BIM-related software employed for this purpose may be Autodesk AutoCAD, Autodesk Revit, Revit add-on MWF, Rhinoceros, and Rhinoceros add-on Grasshopper. The use of BIM software can facilitate the process of designing a new roof. Additionally, it can make the roof more modular which, in return, can make it cheaper and its construction safer. For the purpose of this project, only two software programs were considered for design authoring, Autodesk Revit and the MWF add-on to Revit.

Since the construction industry is a heavy consumer of raw materials and one of the largest contributors to waste generation, i.e., about 40% of the materials that are dumped in landfills are construction waste (Yuan et. al., 2017), there is a strong public interest in reducing this waste. By using BIM/parametric software (e.g., Rhinoceros add-on Grasshopper, Autodesk Revit, etc.) there can be a reduction in construction waste (Yuan et. al., 2017). This may be achieved by predesigning the members in Autodesk Revit and then employing the quantity take-off function to extract the amounts of materials before the construction phase begins. Using Revit can benefit users with real-time quantity amounts that automatically adjust when design changes are made. This assists in cost-sensitivity analysis that could save time, money, and materials (Zhao et. al., 2015). In this study the Insight platform was used to investigate roof design efficacies for lower energy consumption, due to its compatibility with Revit and its parametric energy analysis capability. In order to get consistent results relative to the energy model outputs (and analysis in the cloud platform) other “variables” were maintained “constant” (i.e., envelope materials of the residential units) over the selected models.

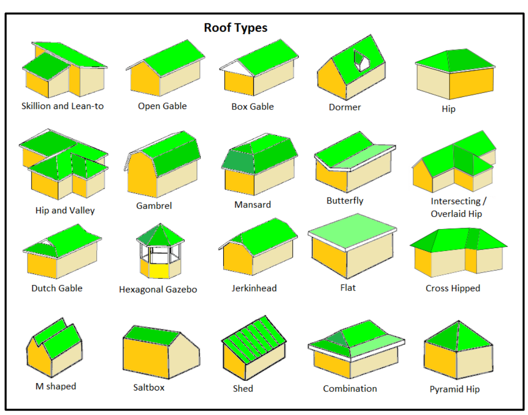

Figure 1. Roof Types (Roofing Calculator, 2019)

Most of the residential structures in southeastern cities have a similar roof design. As seen in figure 1, some of the most common roof structures in this region are a gable, open gable, hip, hip & valley, and cross-hipped. The advantages of the gable roof style is that it easily sheds water and snow, and due to the high pitch in gable roofs, they have large attic space, which is good for ventilation purposes (Roofing Calculator, 2019). However, a gable roof style is problematic in high winds and hurricane areas as some structural members of the roof may not be properly secured and, if the overhang of the roof is too large, the wind could cause uplift (Roofing Calculator, 2019). The advantages of the hip style roof is the strength inherit in the design for example hip roofs perform better in high wind environments (Roofing Calculator, 2019). However, a hip roof style is usually more costly to build compared to a simple gabled roof because it requires more material(Roofing Calculator, 2019).

The roofs of buildings include rafters, ridge board, ceiling joist, struts, and hangers as seen in figure 2 below. The ceiling joists span from the width of the building exterior wall to a center load-bearing wall. The rafters support the main assemblies and determine the roof pitch. The rafters meet at the top at the ridge board which is the highest line on a roof structure. The struts and the hangers are also known as the web, these parts structurally support the rafters and ceiling joists. The most common material used when building these structures is wood. However, the finishes on the roof may vary by owner's preference. The most common roof finishes materials used in the southeast region are asphalt shingles and/or metal panels.

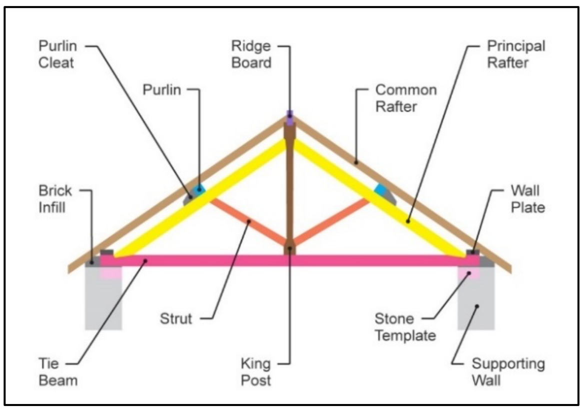

Figure 2. Roof Structure (Home Stratosphere, 2018)

A Cloud-Based Building Energy Analysis Tool

Autodesk Insight

There are several companies that produce software focusing on building performance analyses. One of these software applications is Autodesk Insight, a powerful cloud-based tool that assists users in improving the energy and environmental performance of any model that is parametrically authored in Autodesk Revit. Some of the features found on Insight are real-time feedback, BIM integrations, complete building energy analysis and several more (Introducing Autodesk Insight 360, 2015). To accomplish complete building energy analysis, Insight focuses on heating and cooling loads, day lighting analyses, and solar radiation analyses (Wagner, 2017). Once Insight finishes all analyses of the elements stated above, the results can be outputted as seen in figure 3 below. Figure 3 illustrates several Insight features, such as Benchmark Comparisons, EUI, and model history. To obtain the EUI, Autodesk Insight considers several different factors, such as HVAC systems, lighting power density, and glazing properties (Wagner, 2017). Once it gathers all the parameter that determine annual energy usage, it divides it by the total area of the building, to obtain a normalized quantity by square footage. The result shows maximum, mean, and minimum EUI.

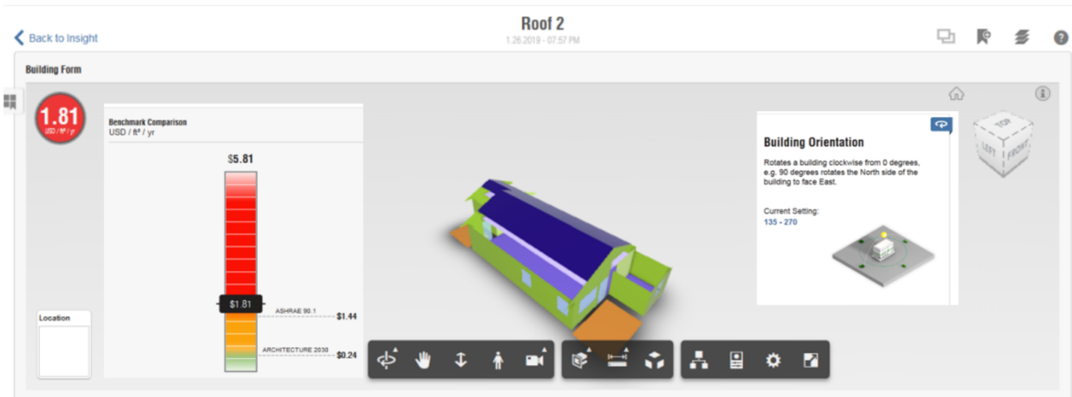

Figure 3. Autodesk Insight Output

The maximum is related to the highest amount of money in EUI dollars, the mean is the average, and the minimum is representing the least amount of money needed for a particular design which, in some instances, can be negative. Users receive results expressed in energy use per area and per year. The Insight computations also show comparisons of the current model's EUI with respect to ASHRAE 90.1 and Architecture 2030 benchmarks (Wagner, 2017). The first standard for comparison is ASHRAE 90.1 which is the energy standard for buildings, except for low-rise residential structures. Insight looks at four major factors, which are the building envelope, HVAC systems, power and lighting system, and complete building energy performance. All these components may vary by location. The building envelope requirements cover the thermal performance of the building envelope (roofs, walls, floors, and doors). For walls and roofs, the thermal requirements are given in terms of either the maximum allowable U-factor 4 or the minimum insulation R-value 5, and can vary on location (Crall, 2009). The HVAC systems requirement of the air ducts and pipes must have a minimum R-value of the building code location. They must also meet energy-efficiency ratios (EER). EER measures energy efficiency at peak loads while the integrated energy-efficiency ratio (IEER) measures annual load efficiencies. Residential equipment must meet seasonal energy-efficiency ratios (SEER) which rate efficiency over a range of outdoor air temperatures. All are expressed in Btu/W*hr., where 3.4 Btu/W*hr. = 1.0 COP (Coefficient of Performance) (Boldt and Rosenberg, 2018).

The second standard that Insight compare models against is Architecture 2030 which started in 2007 and is now adopted by 839 US cities. The goal of the Architecture 2030 challenge is to reduce 100% the world Greenhouse Gas (GHG) emissions by 2030. It states that all new construction must be designed to high-energy efficiency standards and by 2050 these sites must be carbon neutral as well. To receive the Architecture 2030 benchmark in Autodesk Insight, the software tracks the carbon footprint of the model in real-time (AIA 2030 Commitment, 2019). Architecture 2030 provides five steps that can help realize this. The first step is establishing a EUI baseline using Autodesk Insight (Architecture 2030, 2019). The second step is to apply low/no-cost passive design strategies to achieve maximum energy efficiency (Architecture 2030, 2019). These low/no-cost passive design strategies can be related to building orientation, optimizing daylight, solar heat gain, etc. The third step is integrating energy efficient technology and systems (Architecture 2030, 2019). This technology can be programmable thermostats, energy efficient air conditioners, LED lighting, etc. The fourth step will be to incorporate on-site/off-site renewable energy to meet the remaining energy demands such as solar panels (Architecture 2030, 2019). And the last step is to engage in iterative energy modeling throughout the entire design (Architecture 2030, 2019).

Energy Model Output

After the analysis is completed, Autodesk Insight displays the building performance output as seen in Figure 3 above. Some of the outputs include building orientation, daylight & occupancy control, HVAC, infiltration, light efficiency, operating schedule, plug load efficiency, PV (panel efficiency, payback limit, and surface coverage), wall construction, roof construction, window glass, window shades, and window wall ratio (WWR) for various asphalt shingles and metal panel roofs considered in this study.

- Building Orientation shows “the process of rotating the building from 0 to 90 degrees (north to face east)” for a more efficient EUI and cost mean; Daylight & Occupancy Control “shows the process of using a daylight dimming and occupancy sensor system” for a more efficient EUI and costs mean (Autodesk, 2015).
- HVAC shows “a range of HVAC system efficiency, which will vary, based on location and building size”; Infiltration shows “the unintentional leaking of air into or out of conditioned space; often due to gaps in the building envelope” (Autodesk, 2015).
- Light efficiency “shows the average internal heat gain and power consumption of electric lighting per unit floor area”; Operating Schedule shows “the typical hours of use by building occupants” (Autodesk, 2015).
- Plug Load Efficiency shows “the cost of power used by equipment (computers, small appliances, etc.) excluding lighting, heating and cooling equipment”; PV shows “the efficiency, surface coverage, and the payback period of the solar panels”; Wall construction shows “the overall ability of wall construction to resist head losses and gain”; Roof construction shows “overall ability of roof construction to resist heat losses and gain”; Window Glass show “glass properties controlling the amount of daylight, heat transfer and solar heat gain into the building along with other factors”; Window shades show “how to reduce HVAC energy use. The impact depends on the other factors, such as window size and solar heat gain properties”; Window Wall Ratio shows “the interaction with windows properties to impact daylight, heating, and cooling” (Autodesk, 2015).

Experimental Research Methodology

All models used in this research were authored through Autodesk Revit software. The energy analysis completed in this project was performed with Autodesk Insight cloud platform. The RS Means catalog was utilized to create a parallel real-time simulation on cost analysis. The add-on software (MWF) was used to create the actual structure of the roof. It was provided by StrucSoft Solution with a student free trial (https://strucsoftsolutions.com). The floor plans were gathered from local architectural styles to be fitted for the SE-region construction means and methods. Ten floor plans were selected. They all corresponded to residential structures, ranging from 868 Sq Ft (2 Bedrooms, 1 1/2 bathroom) to 4064 Sq Ft (4 Bedrooms, 3 1/2 bathrooms). The style of the residential floor plans was chosen to match the style seen in the SE region of the state. Therefore, some included styles are Craftsman, Coastal Beach, Traditional, and Acadian. Ten structures were created, all the walls, ceilings and floors of the residential units were modeled with predetermined uniform layers. Additionally, all the doors and windows were configured the same to maintain consistency throughout the project experimental models and analyses. When it came to roofing materials, two were used as top layers: metal sheets and asphalt shingles. For this project, five (5) asphalt shingle models and another five (5) metal panel models were configured.

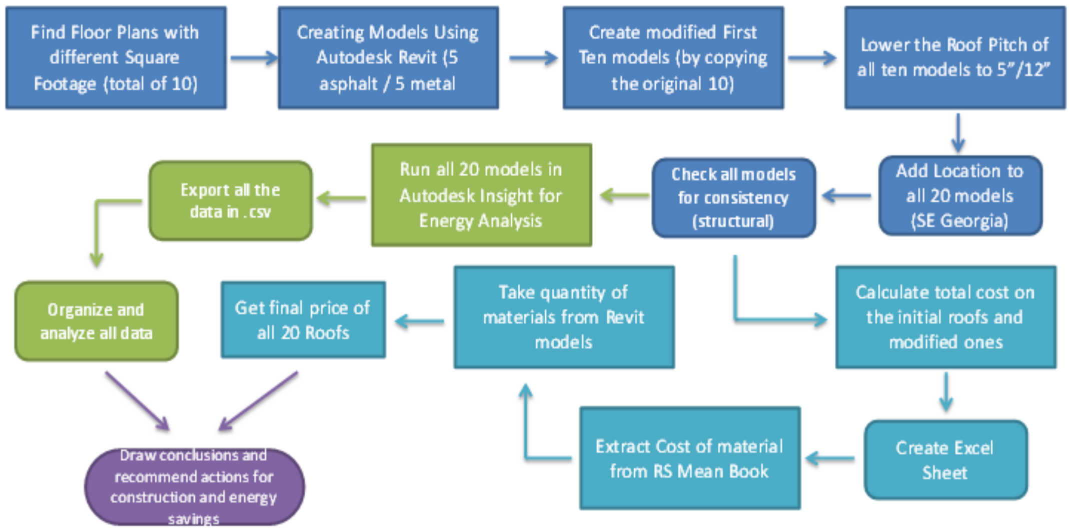

Figure 4. Research Methodology Flow Chart

According to the residential building codes and the local regulations where the project was situated, the minimum thickness of concrete slab on grade by code was 4" (on residential structures). However, in this study, a greater concrete thickness was selected for all the slabs used in the simulations. This preference was adopted to avoid affecting the building energy analysis relative to their thermal masses. After generating all models, the next step was to create the roof structures using MWF. Once these structures were incorporated into the models, the next task was to create the modified models. These models were an exact copy of the first ten (10) original models, with all the roofs lowered to 5"/12" pitch. This roof pitch was chosen because it was the lowest pitch allowed by the code in the SE region of the state. This pitch was also chosen for creating and testing a more efficient roof design. Then, the structure supporting the lowered roof was added by using MWF again (see flowchart in figure 4).

Models' Analysis for Energy Efficiency and Conclusions

Once all twenty (20) models were completed and checked for consistency, they were ready for analysis using Autodesk Insight. Locations were assigned to the models and the next step was to analyze them via the Insight cloud. All roof structures, previously generated via MWF, were included in the models during the analysis process. The energy optimization feature in Autodesk Revit was also used in this process. Once the analysis was completed, the end result showed Real-time feedback, BIM integrations, complete building energy analyses and several other parameters (introduced in Autodesk Insight 360, 2015), as seen at the following website: https://insight360.autodesk.com/oneenergy. Once all the analyses were done and availed for viewing in the cloud, the next step was to export the intermediate results to be further analyzed. All data was exported into a .csv file and then transferred to an MS Excel file for additional processing. In the Excel file, data obtained for each model was expressed as max., mean, and min. costs, in US dollars to power the building throughout the year. The cost mean represents the average cost to power the building throughout the year. The cost min meant the least cost to power the building throughout the year. It should be mentioned that, in some instances, the min cost could be a negative number. Even though in this project a cost analysis was performed to include the cost of all materials used in the roofs of all considered models, the main focus of this work was on the energy output and analysis/interpretation. This was done by generating ten (10) BIM models with their original roof pitches (provided by their actual designers), and by replicating them with lower roof pitches

(5”/12”). Autodesk Insight was used only to analyze and compare the performance of the modified building against that of the original models and RS Means catalog was used to estimate the material costs of each model style. It was decided to exclude the cost of labor, equipment, and tools from the cost comparison analysis due to a high variation on prices. The results are summarily presented in figures 5 and 6 (where OG refers to the “original roofs” and Mod refers to the “modified roofs”). At the beginning of this project, it was assumed the modified models would be less expensive to build and they will attain a better energy performance than the original models on a yearly basis. However, after analyzing the data it was observed that the original models were often less costly when it came to energy performance than the modified models. There were 2 exceptions Model 1 and Model 5 required less energy in after design modification. In Model 1, the cost mean of the modified model and EUI was lower than the original, therefore the EUI and cost mean is found lower in the modified model. However, in Model 5 the costs mean of the modified and original models are both the same, and the EUI is also held at very close values. From all the case studies, only Model 1 meets/beats the Architecture 2030 and ASHRAE 90.1 requirements. Most floor plans and their models were very close to satisfying the ASHRAE 90.1 requirements, with some minor modifications to the building envelope and building orientation. Nevertheless, the other models met ASHRAE 90.1 thresholds. Regarding the cost of construction, the modified models are less expensive as less materials were required to build them (i.e., lower pitches resulted in less roof surface). However, when considering the prices per square foot (unit prices), the modified roof models were more expensive than the original models.

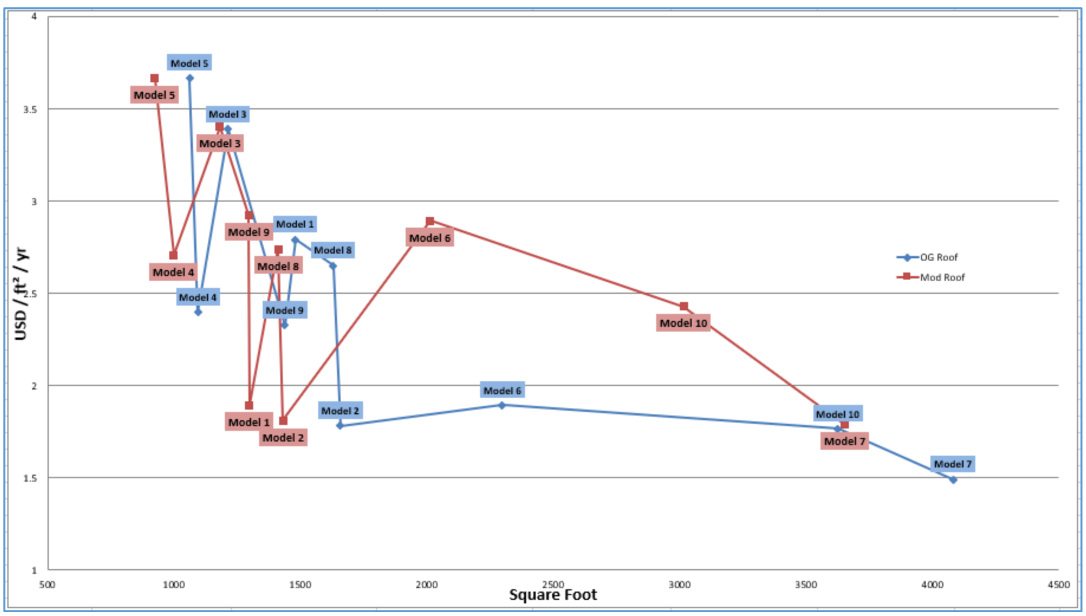

Figure 5. Cost Mean to Roof Square Footage Comparison

Adding to the body of knowledge, when further examining the data, it can be observed that the 5”/12” roof pitch is not the most effective roof when it comes to building performance. This result may have happened because of the reduced space for air circulation associated to the modified roofs. It may have also caused by the heat gain/loss which may increase on 5/12 pitch roofs. Once heat gain/loss increases in the building, the EUI will also increase with it due to the higher demand on the HVAC systems. Even though the low pitch would save the occupant of the building costs in the construction process, in the end, the occupant(s) would actually start losing money after the payback period is completed and therefore one conclusion would be to not recommend lower pitched for humid climate zones such as the southeast United States.

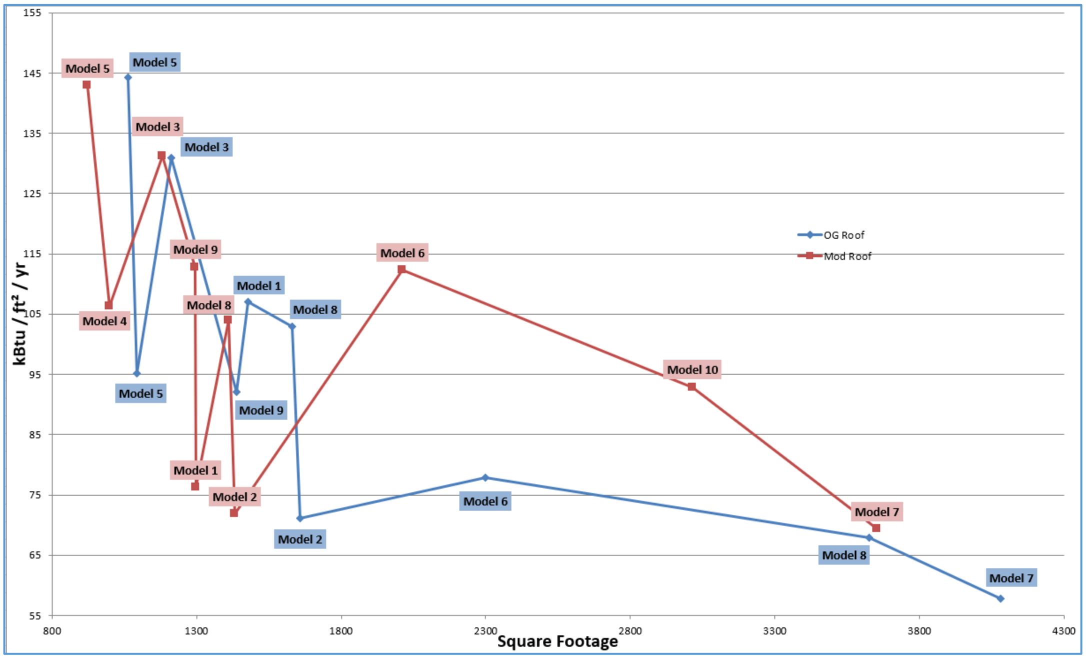

Figure 6. EUI Mean to Roof Square Footage Comparison

For future research another location, such as a city in the northeast region of the United States, could be investigated to determine if increasing or decreasing incrementally the pitch of the roof affects the building energy performance in severe cold winters with large amounts of snow. When choosing another location, the local building codes would need to be analyzed to make sure the future project complies with local/state related codes. Another aspect which is of interest to the authors is how variations in material might affect the performance of residential roof structures (another study limitation). In this project, the insulation analyzed was rigid insulation. In future projects, other types of insulation with a higher R-value and different sized lumber could be used in the models, as such factors could potentially provide better energy performances.

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