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Energy Efficient Housing for the Lower Income Demographic: An Optimization Study

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ABSTRACT

This paper serves to act as a proof of concept for future research to be done on the optimization of single-family low income housing. This study examines the effects of climate location and four distinct building parameters on home construction cost and annual energy demand. The home construction parameters observed are wall stud and batt insulation thickness, attic insulation, window area, and air conditioner efficiency. The annual energy demand of each possible design was determined by computer energy modeling. The cost of each design was also determined based on construction type. With the annual energy demand and construction cost of each home design, an optimization was performed.

Future research on this subject is summarized by first making the residence as variable as possible, and then using a genetic algorithm to perform the optimization once the design space is expanded to full size.

1. INTRODUCTION

According to the United States Census Bureau (www.census.gov), the national average poverty rate from 2006 to 2008 was 13.2% of the population. Based on data from the United States Energy Information Administration (www.eia.doe.gov), 16.6 million households live below the poverty line with another 12.9 million households below 150% of the poverty line income. These 29.5 million households consume and pay for over a fifth of the nation's residential energy use. Given the current state of this nation's economy and such a poverty rate, the need for efficient, affordable housing is paramount.

The optimization of housing for the lower income demographic is an immensely complex problem with many possible objectives and constraints. When considering the possible level of detail and variability within a low income residential structure, the intricacies of this optimization problem become evident. The simplified model evaluation exhibited in this paper demonstrates that an optimization of housing for the lower income demographic is quite possible.

The research proposed not only stresses the need for efficient and affordable housing for the lower income demographic, but also housing that is sustainable. This is housing that a family that falls into the lower income category is able to afford to buy and then maintain. If these houses are built with energy efficient design concepts and construction practices in mind, the cost of the upkeep of the home can be dramatically reduced.

This paper acts as a proof of concept in that several aspects of the possible design space for a home are taken into consideration and varied to determine the optimal design(s) of the considered home characteristics.

2. LITERATURE REVIEW

Several studies have been performed using genetic algorithm optimization of technical building components for commercial construction, but not with regards to single-family residential housing. Several studies have examined the complex interaction of the building envelope and the heating, ventilating and air conditioning systems using genetic algorithms (Caldas and Norford, 2003). Another similar optimization study utilizing genetic algorithms for building envelope and heating, ventilating, and air conditioning interaction also used incremental input values and not discrete, realistic values for residential application. The study itself reports that "further research is required to investigate methods for improving the handling of equality constraints and to reduce the number of control variables (which will also improve the robustness of the algorithm)" (Wright and Farmani, 2001).

Building optimization studies have been performed in other manners as well. Models have been generated to optimize the building envelope construction using various methods with differing end goals in mind (Bouchlaghem, 2000). Day lighting optimization studies have been performed, but the main focus of the study examined was for a media center in Paris, France and made use of arbitrary cost functions. This study observed optimization of lighting and daylighting using an ant colony optimization model which is similar to genetic algorithms. This was a simplistic study that was to act as a proof of concept (Shea *et al.*, 2006). Another study observed the optimization of building envelope construction, but had no cost data and was used to study primarily the heat transfer through the building envelope in great detail (Ciampi *et al.*, 2003). The last study found observed the optimization of cost effective energy conservation measures with regards to the building envelope. The buildings modeled were a low rise and high rise building with non-variable building characteristics. The optimization method used was a Lagrangian method (Kim, 2010).

From the open literature reviewed, no research on single-family low income housing has been done with total building efficiency optimization. One study observed the effects of the housing set point temperature and retroactive remodeling of existing low income homes without central air conditioning in the United Kingdom. This was not primarily a construction optimization study, but an operation optimization study. (Milne and Boardman, 2000)

3. OBJECTIVES AND CONSTRAINTS

As stated, the main objective of this paper is to act as a proof of concept for further research on the optimization of stand alone, low income single-family residential housing. This study attempts to capture the variable effects of insulation, fenestration, ventilation and home location on the overall energy demand and construction material cost of various home constructions in different climate locations. The end result of this is to plot the design space and obtain a Pareto curve of optimal designs.

For the modeling of an optimization study, it is necessary that each parameter being observed have competing operational cost and construction cost functions. Varying a construction parameter that has a cost function that is directly related to its corresponding energy consumption cost function would result in an optimization that always favors the least costly and most energy efficient result. It is necessary that the cost function and energy usage functions be inversely related. These result in an optimal point or set of points at which the operation cost and construction cost are minimized. This can be reduced to a single value in combining the construction cost and operation cost into a lifecycle cost. By this method, a single and most optimal design can be selected. The caveat that comes with lifecycle costing with regards to low income housing is the unpredictability of the lifespan of materials, equipment, and time of occupancy in residential applications. Calculating an accurate lifecycle cost is very difficult because of these variations.

4. PARAMETRICS OF MODELING

The parametric variables studied through modeling all have a construction/material component, which affects the energy usage of the home, and a cost component which affects the construction cost of the home. For this optimization study, there were four different aspects of construction that were varied with respect to a low income home. The four parameters being observed in this study were selected with the intent to capture the effects of different major residential systems. The four categories observed in this study include exterior wall stud and insulation thickness, attic loose fill insulation depth, window area, and the air conditioning seasonal energy efficiency ratio (SEER). In addition to these construction parameters, the energy modeling was performed with a Chicago, Illinois weather data file and a Tampa, Florida weather data file to capture the climate location effects on energy usage. All costs are given in USD.

4.1 Stud and batt thickness

Wall stud and batt thickness was chosen to understand the effects of envelope insulation on cost and energy consumption. This parameter also captures the objective of a competing function because thicker studs with more insulation have a higher initial construction cost, but cause the home to use less energy. For this study, five discrete stud and batt dimensions were considered.

The stud spacing was assumed to be 16 inches (40.6 cm) on center for 2x4 and 2x6 studs, and was then increased to 24 inches (61cm) on center for 2x8, 2x10, and 2x12 studs. This was done in an attempt to introduce spread to the data as the thickest three walls will cost more, but the increased spacing will allow for more insulation in the wall. This results in a wall that is more cost intensive than a thinner wall, but is highly more efficient.

The cost of each stud and batt system was then calculated by taking several parameters into account. First, the cost of the studs was estimated by taking individual board costs from several widely available building material suppliers. The total number of boards was then estimated by summing the number of boards needed for the studs, the sill plate, the top plate, and an addition safety factor to account for windows, door frames, and frame connections. The number of studs was estimated by dividing the perimeter of the home by the stud spacing. The number of base plate boards was estimated by assuming a single base plate and dividing the perimeter of the home by an assumed standard eight foot (2.44m) length. A double top plate was calculated in the same manner as the base plate. A safety factor of 20 additional boards for the windows, doors, and connections was then added on.

Next, cost of the batt insulation was determined from data from several widely available building material suppliers. The cost of 15 inch wide batt and 23 inch wide batt was then calculated as a cost per unit area per unit of thickness, or a volumetric cost. The area of the windows and studs, which is discussed later, was then subtracted from the total exterior wall area and multiplied by the stud depth to calculate the total volume of batt needed. The total whole house cost of each stud and batt system was then calculated and is summarized in the following table.

Window Area	2x4 @ 16"	2x6 @ 16"	2x8 @ 24"	2x10 @ 24"	2x12 @ 24"
5%	\$ 769.20	\$ 1,249.94	\$ 1,838.15	\$ 2,192.79	\$ 3,064.52
10%	\$ 740.32	\$ 1,204.56	\$ 1,762.89	\$ 2,096.77	\$ 2,947.73
15%	\$ 725.81	\$ 1,181.76	\$ 1,725.06	\$ 2,048.51	\$ 2,889.05
20%	\$ 711.30	\$ 1,158.95	\$ 1,687.24	\$ 2,000.26	\$ 2,830.36

Table 1: Total Stud and Batt Cost by Percent Window Area

4.2 Attic loose fill insulation depth

The second parameter investigated is the depth of the loose fill insulation in the attic of the home. Like the exterior wall stud and batt thickness, the attic insulation depth has competing cost functions which allow for an optimization. More insulation has a higher initial capital investment, but makes the home more efficient and cost effective to live in. For this study a commercially available, cellulose based insulation made of treated newspaper shreds was selected for both its widespread availability and the fact that it is a cost effective, recycled product. A baseline attic insulation value of IP-R30 (SI-R5.28) was assumed as standard and then varied to IP-R38 (SI-R6.69), IP-R49 (SI-R8.63), and IP-R60 (SI-R10.57). The corresponding depths and number of bags of insulation to purchase were based off of data from the manufacturer's website. The data gives values based on an assumed roof truss system of 2x6

boards at 16 inches (40.6cm) on center with the corresponding depth of insulation, and number of bags per 1000 sq. ft. to achieve a given R-value.

R-Value [hr·ft ² ·°F/Btu]	Total Settled Insulation Depth [in(m)]	Min. Bags per 1000 sq. ft.(100 sq. m)*	Total Cost
38	10.5 (0.27)	60.1 (64.7)	\$ 645.84
49	13.5 (0.34)	79.9 (86.0)	\$ 861.12
60	16.5 (0.42)	97.1 (104.5)	\$ 1,040.52

Table 2: Loose fill insulation data summary

*Takes into account 2x6 stud truss framing at 16 inches on center

The cost of each insulation depth was calculated simply by taking the area of the home, multiplied by the number of bags per 1000 sq. ft. and then multiplying the number of bags by the average unit cost per bag of \$8.97

4.3 Window to Wall Ratio

The third parameter of the home that was studied was the window to wall area ratio. For this study, the window construction was held constant as a double pane window with low emissivity glass and argon gas between the panes. The percent window area per wall was then varied by assuming a standard top height of 7 ft (2.13m) and a bottom height of 2 ft (0.61m) and then calculating the width of the window to achieve each window to wall ratio.

To calculate the cost of a given window area, cost data from several widely available building material distributors was taken for as many windows sizes of the specified window construction as could be found. For each window size, the cost per unit area was calculated and averaged to find an overall cost per unit area for the window type. Based on the data analyzed, the average cost for a double pane, low-e, argon window was found to be \$11.46 per square foot (\$123.35 per square meter). The window to wall ratios used and the corresponding cost of each are summarized in the following table.

WWR	Total Cost
5%	\$ 714.99
10%	\$ 1,429.98
15%	\$ 2,144.97
20%	\$ 2,859.96

Table 3: Window cost data

4.4 Air Conditioner Efficiency

The final construction characteristic of the home that was studied is the efficiency of the air conditioning system. For this study, three condensing units were studied with differing seasonal energy efficiency ratios (SEER). This was observed by taking cost and capacity data from a commercially available condensing unit supplier for multiple sizes of units for each of the specified SEER ratings. Since energy modeling software was used to size the capacity of the system, the data had to be processed to give a type of unit cost.

Since not all of the units have exactly the SEER rating specified, the data was normalized to give a representative value. The following table summarizes the cost data for the different SEER ratings.

SEER Rating	\$/Btu/Hr Capacity (\$/W Capacity)
13	\$0.0853(\$0.2909)
14	\$0.0942(\$0.3215)
16	\$0.1061(\$0.3621)

Table 4: Air conditioner condenser unit cost

To find the total cost of the condensing unit, the output capacity sizing of the modeling software is multiplied by the appropriate unit cost.

5. MODEL ASSUMPTIONS

Since this study is based on a highly constrained, preliminary model, it was necessary that many assumptions be made with regards to the dimensions, constructions, energy modeling, and cost calculation of the home. The home has been modeled after a typical international philanthropic housing agency home and was broken into three zones: living space, attic, and crawlspace. The largest assumption made was that the living space of the home is a large single zone with no interior partitions.

5.1 Dimensions

The first assumptions made were about the physical dimensions of the home. The home has been as closely modeled after a typical low income house as possible. For the purpose of this study the living space of the home was modeled as 30 feet wide (9.14m), 48 feet long (14.63m), and 8 feet high (2.44m) with each wall facing a cardinal compass direction and oriented with the long walls facing north and south. Each wall was modeled with a window centered on the wall. The crawlspace was modeled as being two and a half feet deep (0.76m). The roof was taken as a one to two slope (26.6°) with gable ends. See Figure 1 for a graphical representation of the home.

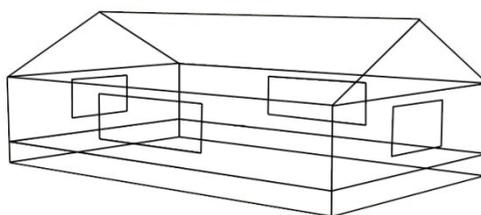


Figure 1: Graphical representation of home model

5.2 Constructions

Like the dimensions of the home, the surface constructions were based as closely as possible on current practice for low income housing construction. The following table summarizes the assumed layers and corresponding thickness (if applicable) for each building surface construction type.

Surface Type	Layers (listed from outside layer to inside layer)
Roof	Asphalt Shingles, 7/16"(13mm) OSB
Gable Ends	Wood Siding, 7/16"(13mm) OSB
Ceiling	Loose Fill Insulation, 5/8"(16mm) Gypsum Board
Walls	Wood Siding, 1"(25mm) Board Insulation, 7/16"(13mm) OSB, Stud and Batt, 5/8"(16mm) Gypsum Board
Windows	1/4"(6mm) Low-E glass, 1/4"(6mm) Argon, 1/4"(6mm) Low-E glass
Floor	Carpet, 3/4"(16mm) Plywood
Foundation Wall	8"(200mm) Concrete Block(filled), 2"(50mm) Board Insulation
Crawlspace Floor	Gravel

Table 5: Detailed list of building surface material constructions

5.3 Energy Modeling

Energy modeling is where the majority of assumptions had to be made. The first modeling assumptions made were about schedules. Standard residential schedules included in the modeling software package were used for lighting, occupancy, and HVAC systems. The next major assumptions dealt with internal loads. It was assumed that there were four residents in the home with a heat gain of 120 watts per hour per person. Lighting was assumed to have a power density of four watts per square meter and a target lighting level of 300 lux. Based on this, daylighting assumptions are that the lights have an on or off control with no dimming. The daylighting reference point is located in the middle of the home two and a half feet off the floor (0.76m). Electrical equipment internal gains are based on a suggested standard residential equipment load of 490 watts resulting in a power density of 3.7 watts per square meter. The set point temperatures were taken as 21 degrees Celsius heating set point and 23 degrees Celsius cooling set point. The HVAC system was modeled as a unitary, one zone system with packaged heating and cooling. Heating was assumed to be a standard gas heating coil furnace and cooling was modeled as a single speed, direct expansion cooling coil.

5.4 Cost Assumptions

Cost data for each of the design iterations was developed by adding the cost of each design component modeled to a set base home cost. In this study, the standard home cost of an international philanthropic housing agency was taken as \$40,000 USD. This cost lends itself well to this study because it mainly represents material costs and not labor costs as the agency relies on volunteers for home construction. This standard home was assumed to have 2x4 walls with studs at 16 inches on center, 10% window area, and IP-R30 attic insulation. The air conditioning condensing unit was assumed to be a SEER 13 unit and was sized and priced accordingly. The baseline cost for the model was determined by subtracting the cost of these assumed design characteristics from the standard cost. This resulted in a baseline cost of \$36,430. To determine the cost of a given design iteration, the cost of the modeling parameters chosen for that iteration were added to the baseline cost of the home to give a final home cost for that design.

6. RESULTS AND ANALYSIS

After running the energy modeling software for each of the possible designs, the cost and annual energy usage values were compiled. Figure 2 and Figure 3 depict the plotting of all designs for both locations.

6.1 Window to Wall Ratio

The WWR clearly had the largest impact on the annual energy usage for both design locations. In both Figure 2 and Figure 3, four distinct trends can be seen. These represent the WWR increasing in a direct relationship to energy usage. This shows that using day lighting controls within the given design home does not have a large effect on reducing the annual energy usage from one WWR to the next.

6.2 Stud and Batt Thickness

The next parameter to observe is the thickness of the stud and batt layer within the exterior walls of the home. Within a given WWR curve for each location, the walls are seen to get thicker from left to right or from less costly to more costly. This parameter clearly highlights the effects of climate location on the optimization. It is clearly evident that the wall thickness has a drastic reduction on annual energy use for Chicago (Figure 3), but that thicker walls only slightly decrease the annual energy use if the home was located in Tampa (Figure 2).

6.3 Loose Fill Attic Insulation Depth

The loose fill attic insulation depth is also quite revealing about the effects of climate location on the annual energy usage within the home. The data showed that increasing the attic insulation depth had a much larger effect on reducing energy usage in Chicago than Tampa. This could demonstrate that the attic insulation is needed to hold the heat down from rising in the colder Chicago temperatures while the larger air conditioning needs in Tampa cause the insulation depth to not have such a large impact.

6.4 Air Conditioner SEER Rating

The final parameter that was modeled was the SEER rating of the air conditioner condenser. The effect of this parameter on annual energy usage was also highly affected by the climate location. The SEER rating of the air conditioner was seen to have a large impact on the annual energy usage for Tampa and not for Chicago. This could be due to the longer cooling season in Tampa resulting in a larger cooling demand while the colder temperatures in Chicago cause there to be less of a need for cooling.

6.5 Optimization Summarization

Overall, the results of the modeling demonstrate that a parametric optimization of low income housing is highly feasible. Very simple life cycle cost analysis was performed using a generic \$0.10/kWh of energy used for a 10, 20, and 30 year lifespan. It was assumed that there would be no replacement or maintenance needed either, but simply the construction cost plus the energy cost for the time period.

For Tampa, the data showed that the optimal design for all three time periods was to use 2x4 studs at 16 inches on center, five percent window area, IP-R38 attic insulation, and a SEER 16 air conditioner. For Chicago, the 10 year lifespan was optimized by using 2x6 studs at 16 inches on center, five percent window area, IP-R49 attic insulation, and a SEER 13 air conditioner. The 20 and 30 year lifespan was optimized by using 2x10 studs at 24 inches on center, five percent window area, IP-R60 attic insulation, and a SEER 16 air conditioner. This means the payback period of the thicker walls and more efficient air conditioner has a payback period between 10 and 20 years.

Tampa, Florida Usage vs. Construction Cost

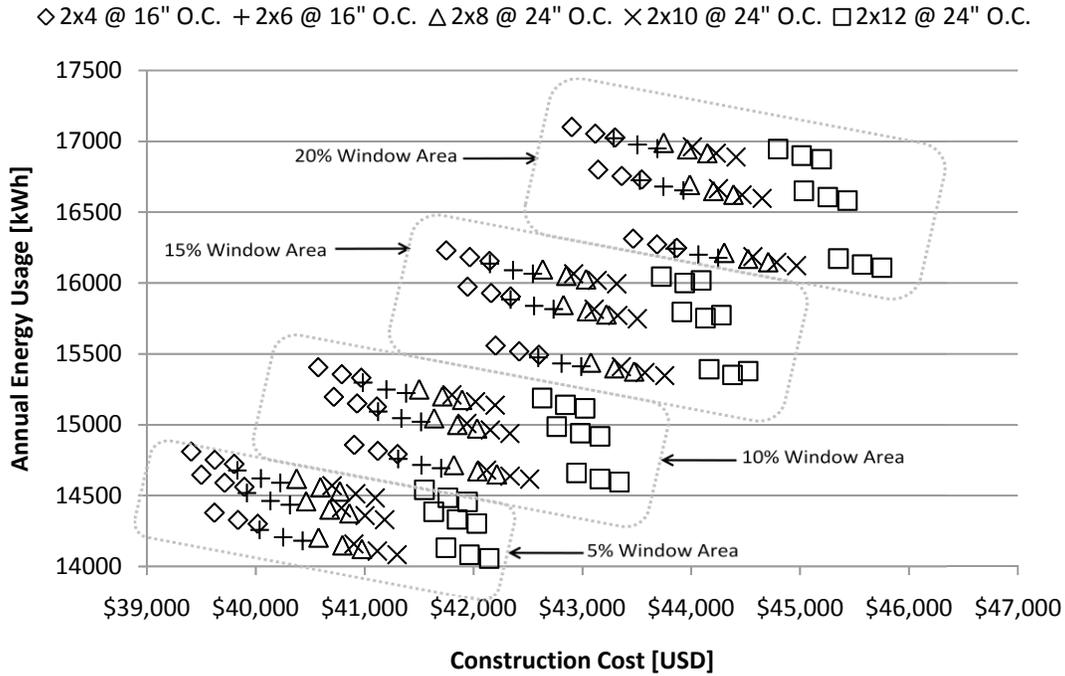


Figure 2: Optimization Results for Tampa, Florida

Chicago, Illinois Usage vs. Construction Cost

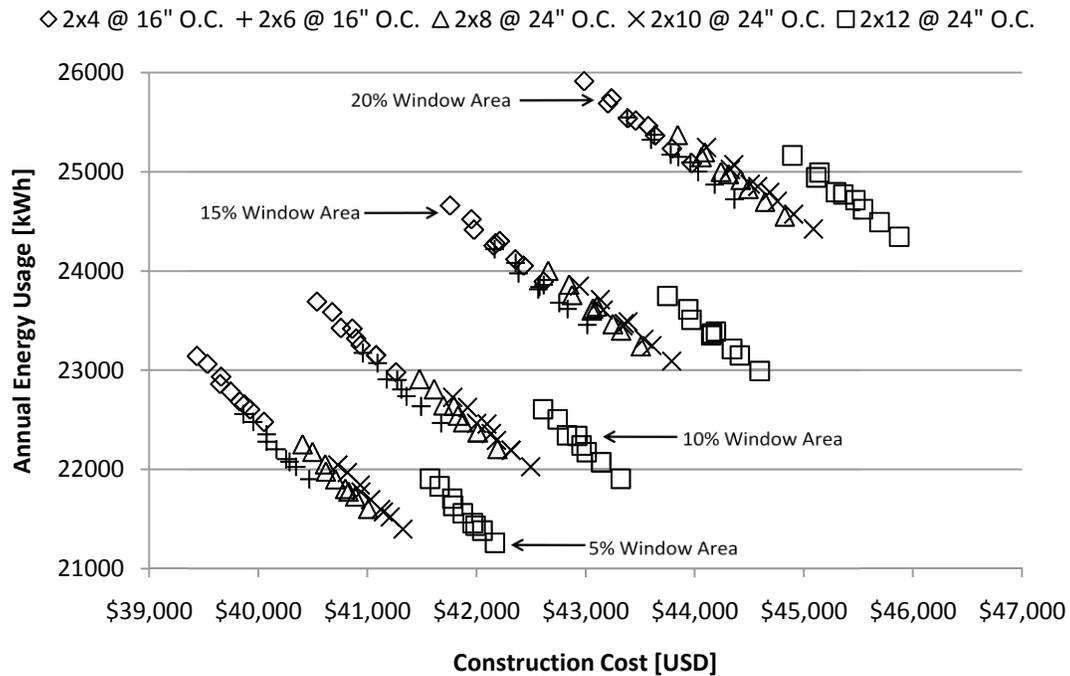


Figure 3: Optimization Results for Chicago, Illinois

7. CONCLUSIONS

Based on the results of the case study, several conclusions can be drawn:

- The window to wall ratio has the greatest impact on the efficiency of the home for both locations in this study.
- Day lighting controls have a relatively small effect on the energy efficiency of the home.
- The effect of some construction parameters are climate location dependant. For example, in Chicago the annual energy usage is reduced drastically as the walls are thickened for a given window area, but remains relatively constant in Tampa.
- The optimal design for a home is highly dependent upon the design lifespan.
- Most importantly, this study demonstrates that the optimization of low income housing by the use of parametric energy modeling is highly feasible.

8. FUTURE WORK

The purpose of this study is to act as a proof of concept of further research. At the current stage of this study, a model home has been completely constrained. Other than the four parameters being modeled, the entire home model is fixed. The main objective of future research is to remove as many of these constraints as possible. This expands the possible design space and allows for as variable an optimization as possible.

The main portion of the future research proposed involves using multi-objective genetic algorithms (MOGAs) to determine a set of optimum designs for a low income house given input location, budget, and design constraints. Since the design space exponentially increases as constraints are removed, there is no feasible way of solving the entire design space as was done in this study. The use of genetic algorithms will allow for close to optimal designs to be found in a reasonable amount of time. From the open literature that has been reviewed, research of this kind has not been performed in the manner proposed.

The final addition to the future work of this study is to allow user input constraints. An optimal home could be designed for a target budget or a targeted annual energy bill. If a home was being built, and a certain type of material had been donated or targeted, that material could be held fixed. Finally, using best estimate lifecycle costing, final designs could be selected.

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