ENERGY MODELING OF LOW-COST HOUSES IN COLDER CLIMATES OF SOUTH AFRICA

A Thesis
by
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Abstract

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The need for housing in South Africa has spawned a number of different methods for providing materials and construction for low-income housing in central South Africa. Within central South Africa, the colder climate necessitates heating during the winter months, and the lack of energy efficiency of the government-subsidized housing creates potentially unsafe indoor temperatures. The elevation of living standards in the region also allows more homes to have a heating system, typically an appliance space heater. These two factors, combined with inflating energy costs, raise the question of the viability of energy efficiency improvements that can be implemented in the house to decrease energy usage and costs and provide more comfortable conditions. This study analyzes typical houses using two energy modeling programs, EnergyPlus and TRNSYS. A parametric study is performed to find which energy efficiency improvements can be implemented for the maximum savings in both energy and cost. A life cycle cost analysis is performed on the selected improvements. Results show that there are significant reductions in energy usage when simple efficiency measures are implemented. The models created are representative of the actual homes when simulated data is compared to recorded temperature data from actual houses.

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Chapter One: Introduction

The citizens of developing countries are in need of housing as populations grow in both urban and suburban communities. Countries such as South Africa have recognized this and built the mandate for new housing policies and plans for adequate housing into their Constitution and other government documents (Republic of South Africa Constitutional Assembly, 1996). By implementing programs for construction of subsidized houses that use a standard design, the replacement of inadequate housing with more permanent structures can be carried out with economies of scale. In attempting to achieve the lowest capital investment for the houses, the construction is limited to a very simple design, which does not take into account the lifetime energy usage of the structure. This impact will become apparent in decades to come as thousands or millions of these houses are constructed and occupied. An energy-efficient design for these standardized houses is necessary to reduce the future energy burden on the country's infrastructure as well as the financial burden on the occupants of these houses, who are of the lowest income brackets in the society. This study will focus on the colder climate of central South Africa during the heating season, when energy efficiency not only saves money, but also improves the health and safety of the occupants.

The design of an energy-efficient standard home can be done by using the current design as a baseline and modifying the various building components to determine where the greatest gains can be made in terms of energy usage reduction and improved internal comfort. Because the buildings will be small, at 40-100m^2, special care needs to be taken in the modeling of such houses for energy usage. With the relatively small models, sensitivity to certain modeling parameters can be picked out by varying parameters independently and analyzing the building's sensitivity to such changes in design (Mechri, Capozzoli, & Corrado, 2010). In addition, the cost constraint of the standardized designs requires suitable materials that are locally available and economically viable. Several existing buildings will be modeled and put through energy simulations to identify changes in heating season energy usage and internal temperatures. Multiple software packages will be used to verify that modeling practices and parameters are done correctly and that predicted energy usage trends throughout the different simulations are consistent. The study will conclude with recommendations for improvements to masonry-based, low-income housing for energy efficiency, considering energy usage and cost.

Statement of the Problem

A challenge for governments of developing countries is to find housing for their constituents. Government leaders in South Africa with quickly growing populations desire to provide modern amenities and to improve the quality of living, while providing housing on a large scale by using modular and pre-designed homes (South Africa Human Rights Commission, 2004). When providing housing for the lowest income groups, using a very basic structure can provide great short-term improvements in comfort levels and safety for the occupants. For example, in the plateau region of central South Africa, which is a colder climate where the dominant energy need is for heating, the government has a home building agenda to replace homes made of sheet metal and newspaper. In the interest of minimizing capital costs as much as possible, the housing designs may not take into account the best practices for insulation, air infiltration, or overall energy efficiency.

Predictive modeling of energy usage in residential buildings has increased in popularity as an effective tool for determining efficient designs and components. The time and effort of analyzing a residential building design typically restricts the application of analytical modeling to larger and higher profile projects. While it is true that a larger building can save more energy when compared to one smaller building in an absolute sense, the number of smaller houses may far exceed the number of larger houses that will be built in the coming years, especially in developing countries (Crossette, 2011), and thus even the small homes provide a target for significant energy savings.

The building industry is aware of several design practices and material choices that result in a more energy efficient house; however, when considering potential improvements in energy efficiency for small, low-cost houses in developing countries, a few energy-efficient design components are implemented with expected improvement in energy consumption based on available data that is often drawn from applications to larger buildings with different construction types. This is useful to a degree; but because of the smaller sizes of Reconstruction Development Programme (RDP) houses compared to those on which simulation and testing is performed, the relative effect of one improvement versus another may not be the same. For example, additional wall insulation may have a different relative effect on the total heating energy load of a small building like an RDP-sized house than it would on a larger stone building. The lack of simulation data on small structures is apparent.

Purpose of the Study

This study will analyze the relative improvement potential of various efficiency best practices on small, masonry-based homes such as those typically built for RDP housing in South Africa. In doing so, the standard design of such homes, which may be adopted or adapted for government-built housing intended to improve the quality of life in developing countries such as South Africa, can be improved. These improvements will lower life-cycle costs of houses and decrease energy burdens on the government, which is building on a massive scale. By focusing on climates where the need for heating energy is dominant, the improvements in home design are needed not only for comfort but also to prevent unsafe temperatures during winter conditions. The analysis of various energy improvements on small homes requires an accurate method of comparison and a controlled study where building features can be varied and the effects analyzed on a variety of potential designs.

Research Questions

How effective are energy-efficient construction techniques when incorporated into the design of low-income, masonry-based, single-family South African homes in optimizing life-cycle costs, considering both construction and energy costs? To answer this question, it is necessary to analyze the effect of building size on the building's sensitivity to insulation materials What are the comparative results of two energy models developed to address the first question, using the energy simulation programs EnergyPlus and TRNSYS?

Limitations of the Study

To allow a deeper analysis of energy usage and improvement techniques, only masonry and stone-based buildings will be considered in this study. The type of building materials used can greatly affect the types of improvements that can be made as well as the relative effectiveness of energy efficiency measures. Countries such as South Africa have based their housing design on a concrete and brick construction for the durability and economic advantages, so this study will focus on that material type only.

Finding energy efficiency improvements for concrete and brick-built homes that are cost effective and can be easily implemented by home builders involves using simple design modifications; therefore, this study will not examine building technologies that significantly alter the concrete block construction and/or require the use of customized structural elements. The selected climate is the central plateau of South Africa. This region requires more heating than the vast majority of regions in Africa and many other developing areas of the world. Even so, the climate is relatively mild compared to more mountainous and colder regions such as northern China, Russia, and parts of South America. The characteristics of the climate greatly affect the suitability of a structure, and the energy efficiency improvements recommended in this study may not be applicable to more extreme weather areas; however, this study aims to provide insight into the behavior of small dwellings through different climatic circumstances and can still give a direction towards the type or predicted effectiveness of efficiency improvements to homes in those more extreme climates.

This study will not compare the government-sponsored housing types of masonry construction to the traditional earthen housing used in South Africa. Other studies have shown that the traditional earthen huts can provide more thermal stability than the uninsulated concrete houses currently in existence (Makaka & Meyer, 2006), and the results of those studies can be cross-referenced with the results of this study. In the interest of a more detailed analysis, traditional types of homes will not be modeled in this study.

Estimation of occupant behavior is based on a sample of homeowners. The usage and times of occupancy in different areas of the house can vary greatly depending on the occupants. If the impact of human occupancy significantly affects the heating energy usage in the home, then these assumptions of occupant behavior can become a key factor in the energy improvement recommendations. Because these assumptions are based on a small sampling of occupants, actual energy usage results may vary.

Significance of the Study

This study is useful for organizations planning to design and build low-income housing using masonry construction. The types of improvements suggested at the conclusion of this study will be analytically verified to lower life cycle costs versus an uninsulated design using realistic assumptions of improvement costs, life cycle usage, weather information, and occupant behavior. The cost and energy savings can be multiplied when a large number of houses will be designed, creating an estimate of the overall savings for the community both in monetary and energy forms. Many housing development plans implemented by the government to supply housing to large numbers of constituents involve a cost sharing model for capital and energy costs. Creating an energy-efficient, low-cost house with standard materials and construction practices benefits not only the occupants of the house but the infrastructure and the government that serve the occupants.

The ability of a building to keep the occupants comfortable inside takes on a new importance when the climate becomes colder. Many developing countries are located in hotter climates where the primary concern is keeping the occupants cool and dry. This study will suggest efficient designs that will increase the ability of the house to stay warm in colder climates with less energy. This will keep the occupants warmer and safer during the coldest conditions, which can drop below freezing at night.

By developing building energy models across a multitude of simulation software packages, this study can provide energy modelers with tools and tips to use in other modeling endeavors regarding small, stone-built structures. The current literature does not document the changing sensitivity of building energy models to different parameters as the size of the building becomes smaller.

Chapter Two: Review of Literature and Relevant Research

Summary of Housing Policies in South Africa

The governmental bodies of many developing countries have taken on the challenge of finding housing for growing populations. The continent of Africa has experienced population growth at a rate of 2.3% per year and is expected to add one billion more by 2044 (Crossette, 2011). Creating adequate communities and homes for these people is a great challenge for the governing bodies of these nation states. Countries are struggling to keep up with housing the growing population, forcing many people to create shelters using materials and methods which provide only the most basic shelter. For instance, the informal settlements of South Africa are often made of a corrugated metal skin with old newspaper inside as a windbreak. While South Africa does have a specific section of its constitution declaring that “everyone has the right to have access to adequate housing,” (Republic of South Africa Constitutional Assembly, 1996, p. 10), the 2001 census in that country estimated that over 1.3 million families lived in these informal settlements (South African Human Rights Commission, 2004). Although there has been a housing code in effect since 1977 that outlines general construction practices for residential buildings, the enforcement of the code cannot be upheld due to the rapidly expanding populations.

There is a large international effort to develop solutions for the housing shortage in these countries. The United Nations Population Fund is promoting the need for urban solutions, since the general migration of population is toward urban areas (Crossette, 2011).

While this does create dense and complete communities, it is not the solution for all inhabitants, as many would like some amount of land and space to call their own. Culturally, there is still a need for suburban and rural communities, even though such settlements may be a less resource-efficient method of housing people. The South African people living in informal settlements are evidence of this cultural influence. Although the inhabitants in these communities do not have adequate housing, they take pride in having a set amount of land to call their own, so they maintain that property and wait for opportunities to improve their housing situation.

South Africa is a country where the government has set up a program to give every person an adequate shelter. This mandate is dictated in Section 26 of the original constitution of South Africa: “The state must take reasonable legislative and other measures, within its available resources, to achieve the progressive realization of this right” (Republic of South Africa Constitutional Assembly, 1996, p. 10). The clause shows that the leaders of the country recognize the importance of providing housing for the growing population and the benefits this has on the well-being of the country as a whole. Before the constitution was put in place, the country already had an initiative to develop a housing program named the Reconstruction and Development Programme, or RDP. The program is meant to facilitate the construction of housing for low-income populations by providing a subsidy for homebuilders in rural and suburban areas. The beneficiaries of RDP houses, who must qualify with an income of 3,500 South African Rand (ZAR or R) per month or less, receive a one-time grant for land, services, and construction costs (Landman, 2010). In the early stages of this program there were insufficient funds and resources available to supply housing to all, especially considering the elevated levels of poverty directly after the fall of apartheid in 1994. The system could only provide a small subsidy as a contribution to those wishing to build a house. The People's Housing Process (PHP) was introduced in 1998, which set responsibility on the people to build their own homes with government-subsidized materials, and the government would focus more on providing people with the necessary infrastructure such as electricity and transportation services. This is often the route for those who do not qualify for an RDP house but cannot afford a house in the private sector. The RDP supply mechanism is effective for the lowest-income population because it avoids the need for a mortgage, for which most people in that income bracket cannot qualify. As of 2004, the South African government indicated that RDP housing had been supplied to 1.6 million households (Housing, 2004).

The RDP houses are generally close to $40m^2$ in floor area on $250m^2$ plots of land, and they are made almost exclusively of concrete blocks or bricks. Builders have experimented with variations on the standard geometry, including combining homes and creating duplexes for larger families, as well as reconfiguring the structure with the supplied materials. In 2004, the RSA Department of Housing indicated the need for improvements in the implementation of housing to create sustainable communities, which, in this context, was defined as "well-managed entities in which economic growth and social development are in balance with the carrying capacity of the natural systems on which they depend for their existence and result in sustainable development, wealth creation, poverty alleviation, and equity" (Housing, 2004, p. 11). This initiative by the government shows that a long-term undertaking such as housing development requires the consideration of not only placing people in shelters, but also of creating an environment for future growth of the community as a healthy, organic entity. This includes proper access to resources and infrastructure. The RDP house design is specifically called out for investigation in order to assess the sustainability of the large-scale housing rollout. The design and quality of the RDP-era houses is to be improved upon to change the face of the typical house and the stereotype it gained as an undesirable dwelling. The Department put forth the intention to "investigate measures and incentives to enhance housing design and promote alternative technologies" and to improve construction quality with better building standards (Housing, 2004, p. 16).

Typical Construction of Modern Government-Sponsored Housing in South Africa

For many developing areas, the climate is mild without a large temperature difference between inside and outside, so the purposes of the house are primarily to provide protection from wind, water, and sunlight, and to give some security and privacy to the family inside. Thermal insulation is not a top priority for mild climates when designing a bare-bones structure for quick construction. Makaka and Meyer (2006) give a good summary of the typical construction of the modern RDP house. As stated above, the RDP houses are usually single-family homes of concrete or brick wall construction. The availability of concrete materials and the ease of construction have made it a common building material for a wide variety of locations around the world in need of durable housing at low cost. RDP houses that use a concrete block construction have a wall thickness of 150mm (6"), while a double-layered brick wall with no air gap, if used, has a thickness of 220mm (8.7"). Walls are 2400mm (7'11") in height. No insulation is used (Makaka & Meyer, 2006).

The roof is often made of corrugated metal with wooden rafters. This material is readily available and easy to install atop stone walls. Again, the roof has the essential duty of keeping out wind, rain, sun, and people. The single layer metal roof accomplishes these tasks. The gaps around the edge of the roof are sealed with plaster to block out the elements. The pitch of the roof is low at 25 degrees or less above horizontal, with overhangs of about 100mm (4”). No ceiling is installed in the house, leaving the corrugated metal roof as the sole boundary between the interior of the house and the sky above.

The floor and footing consist of a concrete slab 80mm (3”) thick, which is poured on grade with a perimeter footing along the outside walls of the house to a depth of at least 300mm (1’). Windows are often built on-site with single panes of glass and custom fitted wood or metal frames for placement into holes in the walls. The three to four windows are about $1m^2$ each and are placed on the north and south sides of the house to promote ventilation. Doors are made of metal.

Improvements in Residential Building Codes and Energy Efficient Construction

In 1977, South Africa released the National Building Regulations and Building Standards Act, which laid the groundwork for the construction industry in South Africa. Over the several amendments to the Act, the structural components of residential buildings became increasingly refined to improve safety and health within the home. South Africa National Standards (SANS) 10400 served as the document to guide builders on the application of the National Building Regulations. Until July of 2011, there was no guidance on energy usage in buildings in SANS10400. There is now a dedicated section that must be followed for all new construction. The scope of this document encompasses all types of construction; for residential single family homes, the specification of requirements comes in the form of minimum thermal resistance values for the various components of the home (South Africa National Standards, 2011). The addition of these requirements shows the ambition and long-term vision of the South African government to control the ever-increasing energy requirements of the rapidly growing population. While the energy efficiency construction requirements are now in-place, comparing the RDP houses with the national energy code highlights the fact that the government-designed homes fail to meet the code in almost every category. This is supported by thermal comfort testing in RDP houses, which indicated large temperature swings between day and night, as well as over the different seasons (Makaka & Meyer, 2006). The thermal response time, or how the temperature inside responds to exterior changes, of RDP houses is relatively short for a residential building, indicating the low thermal resistance of the buildings, which leads to higher energy usage and operating costs. In colder climates, this could lead to unsafe conditions for the inhabitants on very cold nights, which can happen in South Africa’s central plateau during the winter. The method of space heating used by most RDP home inhabitants supports this concern. Many use portable space heaters during the winter, which are carried around to the different areas of the house. For example, at night, the heater would be placed in the bedroom, while during the day it may be placed in the kitchen. The heaters are either electric (if the house has electricity), or kerosene-powered. In a poorly insulated house, the maximum capacity of the heating device can be exceeded, and the interior temperatures will drop to uncomfortably or dangerously low levels. The heat-absorbing concrete walls, in combination with the irradiative heat source, compound the challenge of achieving thermal comfort by not reflecting the radiated energy back into the room. Instead, the heat is conducted through the walls to the exterior of the building.

One consequence of using a lowest-cost design for RDP homes is the poor reputation the homes have among the population. The RDP houses can only perform the very basic function of providing shelter for those people with no viable alternatives, but the homes are not comfortable inside and are not aesthetically pleasing on the outside. Many potential occupants use RDP housing as a last resort and would rather live in a more traditionally built home with better quality that provides greater interior comfort throughout the year. The housing institutions of South Africa are responding by proposing a more flexible housing strategy that develops design guidelines to create a dignified housing product. Instead of implementing a very basic design, the governmental agencies aim to build on local construction methods and to use the expertise of the indigenous people in each region so that the RDP homes can blend into the surrounding community, instead of forcing a new landscape. The redesign of RDP houses will be done to increase the design's quality and to make it more attractive to the South African people who are in need of housing. By improving the design, the South African government hopes to facilitate acceptance of the program and to increase housing quality across the country (Housing, 2004).

The implementation of an energy code in South Africa is a move in the right direction. Considering the housing need across the country, there is a great opportunity to show the benefits of the energy code if it is applied to the construction of the large number of government-designed homes that will be built in the future. The design can show the people of South Africa proper construction techniques and educate them on the importance of energy saving and better thermal comfort. Not everyone who will eventually build a home will understand the energy code; but by building new energy efficiency measures into the design of future RDP homes, the benefits of the energy code can still be realized.

Review of Building Energy Modeling in Small Residential Buildings

In many manufacturing and design industries, the use of computer simulation is fast replacing many previous standards of procedure including rules of thumb and physical prototyping. The practice of analytical simulation allows for the optimization of a design before significant resources are spent building and testing the design. The residential building industry is no different, with several different types of building information modeling (BIM) packages available to help designers adjust and optimize designs. The advantages of building energy modeling are most apparent in large-scale buildings with complex layouts and energy usage components. The dedicated modeling software is applied to this type of structure due to the difficulty of estimating energy usage using hand calculations and simple spreadsheets. Though use of BIM is increasing as the software becomes more mainstream, single family homes are not typically subject to energy modeling via dedicated software due to the relative simplicity of the structure. Builders and designers often use common knowledge and rules of thumb to estimate energy usage of a particular home.

To estimate the savings of design changes to small homes, a number of approaches have been used. One simple method is to use the conductance of a material and to calculate heat flux through the material given a standard indoor temperature and the average temperature outside over a season, using heating degree days to find total heat transfer through the material (Uygunoğlu & Keçebaş, 2011). At the other end of the spectrum are sensitivity analyses which take the architectural plans for a building and import them into a dedicated software tool such as a DOE-2 program, which automatically calculates energy usage based on changing building component properties (Tavares & Martins, 2007). This approach is typically reserved for larger and more expensive buildings where the energy impact is more tangible to the designers and future owners. For small houses, the building project typically has a much lower budget and shorter schedule, and complex energy modeling is normally not used.

The small size of the house could mean the impact of the occupants, though few in number, has a great effect on the heating energy usage of the home. The effect of occupants on energy usage has been studied in residential buildings (Olofsson & Mahlia, 2012), along with the establishment of comfort standards for indoor air quality (Nicol, 2009). In a study particularly geared toward analyzing different types of stone walls with insulation in a warmer climate, Monteiro and Freire (2011) performed a life-cycle analysis of different insulation and façade materials to compare heating and cooling energy usage to initial embodied energy. The study found that, when normalizing wall thermal conductivity by varying wall thickness, the double brick and concrete construction types had the greatest total environmental impact. This may be attributable to the added thickness of brick and concrete to achieve the same thermal conductivity as a wood-framed wall, thus adding material and embodied energy. An interpretation of these results is that masonry building products should be used only for structural purposes and not as insulation due to the high embodied energy and environmental impact.

Overview of Building Energy Modeling Software

Calculation of building space conditioning requirements is based on heat transfer calculations via conduction through envelope materials, fluid mass transfer, and radiation gains. A wide variety of user applications have been developed to complete these calculations, and each has different approaches, methods, and user interfaces (Judkoff, Neymark, Neymark, & Associates, 2001). Highlighted here are a few dedicated software packages that exemplify different approaches to building energy modeling.

Autodesk® Ecotect® is a tool aimed at designers trying to develop an energy efficient structure early in the product life cycle. The software is built around a graphical user interface that visually shows the user the effects of changing geometry and materials of the building in the form of interior comfort, daylight exposure, and resource consumption. Ecotect is powerful as a tool for comparing different designs quickly and easily and seeing the relative effect of different components. The primary objective of the program is to provide sustainable design analysis tools with a relatively short turn-around time to facilitate quick comparisons between design options. A few limitations of the software include its simplified inputs and outputs and a hidden calculation scheme that makes some unexpected results difficult to decipher. Batch runs are difficult to perform in this software, which leads to a labor intensive process of varying design parameters. Ecotect was used in a preliminary study on this subject (Ramsdell, DeLarm Neri, Jacobs, & Verster, 2012), and the results of the Ecotect simulations will be compared to EnergyPlus and TRSNSYS simulations.

EnergyPlus is a calculation engine used for determining heating and cooling loads in buildings. The software is derived from an algorithm developed by the United States Department of Energy (DOE) called DOE-2. The package is typically used in conjunction with a GUI overlay to facilitate user inputs and program outputs. The software is generally regarded as having a complete and relatively accurate algorithm which does well in modeling validation procedures such as the Building Energy Simulation Test (BESTEST), which assesses the accuracy of building simulation programs. The open nature of the software allows the user community to develop customized extensions in order to accomplish extended tasks such as batch operations and parametric simulations.

TRNSYS is not specifically a building energy modeling software but rather a heat transfer calculation engine, which is used for a wide variety of thermal transfer design projects. The TRNBuild component of TRNSYS focuses on building assemblies and offers details on various building component and usage aspects, which make it useful as a tool to cross-reference results from other software packages. Of the three software packages used in this study, TRNSYS is focused the most on heat transfer simulations and is highly regarded in the field for accurately estimating energy transfer. The source code is accessible and allows for easy parameterization of variables and batch simulations.

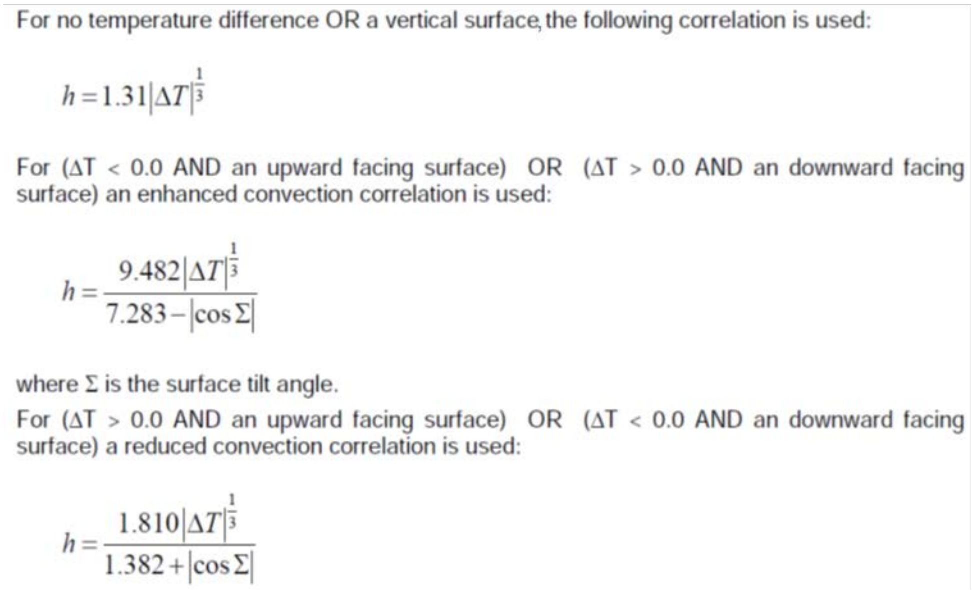
Review of Relevant Energy Modeling Studies

Comparisons of energy modeling programs. Because this study will include a comparison of EnergyPlus results to TRNSYS results, a brief overview of the state of the art of energy modeling is given here. There is a growing body of research comparing different building energy analysis software (see, for example, Brun, Spitz, Wurtz, and Mora (2009), ONeill et al. (2011), Andolsun, Culp, Haberl, and Witte (2012)) . This previous research investigates some of the fundamental differences in energy modeling programs that use iterative energy balance techniques. A few relevant studies are reviewed due to their relevance and importance in this study, as the results indicate best practices for a physically accurate energy model.

A study used EnergyPlus and TRNSYS, among others, in an analysis of the required energy to heat a low-energy building (Brun et al., 2009). The two-story building had a total floor area of 127m^2 and was modeled with one thermal zone per story. A heating system with unlimited capacity was used, ensuring that thermostat temperatures would be maintained. The study focused on convection coefficients at zone boundaries. Two scenarios were used. The first set all surface heat transfer coefficients to the same values across all modeling programs. The values used were the average coefficients calculated in third-party software, so they were not the default EnergyPlus or TRNSYS values. The second scenario used each program's default settings to calculate surface convection heat transfer coefficients. In the first scenario, all programs simulated a similar heating energy usage over the evaluation period. When the programs were each set to their default methods, however, there was a significant difference in energy usage. EnergyPlus predicts the use of less energy than

TRNSYS, as the convection coefficient internal calculation method results in lower average coefficients, which are calculated at every time step. In contrast, TRNSYS does not internally calculate convection coefficients, but they are set by the user as a constant value or input from another TRNSYS module. The default TRNSYS recommendation for convection coefficients on inside surfaces is 11 kJ/hr/m2, or 3W/m^{2}K, while EnergyPlus averages around 1.0-2.3 for inside surfaces. This comparison will be repeated for the current study to evaluate the differences between EnergyPlus and TRNSYS inside and outside convection coefficients.

Regarding the calculation of the convection coefficients for each surface in EnergyPlus, the engineering reference for the program gives the relevant equations. The scheme for calculating the convection coefficients is the Thermal Analysis Research Program (TARP) method, which uses curve fit models for calculating convection coefficients based on empirical data collection. The outside surface coefficient has a forced and natural convection component. Forced convection comes from air flow based on wind speed, and natural convection comes from temperature differences between the surface and the surrounding air. The inside surfaces also use the TARP method, with the relevant equations shown in Figure 2.1 on the next page. According to the reference manual, these equations, created by G.N. Walton in 1983, fit the ASHRAE handbook calculations in the turbulent range for both horizontal and vertical surfaces with a high degree of correlation (USDoE, 2012).



For no temperature difference OR a vertical surface, the following correlation is used:

$$h = 1.31\left|\Delta T\right|^{\frac{1}{3}}$$

For (ΔT < 0.0 AND an upward facing surface) OR (ΔT > 0.0 AND an downward facing surface) an enhanced convection correlation is used:

$$h = \frac{9.482\left|\Delta T\right|^{\frac{1}{3}}}{7.283 - \left|\cos\Sigma\right|}$$

where Σ is the surface tilt angle.

For (ΔT > 0.0 AND an upward facing surface) OR (ΔT < 0.0 AND an downward facing surface) a reduced convection correlation is used:

$$h = \frac{1.810\left|\Delta T\right|^{\frac{1}{3}}}{1.382 + \left|\cos\Sigma\right|}$$

Figure 2.1. Equations to determine inside surface convection coefficients in EnergyPlus(USDoE, 2012, p. 89). The convection coefficient *h* is a function of temperature *T* and surface angle ∑.

Researchers have also studied the modeling of a slab floor and the effect on heating energy usage for a simulated house (Andolsun et al., 2012). These authors highlighted the differences between EnergyPlus and TRNSYS methods of slab load calculation. They modeled a composite slab of concrete, soil, and the air film between the layers. The effective resistance of the slab was used. Emphasized in the study was the importance of representative ground temperature input to simulation models, since the default values will produce faulty results. The study also showed that the Slab preprocessor for EnergyPlus has trouble with smaller structures that have variable indoor temperatures. Convergence is not always achieved when the indoor temperature is influenced by the slab temperature, and with the Slab preprocessor, iterations are performed with input from the house model for slab inside surface temperatures. Because of this, either a user-entered ground temperature set should be used or the indoor temperature of a zone in contact with the slab should be held constant. For this investigation, a user-entered ground temperature set will be used for both EnergyPlus and TRNSYS.

Loutzenhizer (2007) compared the solar irradiance models of different energy modeling programs with empirical data from a physical model recreated in the software programs. Values of incident irradiance on vertical surfaces were output from each program, which included TRNSYS and EnergyPlus, and compared to the measured data from the physical model. The authors found that the experimental measurements showed an average of 186.2W/m^2 over the test period, TRNSYS averaged 187.1W/m^2, while EnergyPlus averaged 191.0W/m^2. For the current versions of EnergyPlus and TRNSYS used in this study, the same model for irradiance calculations is used (USDoE, 2012; UW-SEL, 2010), so this level of accuracy should be maintained.

Studies using parametric evaluation and sensitivity analyses. To evaluate different parameters of a building and their effects on the system energy usage of the building, a wide variety of parametric variation analyses have been developed. While the specific methodology varies depending on the purpose of the study, the overall procedure remains the same. Tian (2013) gives an overview of the sensitivity analysis procedure shown in Figure 2.2 on the next page. An excerpt from Tian's overview describes different methods to approach the creation of a building energy model:

> The two typical choices are to use either a full building simulation program, such as EnergyPlus, ESP-r, TRNSYS, and/or DOE-2, or to create a simplified calculation model usually based on ISO 13790:2008 (Thermal Performance of Buildings – Calculation of Energy Use for Space Heating and Cooling), or similar

> methods. The building simulation programs can be used to input detailed parameters and complete hourly simulations. The programs listed above have text-based input files and are easily edited. The simplified calculation method is computationally less expensive and offers easy access to variable inputs.

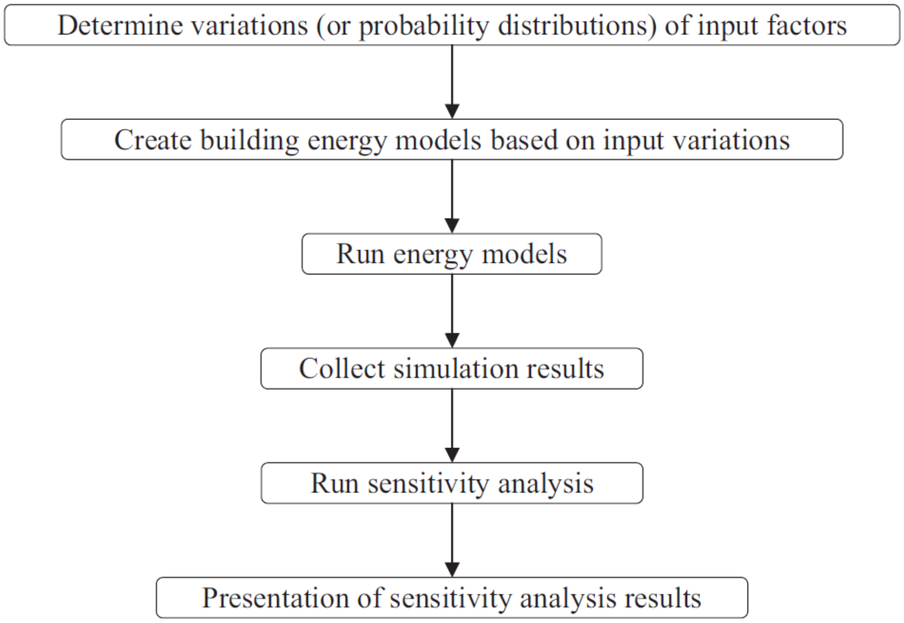


*Figure 2.2***.** Typical process flow diagram for performing sensitivity analyses (Tian, 2013).

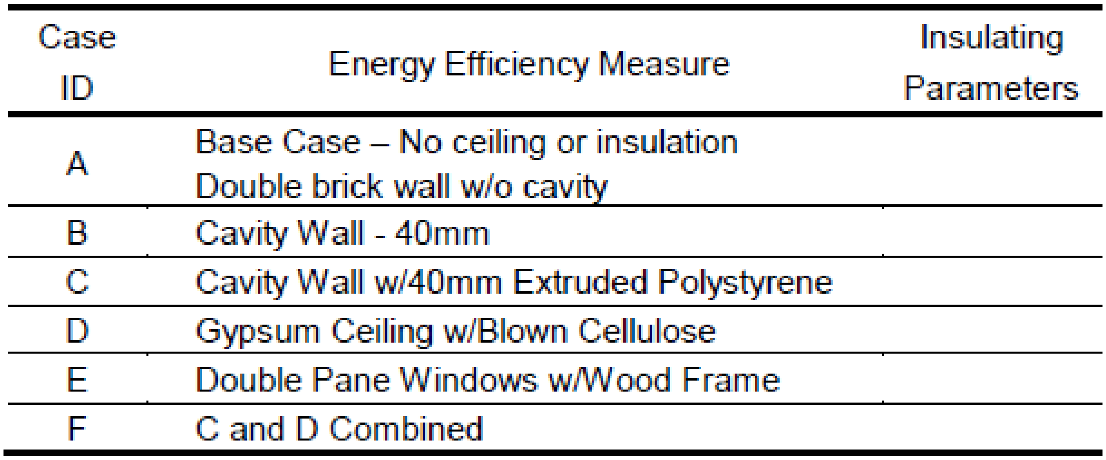
Mechri et al. (2010) used an ANOVA process to evaluate the sensitivity of an office building’s energy usage to several parameters such as glazing area, external shading, and orientation. The study used random sampling of parameter values based on both Latin Hypercube Sampling (LHS) and Fourier Amplitude of Sensitivity Technique (FAST) methods. A simplified thermal simulation was performed on monthly time steps, allowing an analysis where building level factors could be quickly altered in subsequent simulations and large sample quantities could be used. The study found that the largest contributor to building energy use variance, of those variables tested, was percentage of glass to total envelope area.

Thermal mass location and building shape were the next largest contributors, at roughly one third the contribution of glazing. The large contribution of glazing percentage is likely due to the range used during the study, which spanned from 20% to 90%. Interaction effects were low at a maximum of 3% contribution to energy variance. With a simulation model that describes thermal mass affected by direct solar gain, the interaction between glazing area and thermal mass location may be more significant, but the Mechri et al. (2010) simplified model does not include such considerations. This study will draw upon Mechri et al.'s process but will institute a more complex modeling simulation using full hourly weather data. Instead of using randomly selected values, the different parameters will be varied between discrete levels according to local and international building codes.

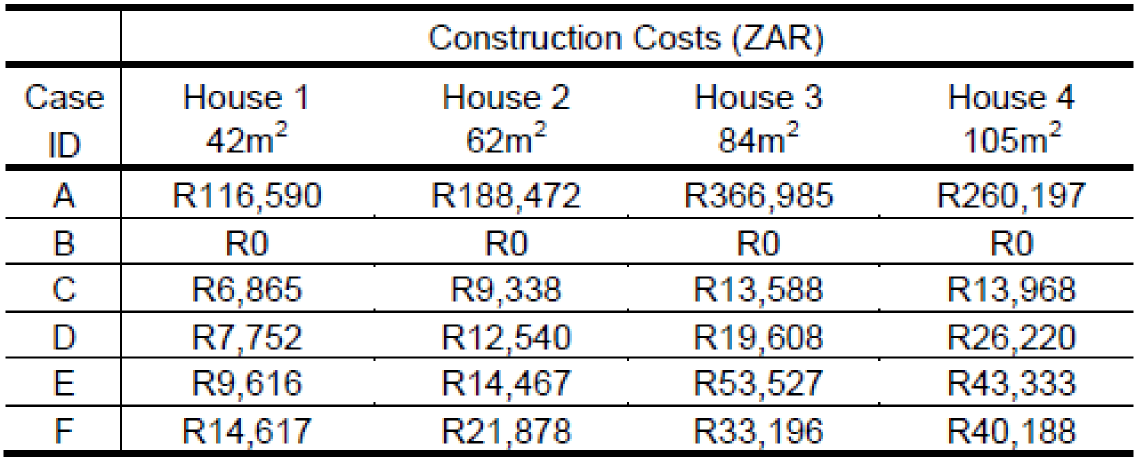
Sensitivity studies have been used when calibrating an energy model with the physical manifestation of the building (ONeill et al., 2011). To identify parameters of an energy model which need to be carefully adjusted, O'Neill and colleagues performed a sensitivity study which varied over 1000 parameters of an EnergyPlus model by +/-20% of their nominal value. After the runs were completed, the results were viewed, and those parameters which created the largest fluctuation in energy usage were noted. An on-site weather station and energy management program were used to determine actual energy usage and enter recorded climate data for the comparison period. After calibration of the sensitive parameters, the resulting model energy use correlated with the recorded data to within 4%. The study highlights how an energy model can be analyzed for drivers of uncertainty in results by systematically varying parameters which affect the output.

Preliminary life cycle analysis on RDP houses. The life cycle analysis conducted in this paper is a follow-up to an investigation performed by (Ramsdell et al., 2012). In that study, Autodesk Ecotect software was employed to simulate annual heating energy usage. The study selected reasonable solutions to improve the energy efficiency of homes in central South Africa. Cost estimates for the homes with and without the efficiency measures were developed and used to perform a life cycle cost analysis to find the payback period and energy savings over a typical mortgage period. A monthly cash flow model was developed for each house scenario using local utility and interest rates. The results showed not only that a significant reduction in energy usage could be realized through simple energy efficiency measures, but that significant monetary savings could also be realized over a thirty-year mortgage life (see Table 2.1). This current study builds upon the original by comparing Ecotect results to EnergyPlus and TRNSYS simulation results and by recalculating the life cycle costs for the original six house scenarios. Construction and material costs from Ramsdell et al. (2012) are used, as shown in Table 2.1 on the next page, as well as financial data for the South African houses (Ramsdell et al., 2012). Note that seven South African Rand was equivalent to approximately one U.S. dollar at the time of this study.

Table 2.1. *Energy efficiency measures and associated costs used in Ramsdell's previous study on RDP houses.*



Case ID	Energy Efficiency Measure	Insulating Parameters
A	Base Case – No ceiling or insulation Double brick wall w/o cavity	
B	Cavity Wall - 40mm	
C	Cavity Wall w/40mm Extruded Polystyrene	
D	Gypsum Ceiling w/Blown Cellulose	
E	Double Pane Windows w/Wood Frame	
F	C and D Combined	



	Construction Costs (ZAR)			
Case ID	House 1 42m^2	House 2 62m^2	House 3 84m^2	House 4 105m^2
A	R116,590	R188,472	R366,985	R260,197
B	R0	R0	R0	R0
C	R6,865	R9,338	R13,588	R13,968
D	R7,752	R12,540	R19,608	R26,220
E	R9,616	R14,467	R53,527	R43,333
F	R14,617	R21,878	R33,196	R40,188

Chapter Three: Methodology

General Overview

This study analyzes the relative improvement potential of various efficiency best practices on small masonry-based homes. In doing so, the standard design of such homes, which may be adopted or adapted for government-built housing intended to improve the quality of life in developing countries such as South Africa, can be improved upon. These improvements will lower life-cycle costs of houses and decrease energy burdens on the government when building on a massive scale, as many developing countries need to do.

Using building energy modeling and simulation techniques, the contribution of building components of the houses can be compared to determine which components become more significant as the buildings become smaller. The study uses two energy simulation software packages, EnergyPlus 7.2 and TRNSYS 17, both to test the goodness of the models and to compare how each program simulates the small buildings. Figure 3.1 provides a graphic description of the process used to carry out these analyses.

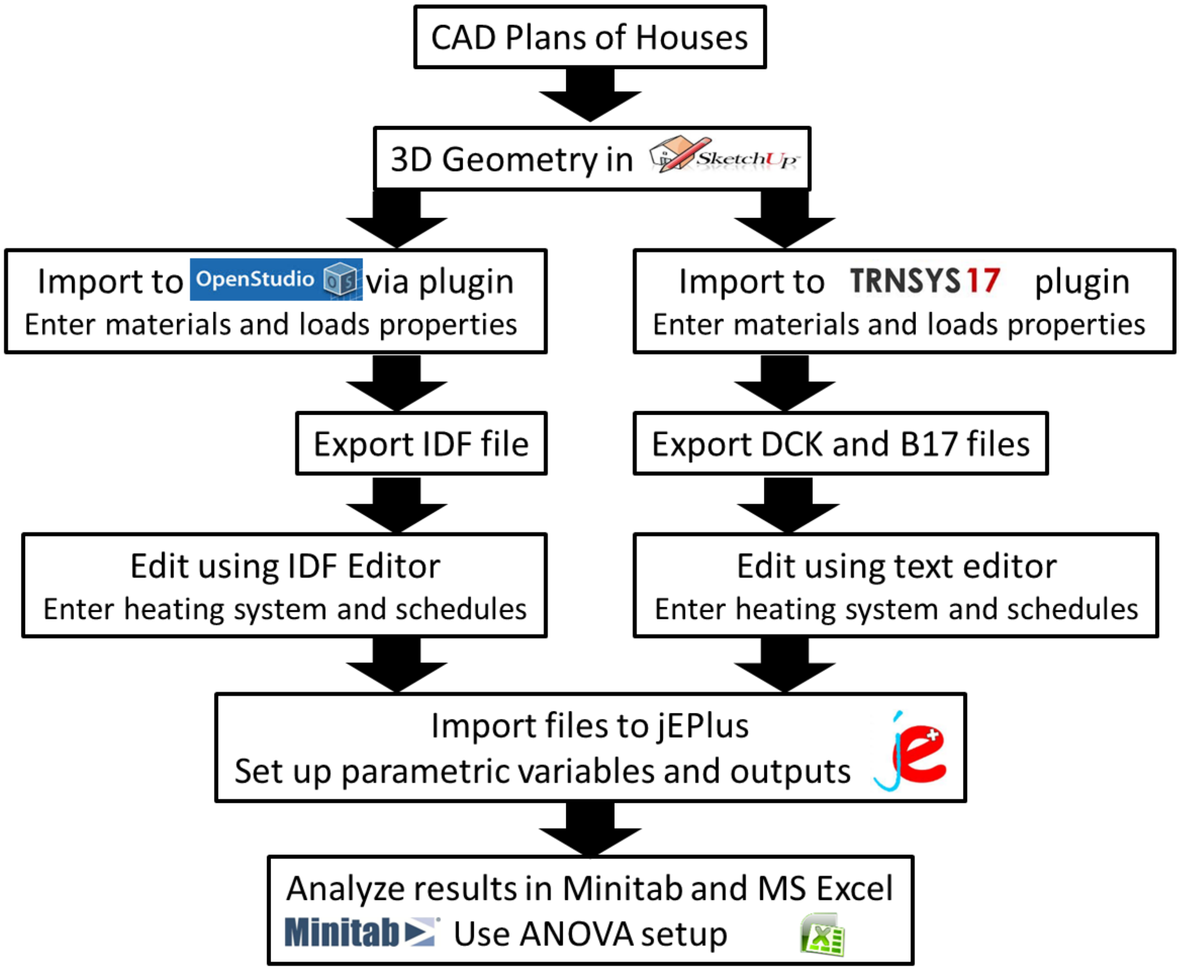


Figure 3.1. Overall process flowchart for the study. Each step is detailed in this section.

House and Climate Information

The houses selected for this study represent a spectrum of sizes and layouts of homes in central South Africa. All are brick and/or concrete walled with slab-on-grade construction. The houses range from $42m^2$ to $105m^2$ in floor area. These houses will be used because they offer a realistic scenario of building layout and construction. A review of the typical RDP home construction indicates that the smallest house of this group is very similar to the RDP specification and is a good representation of the program’s intended design. The larger houses represent optional larger sizes of the RDP specification and introduce different design features such as sunrooms, larger glazing percentages, and higher roof pitches. By looking at the energy usage normalized for overall floor area, the effect of these geometric differences in the houses can be identified during the analysis. The smallest house would be designed for three to four people, while the largest house could accommodate a larger family of six or seven.

The four actual houses that are the basis of this study have slightly different constructions (Figure 3.2), but are similar enough that normalizing parameters will not change any house’s fundamental thermal behavior. All houses are one story, have a similar north-south orientation, and have spaces that can be classified as either lounge/kitchen/dining or bedrooms, which can be simplified into daytime use or nighttime use. Table 3.1 shows a summary of the houses with floor area, envelope area, and glazing percentages. Each house has some unique geometry, which creates a fifth parameter: geometry. By looking at the different geometry of each house when analyzing energy usage normalized for floor area, the contributions of some of the unique features of each house can be assessed. For instance, House 3 has the largest window area of the group, so the sensitivity of that model to changes in window properties is expected to be larger than for House 1, which has a lower ratio of window to envelope area.

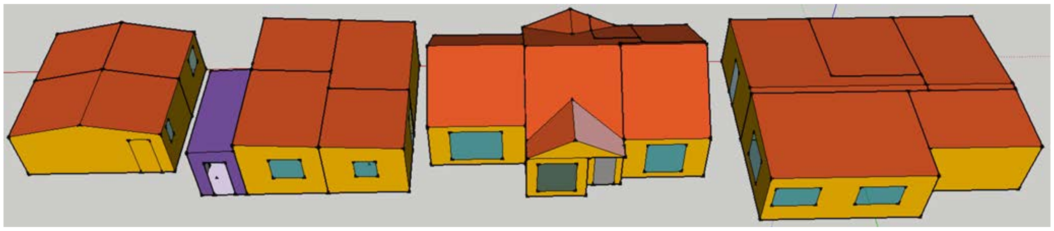


*Figure 3.2***.** Visual comparison of the four house models, ordered left to right with increasing floor area.

Table 3.1. *Summary of Parameters for Each of the Four Houses Modeled*

	Units	1-Jeminah	2-Susan	3-Verster	4-Albert
Interior Floor Area	m^2	42	55	84	105.7
Envelope Area	m^2	150	197	305.1	326.6
Glazing Area	m^2	3.3	6.7	14.9	12.2
Glazing Percentage of Envelope Area	%	2.2	3.4	4.9	3.7
Glazing Percentage of Floor Area	%	7.9	12.1	17.7	11.6

The baseline construction for the models complies with the typical RDP house construction described in Chapter 2. Models all use a double brick layer wall construction. Each layer of brick is 110mm thick with a thin layer of mortar between and five millimeters of cement rendering on the inside face. The baseline roof is a single layer of corrugated metal resting on rafters with no insulation or radiant barrier beneath. The slab is concrete with no insulation and no flooring above it. Windows are single-paned with a metal frame, and doors are a single layer of steel.

All houses are located in the central South African region near Bloemfontein. This area is part of the central plateau of the country, with an elevation of about 1,400 meters (4,600 feet), and is classified as a semi-arid climate with cool and dry winters where frost is common at night. The climate is classified in South African Bureau of Standards (SABS) 10400-XA as Climate Zone 1, the coldest region in the country. Temperatures at night during the winter months of July and August can regularly drop below freezing outside, and daytime temperatures may not rise above 5°C during a cold spell.

Weather data was acquired from the Energy Efficiency & Renewable Energy website for Johannesburg, South Africa. The data is freely available in EnergyPlus format (.EPW) and was converted for use in TRNSYS for this study. To convert the weather file from the EPW format to the TRNSYS-required TMY2 format, the arrangement of the data columns was changed. This was done by importing the EPW weather file into a spreadsheet and rearranging the columns to fit into the TMY2 weather data formatting requirements. Some units needed to be converted between the programs, but the actual data was identical. Using this method assured that the same climate data was used in both programs. Weather data represents a typical year and is created through the analysis of several years of weather data according to International Weather for Energy Calculations (IWEC), created by ASHRAE in 2001. Because the weather data is designed to represent a typical year, any individual year of weather data may not exactly correlate with the typical weather data; however, over longer periods (over 10 years), the average recorded climate data should be close to the weather data file supplied for the energy modeling programs. Figure 3.3 shows the dry bulb temperature range for each month of the year, extracted from the weather data file. In reality, the climate data is slightly incorrect since it represents the weather in Johannesburg, while the houses are much closer to Bloemfontein. Bloemfontein is closer to the geographical center of South Africa and is slightly colder during the winter, meaning that the heating energy usage calculated during simulations is somewhat conservative in that if actual Bloemfontein data were used, the heating energy usage would be higher due to the colder temperatures.

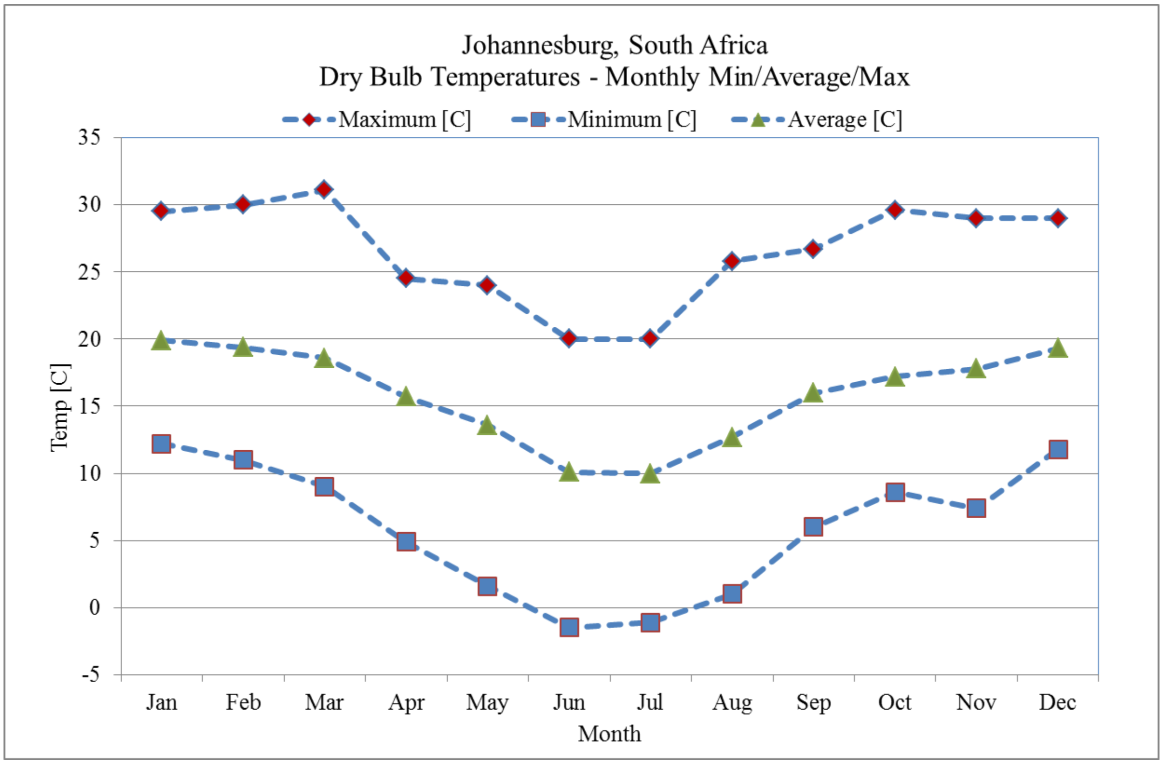


*Figure 3.3***.** A summary of dry bulb temperatures in Johannesburg, South Africa, as indicated by the supplied weather data file.

The climate zone rating defines the insulation values required for the surface envelope using the IECC standard. The climate in the location of the houses complies with the IECC 2012 rating of Climate Zone 4A. A summary of the climate zone ratings is shown in Table 3.2 on page 34, which reproduces Table C301.3(2) from the IECC 2012 standard. The rating is based on the number of heating degree days and cooling degree days as well as on annual precipitation. According to the weather data, annual precipitation for this area averages 46.8cm and has an annual average temperature of 15.85 C, which equates to a “moist” area rating. The number of cooling degree days above 10°C (CDD10C) are 2304, and the heating degree days below 18°C (HDD18C) are calculated as 1263. The IECC tables classify this region as Climate Zone 4 for temperature, and “A” for moisture. These calculations were made using the climate data file for Johannesburg. While the Bloemfontein data may be slightly different, both the heating and cooling degree day numbers are well within the brackets for maximum and minimum values, so the climate zone is still applicable using this data.

Ground temperatures are not included in the climate data files, so this boundary condition for the models was generated based on the ambient temperature data throughout the year. The ground temperature approximation was set up as a cosine equation that reflects the average air temperature throughout the year. This cosine equation results in ground temperatures of 16°C +/-5°C, in phase with the changing ambient temperature. The direct relationship is due to the small size of the models and the slab-on-grade construction of the floor, resulting in ground temperatures at very shallow levels without much insulation from the building.

Table 3.2. *Excerpt from the IECC2012 specification, showing the classification for international climate zones based on temperatures and precipitation (International Code Council, 2011, pp. 25-26).*

Zone Number	Thermal Criteria	
	IP Units	SI Units
1	9000 <CDD50F	5000 <CDD10C
2	6300 < CDD50F≤9000	3500 < CDD10C ≤ 5000
3A and 3B	4500 < CDD50F≤ 6300 AND HDD65F≤ 5400	2500 < CDD10C≤ 3500 AND HDD18C≤ 3000
4A and 4B	CDD50F≤ 4500 AND HDD65F≤ 5400	CDD10C≤ 2500 AND HDD18C≤ 3000
3C	HDD65F≤ 3600	HDD18C≤ 2000
4C	3600 < HDD65F≤ 5400	2000 < HDD18C≤ 3000
5	5400 < HDD65F≤ 7200	3000 < HDD18C≤ 4000
6	7200 < HDD65F≤ 9000	4000 < HDD18C≤ 5000
7	9000 < HDD65F≤ 12600	5000 < HDD18C≤ 7000
8	12600 < HDD65F	7000 < HDD18C

South Africa defines climate zones differently based on the relative conditions across the country. The South African National Standard (SANS) 10400-XA:2011 defines climate zones across the country. The climate zone definitions are shown in Figure 3.5, overlaid on a map of South Africa. Bloemfontein and Johannesburg fall into Climatic Zone 1 – Cold Interior. As with the IECC standard, the climate zone classification dictates the building envelope insulation requirements.

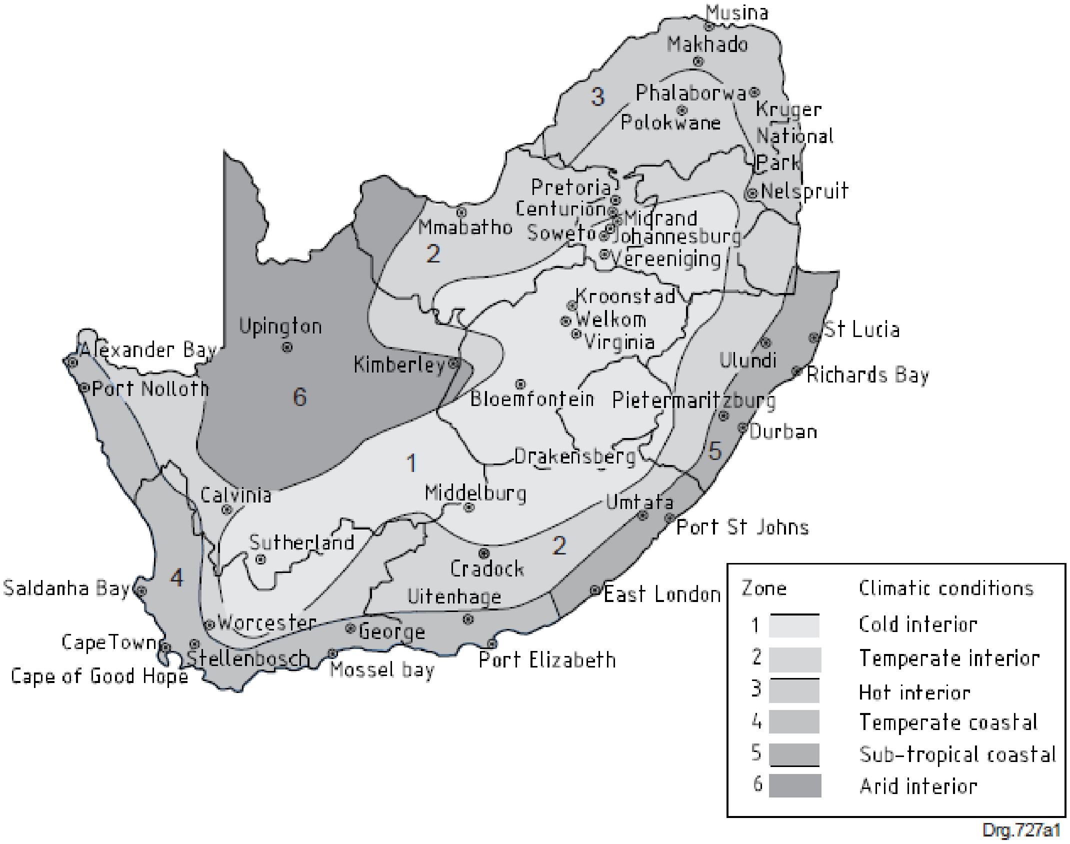


*Figure 3.5***.** Climatic Zone definitions in South Africa, taken from SANS 10400-XA (South Africa National Standards, 2011, p. 12).

Building Parameters Varied for Sensitivity Study

Four different construction parameters were varied in this analysis. Each parameter was varied to have one of three values. The first level represents how the typical RDP house is built as described on page 12. The second level represents the minimum requirement specified by the SABS specification SANS 10400X-A, which is the minimum for new constructions in South Africa. Because the South African building energy code is relatively new and not widely followed, it was chosen as the second parameter level. The third level was the minimum requirement specified by the IECC2012 building standard. A table of the required conductivity values is shown in Table 3.3. For the current construction level, the assembly-level conductivity values shown in Table 3.3 were calculated from the actual construction techniques.

Table 3.3. *Envelope Insulation Requirements According to the Relevant Specifications*

Conductivity (W/m^{2}K)	Mass Wall	Fenestration	Ceiling	Slab-on-Grade
IECC2012 Zone 4A	0.68 (insulation layer)	1.985	0.147	0.567
SANS10400-XA Zone 1	2.85 (assembly)	4.23	0.270	1
Current Construction	5.62	7.9	48.8	5.89

Table 3.4. *Constructions Which Comply with Each Level's Requirements*

Level		Mass Wall	Fenestration	Ceiling	Slab-on-Grade
First	Current Constr.	Solid Brick	Single	None (metal roof only)	80mm slab no insulation
Second	SA Code Min.	Brick cavity wall - 40mm air gap	Low-end double pane	Metal roof with 18cm batt insulation	Insulated slab
Third	IECC2012 Min.	Brick cavity wall - 40mm XPS foam	Mid-range double pane	Metal roof with 33cm batt insulation	Insulated slab and perimeter

Table 3.5. *Assembly Conductivity Values of the Constructions Summarized in Table 3.3*

Assembly U Values [W/m2*K]	First Level	Second Level	Third Level
Walls	5.623	1.419	0.603
Ceiling	48.804	0.270	0.147
Windows	7.900	4.230	1.967
Slab	5.888	0.883	0.528

The types of constructions these requirements represent are summarized in Tables 3.4 and 3.5. The wall system goes from a solid brick wall to using an air gap between layers, which is a common building practice in South Africa, although typically present in the hotter climates where the construction is used to reduce overheating inside the building. One issue with modeling an air gap greater than 25mm is that a convective current can form, increasing heat transfer between wall layers. This is accounted for in the simulation models by not just using the conductivity of the air, but also by calculating the overall convective coefficients on the inside surfaces of the wall layers and creating an overall conductivity value that incorporates both the material conductivity and the loop convection value. The third wall level fills the 40mm gap between brick layers with a solid layer of extruded polystyrene foam. This construction modifies the common building technique of an air gap by simply putting a standard size foam board between the layers, so it represents a viable alternative to the air gap.

The roof system starts as the metal roof with no insulation and moves to the second level by adding the equivalent of approximately 18cm of batt insulation. The third level increases the insulation value to have the equivalent of 33cm of batt insulation. In the case of the roof insulation, the additional space considerations required by this thick layer of insulation were not considered and are not accounted for in the model. In other words, the interior volume of the house did not change with this added insulation. A physical representation of this level of insulation would be to raise the roof by the required amount to fit in the insulation without reducing the head clearance underneath.

Windows are represented as single-pane glass with a metal frame for the lowest level and move to a basic double-pane window to meet SABS requirements. A better double pane window is required to comply with the IECC standards, with a lower U-value and bringing with it a lower solar heat gain coefficient (SHGC). The slab gains two levels of insulation both horizontally (underneath) and vertically (perimeter) to meet the minimum insulation requirements for the second and third levels. The ground models use a sinusoidal ground temperature variation, which applies both at the perimeter and underneath the slab, so insulation on both surfaces is required. For the relatively small footprint that these houses have, the ground temperature underneath the houses can vary substantially more than in larger buildings, since the building itself does not isolate the soil from the ambient conditions as much as a larger building would. For this reason, the insulation may be necessary not only on the perimeter but also underneath the slab.

It should be noted that while the different envelope components change in thickness as insulation is added, this thickness does not change the internal volume of the building. Once the heat transfer properties are calculated, the thickness values are discarded and the heat transfer components are carried through as total conductivity and heat capacitance. For this reason, each wall, roof, window, and floor system can have a different thickness without changing the air capacitance inside each room.

Model Outputs for Analysis

The main output of concern is the annual heating energy consumed by the house. The quantity was presented in kilowatt-hours per year, and represents how much energy is consumed by the space heater placed in the house throughout the entire year. An electric heater is simulated, which has an efficiency of 100%, or a COP of 1.0. This means that all energy used by the heater goes into the house as heat, whether by convection or radiation. The energy quantity accrues over the entire year, not just in the colder months. This means that whenever the interior temperature drops below the thermostat set point, the heater will be activated. While the heater may not always be activated in the actual houses, the effect should be small, since the heating load will be small when the temperature temporarily drops during the hotter months. This scheme may also offset the times where the heater may be left on even when the temperature is above the thermostat set point, a situation that likely happens in the actual houses, for which the models do not account.

In addition to annual heating energy, the interior temperatures of the model were logged and analyzed for certain scenarios as a check on the operation of the model. The ability of a house to maintain an interior temperature with changing outdoor conditions is another way to compare energy demand of the models. A house with better insulation is able to maintain comfortable interior conditions, and the interior temperatures can be analyzed alongside energy usage to understand how demand changes throughout the day and year. The interior temperatures were especially useful for this study because finding accurate energy usage for the actual houses could not be done, so measurements of actual interior temperatures provided a point of comparison to the simulated models in the effort to create representative models of the houses.

During the model creation process, a large number of other parameters were analyzed for debugging and adjusting the model inputs and calculation methods. While energy usage and interior temperatures were important parameters during model creation, it was also necessary to look at irradiance on surfaces, surface temperatures (as opposed to air temperatures), and gains from internal loads and outdoor air exchange. Looking at a wide variety of parameters ensured that the two software programs were set up with the same inputs and similar calculation methods. Analysis of these supplementary outputs made the calibration and comparison between the two models possible, as the complexity of the simulation software packages cannot be expressed by looking at the energy usage and interior temperatures alone.

Software Programs Used for Simulations

EnergyPlus models are constructed through a series of plugins and auxiliary interface programs. The freeware program OpenStudio serves as the interface to apply materials and thermal zones to the model geometry, which is created in the freeware Trimble Sketchup using an OpenStudio plugin. The final adjustments to the model before running the parametric analysis are made in the IDFEditor program distributed in the EnergyPlus simulation software package. The final models are executed in the jEPlus batch simulation software. The detailed procedure for creating and simulating the house models using the EnergyPlus software is described on page 47.

A similar procedure used with EnergyPlus is employed for building and simulating models using the TRNSYS engine. Model geometry is imported from a Sketchup file using the TRNSYS3D plugin into the Simulation Studio software, where materials and loads are applied. The simulation and building files are modified in text format to their final state and imported to jEPlus for simulation. A detailed procedure for creating and simulating the house models using the TRNSYS engine is described on page 52.

Crucial to this process is a method for automating the annual simulations while changing the desired parameters to pre-defined values. The freeware program jEPlus, created by the Institute of Energy and Sustainable Development (IESD) at De Montfort University, accomplishes this task for both EnergyPlus and TRNSYS simulations. The program uses search strings placed in the input file to find and replace parameters and to perform batch simulations while systematically varying the selected parameters. Outputs from the simulations are compiled into tables for analysis.

Common Modeling Parameters

Although models were created in both EnergyPlus and TRNSYS, the parameters of the models were kept as similar as possible across the different houses and programs. All parameters that were communized between the two are outlined in this section.

The simulations used the hourly conditions throughout the year, including dry bulb temperature, relative humidity, irradiance, wind speed, and wind direction. The simulation programs offer simulations of design conditions to evaluate maximum energy demands for heating and cooling. These options are generally used to determine required cooling and heating capacities. Because this study worked only with space heaters that have a known and limited capacity, the design day analyses were not conducted, so the design conditions did not need to be included in the simulation file.

Envelope component constructions. Using the requirements for each level and the constructions outlined in Table 3.4 on page 36, the model constructions could be created using materials in the program libraries. The wall material properties are shown in Table 3.6. Mortar was used for the first level wall, followed by an air gap and polystyrene insert for the second and third level walls, respectively.

Table 3.6. *Wall Layer Properties, Including U-values at the Specified Thickness*

Property	Units	Brick	Mortar	Air Gap	XPS Insert	Int. Render
Thickness	Meters	0.11	0.001	0.04	0.04	0.005
Conductivity	W/m*K	1.297	0.53	0.07566	0.027	0.79
Density	kg/m^3	1980	1280	1.2407	265	1330
Specific Heat	J/kg*K	732.2	840	1006.6	836.8	1000
U-Value	W/m^2*K	11.8	530.0	1.9	0.68	158.0
R-Value	m^2 *K/W	0.0848	0.0019	0.5286	1.4815	0.0063
R-Value	Ft^2*F*hr/Btu	0.481	0.011	2.997	8.400	0.036

The window assembly properties are shown in Table 3.7 on page 43, which were selected from the available component library in TRNSYS and applied to EnergyPlus. The selected windows represent the requirements at each level in accordance with the standards. Note that these properties include only the window assembly without inner and outer air films. The properties of the air gap between glass panes were included in these properties. Windows were always considered closed during the simulations.

Table 3.7. *Window Fenestration Properties*

Property	Units	First Level	Second Level	Third Level
Window Type	NA	Single Pane	Double Pane	Double Pane
U-Value	W/m^2*K	5.68	2.83	1.4
SHGC	Fraction	0.855	0.755	0.589
Visible Transmittance	Fraction	0.901	0.817	0.706

The modeling method for the roof was to start with a single layer of metal and add insulation beneath in accordance with standards requirements. Because a layer cannot be added during parametric evaluation, a very thin layer of insulation material was present in the model when simulating the first level roof scenario. The layer was thickened for the second and third levels to reach the required insulation level. Table 3.8 shows the properties of the different layers to represent all three levels of roof system. The U-values of each layer indicate how the very thin layer of insulation at the first layer is negligible when compared to the second and third level values, as it has 180 times the conductivity of the second level.

Table 3.8. *Roof Layer Properties*

Property	**Units**	**Metal Layer**	**First Level Insulation**	**Second Level Insulation**	**Third Level Insulation**
Thickness	Meters	0.005	0.001	0.181	0.333
Conductivity	W/m*K	61	0.049	0.049	0.049
Density	kg/m^3	7310	265	265	265
Spec. Heat	J/kg*K	225.9	836.8	836.8	836.8
U-Value	W/m^2*K	12217.2	49	0.27	0.147
R-Value	m^2 *K/W	0.0001	0.02	3.7	6.79
R-Value	Ft^2*F*hr/Btu	0.0005	0.12	20.98	38.48

Table 3.9. *Slab Floor Layer Properties*

Property	**Units**	**Concrete**	**First Level Insulation**	**Second Level Insulation**	**Third Level Insulation**
Thickness	Meters	0.1000	0.0010	0.0270	0.0476
Conductivity	W/m*K	0.753	0.027	0.027	0.027
Density	kg/m^3	3800	265	265	265
Specific Heat	J/kg*K	656.9	836.8	836.8	836.8
U-Value	W/m^2*K	7.5	27.0	1.0	0.6
R-Value	m^2 *K/W	0.13	0.04	1.00	1.76
R-Value	Ft^2*F*hr/Btu	0.75	0.21	5.67	9.99

The slab concrete and insulation properties are shown in Table 3.9. As with the roof system, the thickness of the insulation layer was changed from a very thin layer to the required values for the second and third levels. All insulation material properties remained constant.

The door was made of a single layer of steel for all scenarios. The properties of the door are shown in Table 3.10. Note that these are the material properties of the metal, and do not include air films on either side of the door, which are assigned according to each program's algorithm for vertical surfaces.

Table 3.10. *Door Material Properties Used in All Simulations*

Property	**Units**	**Metal Door**
Thickness	Meters	0.0100
Conductivity	W/m*K	45
Density	kg/m^3	7800
Specific Heat	J/kg*K	836.8
U-Value	W/m^2*K	4500.0
R-Value	m^2 *K/W	0.0002
R-Value	Ft^2*F*hr/Btu	0.0013

Internal loads and schedules. All scenarios had the same internal load structures. Table 3.11 on page 46 summarizes the internal loads present in every house. The values used were constant throughout the simulation. This was a concession for the sake of simplifying the simulation, since a more detailed schedule of the loads in the building would require surveying the inhabitants for load usage behavior and developing daily and weekly schedules around the actual behavior. This is an area where future research could build upon this study to provide more accurate usage patterns for the internal loads. For this study, the loads were kept constant throughout the day and year.

The lighting value was on the slightly higher side of consumption, due to the mix of incandescent and compact fluorescent lighting methods in the houses. A new energy efficient public building would strive for a lighting load of 10W/m^2 or less, especially if an energy efficiency certification is desired. The loads from people inside the building were estimated as about one person per room at a nearly resting state, as stated in the EnergyPlus documentation. This equates to 80 Watts per person, thus giving the load of 80 Watts per zone in this simulation. Since the larger houses are likely to have more inhabitants, this load was set up to be one person per room to account for that.

Plug loads were averaged for a twenty-four period including all non-heating appliances in the house such as ovens, refrigerators, irons, televisions, etc. This value was varied to get to the approximately correct loads, but could also be more closely analyzed in future studies of occupant behavior and electricity use in the typical RDP homes in this region. The infiltration values were estimated based on the type of construction, which includes little to no weatherproofing around openings, and the climate and average behavior of the occupants in opening doors and windows.

Table 3.11. *Internal Loads for All Simulations, Including Outdoor Air Exchange Rate*

Load Type	**Unit**	**Value**
Lights	Watts/m^2 floor area	15
People	Watts per zone	80
Plug Loads	Watts per zone	200
Infiltration	air changes per hour	2.0

Thermal zone and thermostat setup. One thermal zone was defined as only containing one room in all models in both programs. In modeling a building environment with thermal zones, the simplest model should be used without compromising how the model represents an actual building of the same architecture. For the houses used in this study, which are generally small and of simple layout, each room can easily be modeled as a single zone, and the combination of rooms into a smaller number of zones would not provide much savings in terms of calculation times, so each room is a thermal zone. In addition, because of the variety of rooms in each house, each room has a different interaction with the environment, so it makes sense to model each room as a discrete thermal zone. Thermal zones are named according to the supplied house plans.

The thermostat schedules were set up based on room usage. To simulate properly a single space heater supplying heat to the entire house, the heating was only available either in bedrooms or in other rooms, but never both types at the same time. This scheme was set up with thermostat schedules where the day heating and night heating schedules did not overlap each other during the daily cycle. In the model, the heating system for the bedrooms had a thermostat that turned on only between the night hours of 6:00pm and 6:00am, while the daytime-occupied rooms had the heating system available between 6:00am and 6:00pm. The temperature set point was 18°C for both room types, because previous studies indicate that or a higher temperature as a comfort point for naturally ventilated buildings (Harris, 2005) . While evidence found in measurements of actual interior temperatures of the houses showed that there was no effective thermostat setting in terms of a temperature control, the set point of 18°C was used for purposes of reproducibility of the models and for simplification. In reality, the heaters in these houses are activated when the people feel cold, which is not always at an 18°C interior temperature. The limits of human comfort are based on more than simply the dry bulb temperature in the house and are related to outdoor temperature, humidity, and other climate conditions; however, since the literature projects this temperature to be generally acceptable for interior comfort, the thermostat set point used 18°C.

Houses of this type in South Africa do not have an active cooling system, so a mechanical cooling system was not defined in the models. The thermostat cooling set point was therefore set to a very high value of 60°C, which ensured that the model did not call for cooling at any time throughout the year. This step was only required in EnergyPlus, since the heating system is attached to a dual set point thermostat, which requires an input for cooling set points.

Model Setup for EnergyPlus Simulations

Each house was modeled individually with the geometry being created in Trimble Sketchup using the OpenStudio plugin, available for free from the EERE. The geometry is adapted from the CAD plans provided by the UFS Quantity Surveying department. Each zone was modeled using the interior dimensions to have accurate volumes and envelope surface area. For the interior walls, half of the thickness of each interior wall was used as part of the zone.

Each house geometry was imported into the OpenStudio (version 0.10) application once all zones were complete with all surfaces and openings as defined in the plans. The OpenStudio application assigns default schedules, constructions, and internal loads, which were all modified or deleted to simplify the model and to more accurately represent the buildings. In the OpenStudio application, the common modeling parameters were applied to each house model. For this study, all internal loads were given the same value described above on page 45. A common parameter library was created to easily load in the desired setup for the OpenStudio model.

One issue that OpenStudio has at the time of this writing is the lack of an electric convective/radiation heating system. Thus, each model was given a temporary heat pump system with the heating and cooling COP set to 1.0 and all electrical and motor efficiencies set to 100%. This created at least a similar system to an electric heater system, which could be used while debugging the rest of the model; however, it could not be used for comparison purposes to a model with an appliance space heater, since the heat pump system has no radiation component and uses forced air to keep all surfaces at a uniform temperature. The heating system was changed using a text editor or the EnergyPlus IDF editor to enter more accurately the heating system parameters using the ElectricBaseboard:Convection/Radiation object class, which is not available for use in OpenStudio as of this writing.

For the parametric study, only the sensible heating energy supply was needed for each zone, with the output at the end of the run period, which is the end of the year simulation. This output shows the total heating energy required by the heating system for each zone for the entire year. This number is output in joules for each room, which can be converted to total house kilowatt-hours in the output spreadsheet. For debugging purposes, other dependent and independent variables can be viewed, such as interior temperatures, surface temperatures, and internal loads. These outputs are invaluable for making sense of the model and ensuring that all behaviors dictated by the simulation program make physical sense.

Once a working model is created in OpenStudio, the IDF file can be exported and finalized. By adding all materials and constructions that will be used for every scenario to the model library, the parametric changes during automated runs will not create an error where a new material or construction is not found in the input file. It is important to note that OpenStudio will duplicate, rename, and reconnect components that are imported in a common library if another component in the model has that component's name, so reviewing all components before, during, and after import and export is crucial for proper model inputs for automated simulations.

Before the model can be finalized for parametric variations, some reformatting and editing is required to make the IDF file concise and usable. The EnergyPlus IDF editor is a good tool for accomplishing this task. By using IDFEditor, the syntax is placed in the IDF file without the need for formatting, but all features available in EnergyPlus can be utilized. Once the components that stay constant across house models are set up correctly in IDFEditor, the input code can be copied and pasted using a text editor, but the first iteration should be completed in IDFEditor to ensure correct syntax and connections between components, as well as to have a layer of automated error checking in the model by the program itself.

As stated earlier, OpenStudio adds many components to the IDF file by default, and many are not needed or can be replaced with simplified versions that are easier to edit and debug. The reason for this is because of OpenStudio's focus on larger building with more complex space conditioning systems and interior loads. Much of this complexity is needed for building certification purposes, but for these houses it was not necessary, so many of the default setups could be deleted. Without modifying geometry and zone data, the following objects could be deleted from the file:

- Outdoor air, mixers, and nodelist objects – outdoor air comes solely from infiltration in the houses, so mechanical ventilation is not present.
- Zone air distribution – the space heating comes from appliance heaters, which use no distribution system to circulate air.

- Sizing parameters – the heating system has a fixed capacity which is entered manually. Sizing parameters are only needed if the program is to calculate the required size of a system based on heating loads.
- Extra thermostats – The only thermostats needed for the models are one for daytime heating and one for nighttime heating. OpenStudio creates multiple thermostats for each zone, when in reality the thermostats can be shared between zones, so many can be deleted.
- The heat pump systems required for use in the OpenStudio program can be deleted. This includes not only the actual heat pump objects, but all fans, coils, performance curves, and schedules that go along with the system.

For any common components that were copied and pasted from one file to the next, the connections needed to be modified, since each house had a different number of zones and surfaces. For this reason, it was helpful to create a generic space type which contained the list of all internal loads and schedules that were applied to every zone in the house model. This template cut down on potential data entry errors by minimizing the amount of data to enter for each unique circumstance in the model. It also significantly reduced the size of the input data files. The deletion of unnecessary items reduced the input file size by approximately 75%. This reduction also made debugging and coding much simpler tasks, since there were no more superfluous items in the files to cause confusion. All of the models had common constructions and internal loads, which could be saved to the template. For this study, a template called “SA Home Low” was used to apply universally the same constructions and internal loads to every zone of every house.

To model a more accurate heating system, a common baseboard heating system was created in IDFeditor, and the code was copied into each house file. Each thermal zone needed a discrete heater, so the capacity of each zone's heater was a portion of the maximum total heater capacity of 2500W. In reality, each house had only one heater with a maximum capacity of 2500W, which this scheme recreated. This means that if the house had two bedrooms that were both heated at night, each room needed a heater with a maximum output of 1250W. Since bedrooms in these houses are similarly sized, the loads on each room should be similar, and thus an equal heating capacity was considered acceptable. Care needed to be taken to split power output to zones that shared the heater at night and during the day. The heating system is not used in the bedrooms during the day, as it would be carried to the more occupied rooms. This was modeled by having the thermostat turn the heating off in those rooms during the day and having heating only available at night. Thus, the heating capacity of each zone was set up as 1/N *2500W, where N is the number of zones that share the same thermostat schedule, with a minimum of 1250 watts per zone, to account for the larger houses potentially having more than one heater.

The space heater model has not only a convective heat transfer component but also a radiation component. With radiation modeled as 25% of the heat output of the system, individual surfaces were defined in EnergyPlus to receive the radiation from each heater. Three surfaces were defined for each zone that each received a fraction of the radiant energy. A total of the fractions equaled one.

The complete models were saved as IDF files and opened for parametric automated simulations using jEPlus. See page 55 for a description of that procedure. A procedure for modeling the houses using TRNSYS was also developed and is described in the next section.

Model Setup for TRNSYS Simulations

The TRNSYS model begins in Sketchup just as with EnergyPlus, except the TRNSYS3D plugin is used to create the thermal zones. While the plugin saves the data as an IDF file type as in the EnergyPlus model, importing the file into TRNBuild changes the format and brings the data into the TRNBuild program to be manipulated for use with a TRNSYS input file.

The construction materials are created using the layers and properties given in Table 3.3. In TRNSYS, it is necessary to define convection coefficients for all surfaces of heat transfer surfaces. In contrast to EnergyPlus, the values must be entered manually. For inside surfaces, the convection coefficient can be evaluated as a vertical surface, a ceiling surface, or a floor surface. The outside coefficient is input as a constant to determine assembly thermal conductivity. For this study, a comparison was done to determine the more realistic convection coefficients and the software package with a more representative algorithm provided values exported to the other program. The underside of the slab component, which touches the earth and thus has no convective component on the outer layer, has a convection coefficient of zero.

A correction that needed to be made for all thermal zones created in the TRSNYS3D plugin had to do with air pressures. The zones are created before the weather data file is accessed by the model, so the default values are used for the properties of air. The default properties correspond with air at sea level. The elevation of the geography where these houses are located is at 1400m, where the air has different properties. Atmospheric pressure is about 80kPa as opposed to 101.2kPa at sea level; therefore, the density of the air is about 1 kg/m^3, as opposed to around 1.22 kg/m^3 at sea level. TRNSYS calculates the air capacitance, which is the heat capacity of the air in a thermal zone (found by multiplying density, volume, and specific heat capacity together), for each zone using these values, so the air capacitance needed to be corrected for each zone in each house. The air capacitance dictates how much energy is required to change the temperature of the room air by one degree, so this value needed to be corrected to get an accurate depiction of each zone. Without changing this value, the heat required to change the room air temperature would have been approximately 20% too high since that is the difference in air density at the correct elevation versus at sea level.

The windows are selected from the built-in library based on construction and U-value. The selected models for this study were Types 1001, 1002, and 2001 for the low, middle, and high levels, respectively. A summary of the window properties is shown in Table 3.11.

Table 3.11. *Window Parameters Taken from TRNSYS Component Library*

Window Grade	Construction (Glass/Air/Glass)	U value (W/m^2)	SHGC
Type 1001	4mm/0mm/0mm	5.68	.855
Type 1002	4mm/16mm/4mm	2.83	.755
Type 2001	4mm/16mm/4mm	1.4	.589

The heating system was defined as a central unit with capacity limited to 2500W (9000kJ/hour) and shared between thermal zones automatically whenever there was heating demand. Heating demand times were governed by the heating availability schedule. This followed the same day-or-night heating schedule as in the EnergyPlus model. The irradiated portion of the heat output was set to 25% with no latent heat output to simulate a convective-radiation space heater.

TRNSYS compiles the construction data for each envelope component at the beginning of a simulation and calculates heat transfer coefficients for the components. The algorithm uses consecutive time steps to converge on a solution for these coefficients, which are then used in heat transfer calculations. By default, the number of time steps, known in the software as the timebase, is set to one. This means that if the simulation time step is one hour, then the timebase is one hour and the program uses up to 20 time steps to try to converge on a solution. If convergence is not found within 20 iterations, then the program returns an error. When there are layers in the constructions that have very different densities and heat capacities, there can be some trouble converging on a solution to develop these coefficients. To account for the differences between the brick and air layers in the walls, as well as between the metal and insulation layers in the roof, the timebase needed to be increased to three time steps. This allowed for the thermal storage properties of the heavy wall components to play out in the iterations over 60 hours instead of 20. All simulations used the same time base of three time steps for consistency.

Batch Parametric Simulation Setup in jEPlus

The EnergyPlus and TRNSYS simulations each required a separate jEPlus file for correct syntax and search strings, but the function of the two jEPlus files accomplishes the same task in the same order. For EnergyPlus, an .rvi file is also needed, which sorts the outputs from each EP simulation for output to a .csv file using the built-in EnergyPlus feature ReadVarsESO. For simplicity, the file for this project simply converted the EnergyPlus output file, eplusout.eso, to a comma-separated file that could be compiled when performing batch runs.

When the desired output is annual heating energy usage, the jEPlus program will compile all annual heating energy usage data into a single file with each row accounting for one simulation, containing the annual energy usage of each zone. This can be summed per row to get total house energy usage for heating for the year. If desired, the interior temperatures can also be reported on an hourly basis, although when calculating all combinations of parameters, it is not recommended to have any hourly-reported items, since the data may become overwhelming to analyze.

A parametric tree was created with four levels: wall properties, window properties, ceiling/roof properties, and slab properties. Each level corresponded to a parameter that was changed, and thus had three possible values, based on the experimental setup. Each parameter was varied using a string search, where the program searched the input files for a specific string and replaced that string with the parameter’s current value. For example, when the wall insulation was set to be an air gap, the program searched the input files for the text string “@@Wall Ins@@” and replaced it with the text “SA Airgap40”. The program did this for all four parameter branches at the beginning of each simulation to set the correct values, then saved the input files and executed EnergyPlus with that IDF, or TRNSYS with the DCK and B17 files.

The way that the parameters are entered depends on what parameter is to be varied. When a layer of an envelope component is to be swapped out for another, then the name of the material layer in the construction is the parameter being varied. In the case of the wall component, the layer between the two layers of brick is being swapped, so the values in the parameter tree are the names of the different layers that will be used to slot into the mid-wall gap. For a parameter variation which corresponds to changing only one material property, and not changing an entire layer, the parameter to be varied is a numerical range corresponding to the three levels of insulation. For example, the slab insulation parameter changes the thickness of insulation underneath the concrete slab. The lowest value is set to one millimeter and is essentially a negligible amount of thermal insulation. The highest value corresponds to a thick layer of the same insulation. In this way, only the thickness value of the insulation is changed, and all material properties of the insulation remain constant.

A key point to remember is that each IDF file needs to have a material library which contains the materials that will be used for all simulations, not just the materials used for that specific simulation. This is because the only changes made to the IDF file are the strings edited by the parameter tree; therefore, all building components need to be in place before the parametric variations are run. If not, EnergyPlus will not be able to find certain materials in the library when the values are edited at the construction level.

With the parameters defined and the correct strings placed in the IDF file, the project file can be executed to automate the simulation of all parameter variations. The 81 simulations for this study were run in sequence and an output file was created for each simulation. A compiled results file was created when all simulations were complete. Once the simulation is complete, the outputs are automatically extracted using the ReadVarsESO program and compiled into a single file. This file contains outputs from each simulation and can be sorted for analysis of effects of envelope component variation on heating energy usage.

Data Analysis

To perform the sensitivity study, an analysis of variance (ANOVA) was conducted. By attaching to each simulation result the values of parameters used to achieve that result, the effects of certain parameters could be extracted and evaluated. The Minitab Statistical Software package was used to perform this extraction and visualization of data. Sorted output from the parametric evaluation of each house was brought into Minitab. The result of each simulation was placed into a single column as kilowatt-hours per square meter (kWh/m^2) floor area. Five parametric columns were created to indicate parameter values for each data point. In addition to the four construction parameters described above, the fifth parameter was house geometry, since the energy usage was normalized to floor area. Once the data was entered and organized, the ANOVA analysis was run and results were viewed in two ways. The main effects plot showed how the variation of a single parameter affected the energy usage with all other parameters held constant. The interactions plot showed an array of all the parameter interactions with one another to aid in evaluation of parameter dependencies on one another. For specific comparisons and more detailed analysis of scenarios, the data were manipulated in Microsoft Excel, which allowed more focused views of relationships between parameters. The data output from the simulations needed to be tagged with the value of each insulation value for each parameter so that analysis of the effects could be accomplished. A column was made for each parameter beside the heating energy usage value for each simulation, which contained that parameter’s value for that run. The heating energy usage is also divided by the total floor area for each house model to convert the energy usage from kWh/year to kWh/m^2/year.

Chapter Four: Results and Discussion

Energy Simulation Results

Energy usage simulations were carried out for each of the four houses for all variations of the four parameters. Each parameter had three values: current RDP construction, SANS 10400-XA building code requirements, and IECC2012 building code requirements. Simulations were performed in two energy modeling programs, EnergyPlus and TRNSYS. As a result, $3^4 = 81$ simulations were performed per house, meaning 324 simulations per software program, with a grand total of 648 annual hourly simulations performed. Figure 4.1 shows the run order used for each house. The simulations were run consecutively with no randomization. Levels one, two, and three correspond to the parameter value in order of increased insulation value.

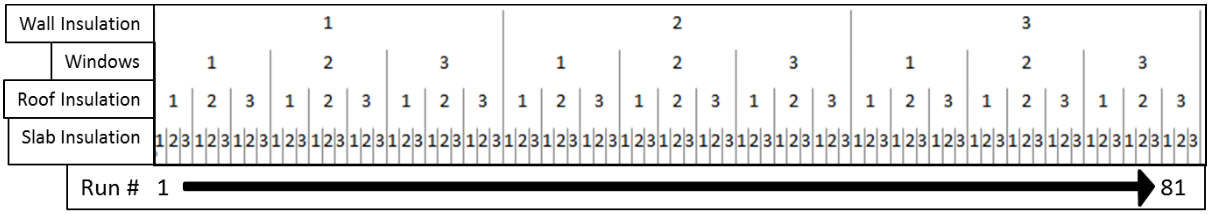


*Figure 4.1***.** Simulation run order per house.

The results were analyzed in a multitude of ways during the debugging and modeling process and are presented here using accumulated averages per parameter value while all other analyzed parameters were varied, otherwise known as a "main effects" analysis. The results are shown as heating energy kilowatt-hours per square meter per year. An analysis of interactions was also performed and will be discussed below. The following sections review the results using EnergyPlus first, followed by the TRNSYS results, and finally by a comparison of the two programs with a discussion on potential sources of variation between the EnergyPlus and TRNSYS. The main effects analysis of the results from the EnergyPlus simulations is shown in Figure 4.2, with a detailed analysis of the results below.

EnergyPlus Simulation Results

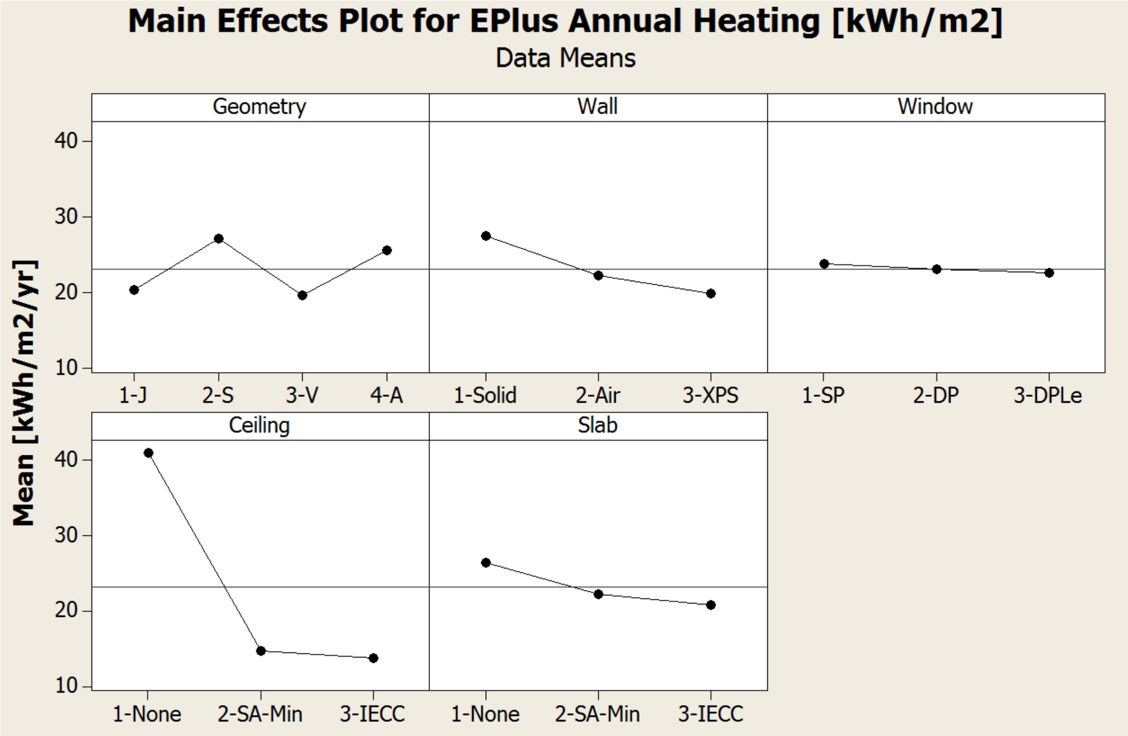


Figure 4.2. Main effects visualization of the results from the EnergyPlus simulations.

Main effects – wall insulation in EnergyPlus. The effect of increased wall insulation, in this case between the two layers of solid brick, is a steady decrease in heating energy usage. For the second level of wall insulation, an air gap is used. The properties of the air gap incorporated mean that the gap is wide enough for some convective flow, which increases the conductivity value of the layer of air; however, the overall effect is still an increase in insulation as well as a thermal break between the two layers of brick. The mean value of heating energy reduces from 27kWh/m^2 to 22 kWh/m^2 when adding the air gap, equating to an average reduction of 19%. Given that this energy efficiency measure adds no cost to the building, it is a viable measure to include in the model. Table 4.1 shows the relative reductions in energy use per house modeled in EnergyPlus. The variations are due to geometric differences in the houses considering relative wall areas to other envelope components. House 1-J has a more wall area as a percentage of total envelope area than House 4-A, which explains why more savings are possible in House 1-J. The characteristics of House 1-J are the most similar to the RDP house size and shape.

Table 4.1. *Mean wall insulation effects per house in EnergyPlus*

Percentage Reductions in Energy Use	**1-J**	**2-S**	**3-V**	**4-A**
Wall Level 2 - Wall w/ Air Gap	24%	19%	22%	13%
Wall Level 3 - Wall w/EPS	34%	27%	30%	18%

Stepping up from the air gap insulation to the layer of polystyrene insulation brings additional energy savings. The mean energy usage is reduced by 27% averaged across all models, down to 20 kWh/m^2. This shows that the walls can benefit from an increase in insulation at either level. In fact, the relatively linear reduction in energy usage across the three levels means that there are likely further savings that can be accomplished with additional insulation. The energy savings curve has not yet approached the asymptote of the curve.

Main effects – roof insulation in EnergyPlus. For all houses in the EnergyPlus simulations, the effect of adding roof insulation is a drastic reduction in heating energy usage over the year. The current RDP construction technique uses a single layer of corrugated metal sheet for the roof, with no ceiling or insulation underneath it. As a result, the conductivity value of the roof component is very high. The largest insulator of the roof system is the inside surface air film. The inside surface convective heat transfer coefficient is the main contributor to overall insulation since the air inside the house is not mechanically circulated during these simulations, reducing the free convection component and eliminating the forced convection component. Using the South Africa code minimum roof system results in a 63% average reduction in heating energy usage. The IECC2012 representative roof system results in a 66% average reduction in heating energy usage.

Table 4.2. *Mean roof insulation effect per house in EnergyPlus*

Percentage Reductions in Energy Use	**1-J**	**2-S**	**3-V**	**4-A**
Ceiling Level 2	65%	67%	54%	67%
Ceiling Level 3	67%	69%	58%	69%

When looking at the main effects plot for roof insulation in Figure 4.2, as well as the tabulated data in Table 4.2, the incremental reduction in energy usage from level two to level three is small. Figure 4.2 shows that the reduction in energy usage is likely near an asymptote, meaning that the majority of the energy savings achieved at level two could be accomplished with even less insulation. It also means that the amount of insulation used in level three is not worth the added material expense, since the Level 3 insulation has almost twice the amount of added material and insulation value as Level 2.

Main effects – window types in EnergyPlus. The results show that there is not a large reduction in energy usage when varying window type. The first level window represents a steel framed single-pane window, with the second and third levels being increasingly better-insulated double-pane windows. This is likely because of the relatively small window areas and the low insulation values of the other components.

Table 4.3. *Mean window insulation effects per house in EnergyPlus*

Percentage Reductions in Energy Use	**1-J**	**2-S**	**3-V**	**4-A**
Window Level 2	2.1%	1.9%	4.2%	2.7%
Window Level 3	3.8%	3.6%	7.7%	5.0%

Table 4.3 shows the small reduction in energy usage of when the Level 2 and Level 3 windows are used. The heat retention from the increase in thermal resistance of the heavier windows is likely cancelled out by the lower solar heat gain coefficient, meaning less solar gain during the day, which helps offset heating demand.

Main effects – slab insulation in EnergyPlus. The slab insulation layer represents both perimeter insulation and under-slab insulation in one layer. This is achieved by including a layer of soil in the slab layer and assuming that the surface contacts only the ground and not the ambient air directly. Because the RDP house has brick walls, the difference in conductivity between the wall and the slab is relatively small, so the thermal bridging from the slab contacting the air is represented by the base of the wall contacting the air.

Table 4.4. *Mean slab insulation effects per house in EnergyPlus*

Percentage Reductions in Energy Use	**1-J**	**2-S**	**3-V**	**4-A**
Slab Insulation Level 2	15%	15%	17%	16%
Slab Insulation Level 3	20%	20%	23%	22%

The results from the EnergyPlus simulation show a moderate decrease in energy usage when adding an insulating layer to the slab. The cold winter ground temperature is isolated from the house with increases in insulation, and the energy savings reflect that there is value to the additional insulation. The linear relationship shown in Figure 4.2, as well as the tabulated data shown in Table 4.4, indicates that there is additional savings available even at the IECC2012 level of insulation over the SANS level.

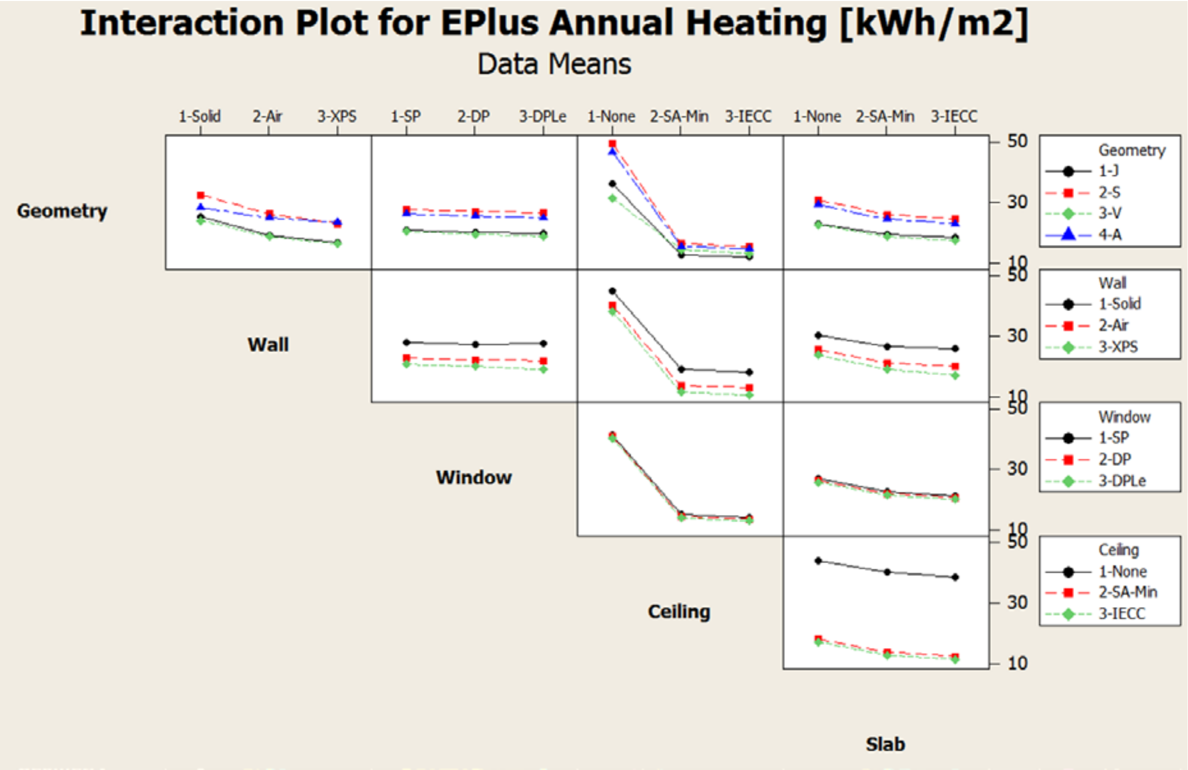


*Figure 4.3***.** Interaction effects visualization for the EnergyPlus simulations.

Interaction effects in EnergyPlus. The interaction between parameters is shown visually in Figure 4.3. If two parameters create an effect which neither would create individually, it can be seen on the plots as deviations between the sequences of lines. For example, in the Geometry-Wall plot at the upper-left corner of Figure 4.3, the combination of geometric layout and wall insulation level create visible differences in energy usage reductions of the different house models. Because all of this data is normalized for floor area, it is only the relative areas of envelope surface components which are included in the

“Geometry” parameter. Those different geometries, when combined with changing wall insulation levels that change heat gains and losses through just one envelope component, create differing trends in energy usage. The outlier of the group, it seems, is House 4-A. This house has the largest floor area and a very flat roof. This house geometry has a lower percentage of wall area to overall envelope area, explaining why the reductions in energy usage are not as large. There is another example of geometry and ceiling/roof insulation when looking at the slope of energy usage reduction in the appropriate plot (third from left, top row). The different values of insulation under the roof affect the energy usage of each house differently based on the geometry. House 3-V has a large roof area, but it is much more steeply pitched than all other houses. Houses 2-S and 4-A have low and flat roofs and are more affected by the changing insulation values. These differing geometries result in House 3-V having more interior volume per square meter of floor area than Houses 4-A and 2-S. This may make House 3-V less sensitive to envelope changes, as the capacitance of the house is larger due to the extra mass of air. Relative to the main effects of each parameter variation, all interaction effects are minor, and due more to geometric differences in the models than to the actual parameters being analyzed. This study is focused more on the envelope components than on house design, so these interactions are not considered significant.

TRNSYS Simulation Results and Comparison to EnergyPlus Results

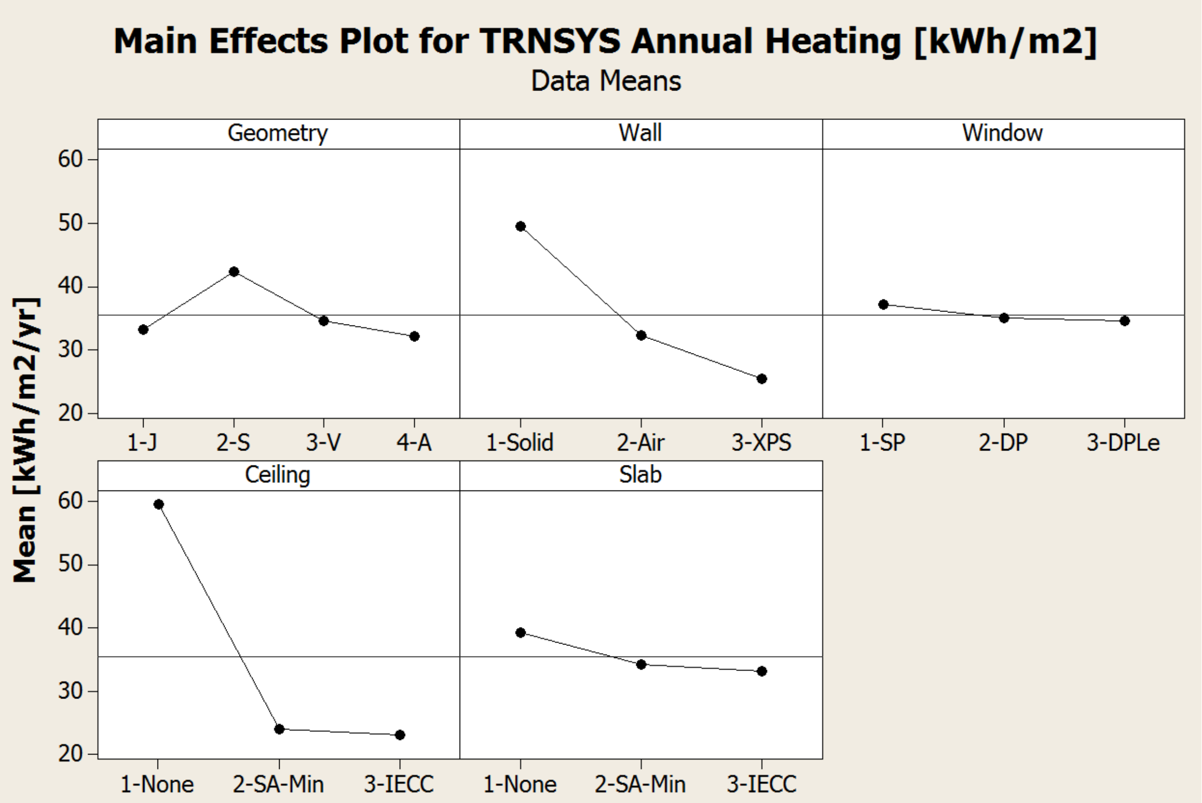


Figure 4.2. Main effects visualization of the results from the TRNSYS simulations.

Main effects – wall insulation in TRNSYS. Using TRNSYS, the trend in energy usage reduction by adding wall insulation is similar to the EnergyPlus results in that there is a significant reduction in energy usage. The results are summarized as average reductions from the current construction case in Table 4.5.

Table 4.5. *Mean wall insulation effects per house in TRNSYS*

Percentage Reductions in Energy Use	**1-J**	**2-S**	**3-V**	**4-A**
Wall Level 2 - Wall w/ Air Gap	42%	36%	33%	36%
Wall Level 3 - Wall w/EPS	55%	49%	46%	48%

The reduction in heating energy requirements is larger in the TRNSYS simulation than in the EnergyPlus simulation. With the same mass and material properties used, the effect of adding an air gap between the layers of brick is much larger, on the order of 1.5 times the reduction in EnergyPlus. This is likely due to the differences in the time scale and calculation method of TRSNSYS versus EnergyPlus. Both programs use an algorithm that uses the material properties of the wall assembly to create a heat conduction transfer function. The coefficients of the transfer function are subject to an iterative process of calculations until the convergence limits are satisfied. TRNSYS limits the algorithm to twenty consecutive iterations to converge on a solution, with each iteration taking one time step. For this simulation, the high mass of the brick layers and the low mass of the air gap layer caused the algorithm to fail in finding a solution under the default settings of one time step per algorithm iteration. The program documentation suggests extending the time step, or "time base," to allow for the thermal capacitance values present in the high mass walls used in this study. The shortest time base in which convergence could be attained for the wall system was three hours. This time base was used for all scenarios and parameter evaluations. In contrast to this, the time step used in EnergyPlus was kept at the default of six time steps per hour, and no convergence issues arose using these settings. While this may contribute somewhat to the differences between the results, in the scenarios where convergence could be attained in TRNSYS with the default time base of one hour, the results did not differ by more than 5% from the simulations using a time base of three hours.

Another likely cause of the difference between the simulation results is due to the calculation of convective heat transfer coefficients. TRNSYS has the capability within the

Type 56 model to perform simplified convective heat transfer coefficients on inside faces, and only constant values can be used for outside faces. EnergyPlus has several methods for calculating the convective heat transfer coefficients. The Thermal Analysis Research Program (TARP) used in EnergyPlus uses air and surface properties at each time step to calculate convection coefficients. As stated on page 19, the calculated values for TRNSYS and EnergyPlus differ significantly from one another. Due to the more detailed calculations used in EnergyPlus (see Figure 2.1 on page 21), the resulting convective heat transfer coefficients may be more representative of the actual conditions. The coefficients from the EnergyPlus simulations were input into TRNSYS for both inside and outside faces; however, since the inputs to TRNSYS can only be constant values in the Type 56 model, the annual average was used for the inside and outside coefficients separated into wall, roof, and floor components. As discussed in Chapter Two, the average values calculated in EnergyPlus are lower than the TRNSYS coefficients for the inside faces. For the outside faces, which are exposed to the wind, the coefficients calculated in EnergyPlus average 35W/m^2, or two times larger than those in TRNSYS, which defaults to 17W/m^2. By using the EnergyPlus values for outside convection heat transfer coefficients, the conductivity of the wall and roof components is increased throughout the year. The key difference is that while the annual averages are the same, EnergyPlus has the coefficients varying at each time step, and TRNSYS uses the same value throughout the simulation. The wind speed and temperature delta between the ambient air and the surface means that, at some points in the simulation, EnergyPlus will have lower or higher heat transfer rates through the building envelope than TRNSYS. An analysis of the overall effect of this difference was not conducted.

Main effects – roof insulation in TRNSYS. As with the EnergyPlus simulations, the house models are very sensitive to the roof component insulation level in TRNSYS. From the base model roof with no insulation to the second insulation level, the percentage reduction in energy usage, averaged over all parameter variations, is shown in Table 4.6.

Table 4.6. *Mean roof insulation effect per house in TRNSYS*

Percentage Reductions in Energy Use	**1-J**	**2-S**	**3-V**	**4-A**
Ceiling Level 2	65%	57%	56%	60%
Ceiling Level 3	66%	58%	58%	61%

As with the EnergyPlus simulation, the energy reduction when adding insulation to the bare metal roof is very large. This, again, is due to the high conductivity value of the metal roof, which provides very little insulation from the exterior temperature. The heat transfer across the roof component is much higher than any other component in the model, especially considering the relatively low mass and thermal capacitance of the metal roof compared to the walls and floor.

For the simulation to reach convergence in finding the conduction heat transfer coefficients, the thin metal roof required special modeling considerations. With the high mass walls and floor compared to the low-mass metal ceiling at the RDP-equivalent first parameter level, the simulation could not reach convergence for the roof when the time base was set to three hours. Since the three-hour time base was required to reach convergence in the wall system, the roof was modeled as a massless system. Modeling the roof as a massless component means that the normal material properties of conductivity, specific heat, and density are replaced with a single thermal resistance value. This creates a much simpler model so that the algorithm will converge. The resistance values were calculated by hand based on the metal and insulation material properties. While this method does deviate from an accurate physical representation, the relatively low mass and thermal capacity of the metal roof and insulation compared to the wall and floor systems makes this a minor change in the overall behavior of the model.

The percentage energy reduction when adding more insulation to reach the IECC2012 requirements is minimal, indicating again in this model that the majority of the savings are in the initial step from no insulation to moderate insulation. In TRNSYS, the overall reduction from the second to the third level, which represents adding approximately four more inches of fiberglass insulation, is a difference in energy usage of just one percent, meaning that the heat transfer through the roof has already been diminished by the second level scenario to the point where adding more insulation is not necessary and would not be a cost effective investment.

Main effects – window types in TRNSYS. The effects of adding higher quality double-pane windows to the TRNSYS-simulated houses are small relative to the other component variations; however, the results show a larger reduction in energy usage compared to the EnergyPlus simulation. To add a low-quality double-pane window shown as Window Level 2 in Table 4.7 results in a 4% to 8% reduction, while the higher quality double-pane window represented as Window Level 3 creates a 6% to 10% reduction and a 1% to 2% incremental reduction over Window Level 2. This could be due to the more complex window model used in TRNSYS, which calculates heat transfer based not only on a single conductivity value and solar heat gain coefficient, but also uses the assembly material properties such as reflectivity and transmittance to calculate varying heat gains and losses based on solar incidence angles. In EnergyPlus, the actual parameter that varied was the conductivity of the window, whereas in TRNSYS, the entire window model changed, incorporating all the different properties of the glass and air layers.

Table 4.7. *Mean window insulation effect per house in TRNSYS*

Percentage Reductions in Energy Use	**1-J**	**2-S**	**3-V**	**4-A**
Window Level 2	4%	5%	8%	6%
Window Level 3	6%	6%	10%	7%

Main effects – slab insulation in TRNSYS. The slab model in TRNSYS was built identically to the model in EnergyPlus, and the results were similar. The average reduction per house is shown in Table 4.8, with the overall trend visualized in Figure 4.2 on page 66. The results indicate that increased energy savings can be had from the second level and third level insulation values. These results are slightly lower than the EnergyPlus results, and this may be partially due to the different methods of ground temperature input between the two programs. With EnergyPlus, there are two approaches to ground temperature input. The first uses a pre-processing program to conduct a finite element analysis on the ground beneath the model. By using preliminary data on the model interior temperatures and known deep ground temperatures in the region, the temperature at the bottom surface of the floor system is calculated on a grid across the floor. While this can be a physically accurate method of calculating the ground temperatures, it was not feasible to pre-process each scenario before commencing each parametric run. It would also have required a further analysis on soil properties and training on the pre-processing program. Instead, an approximation was used, which took the ambient temperature and used a cosine wave variation to simulate the varying ground temperature throughout the year. To include some soil variation, a layer of soil material was included in the floor assembly for all scenarios. The same cosine wave was used for both programs; however, EnergyPlus only accepts monthly ground temperatures if this approach is used, so each month of the year has a constant ground temperature. TRNSYS, on the other hand, has an input for ground temperature at each time step, so every hour the cosine wave is input to the building model. This difference may explain the difference in heat flux through the slab during times of heating in the winter.

Table 4.8. *Mean slab insulation effect per house in TRNSYS*

Percentage Reductions in Energy Use	**1-J**	**2-S**	**3-V**	**4-A**
Slab Insulation Level 2	14%	13%	8%	13%
Slab Insulation Level 3	17%	16%	10%	16%

Interaction effects in TRNSYS. The effect of interactions between parameters from the TRNSYS simulations is shown in Figure 4.4. As in the EnergyPlus results displayed in Figure 4.2, the geometry of the building is also shown as the fifth parameter for comparison. There is some interaction between the geometry type and the energy usage of different levels of wall and roof insulation, but there is little interaction between the four insulation parameters of wall, window, ceiling, and slab. The results from both EnergyPlus and TRNSYS show small interaction effects of the four parameters.

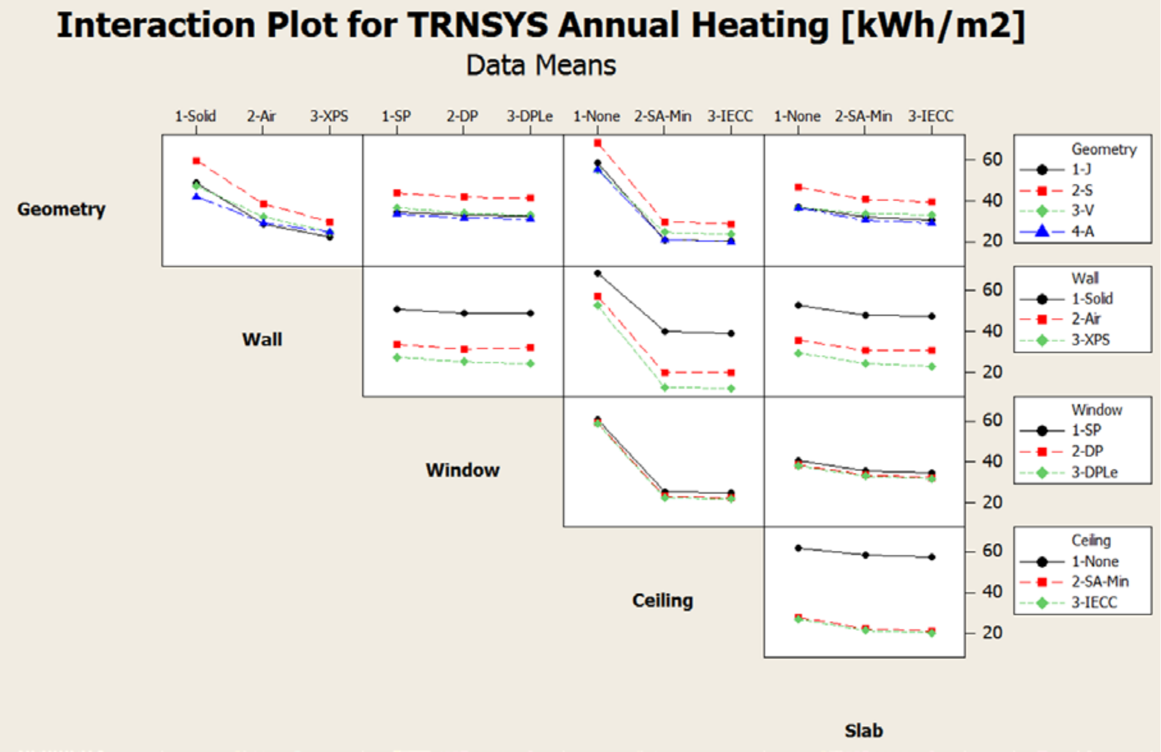


Figure 4.4. Interaction effects visualization of the TRNSYS simulation.

One area where there may be interaction effects is between the window type and slab insulation. Theoretically, the solar gain through the window can be absorbed by the concrete slab, which is bare as the finished surface in all models. With more insulation under the slab and a higher solar heat gain coefficient in the windows, the passive solar gains of the house should be higher than if the slab were less insulated and if the windows had a lower solar heat gain coefficient, as in the second and third level window types; however, this does not seem to be present from the simulation results. This is because there is no ray tracing beyond the zone envelope for either EnergyPlus or TRNSYS. When irradiance is calculated to strike the window, a certain amount of heat enters the zone based on solar heat gain coefficient and conductivity of the window assembly, but the radiation stops at the outer layer. This means that the concrete slab floor never receives the solar gain directly. Instead, the slab gains heat from the zone air and internal radiation sources such as the space heaters. A confirmation of this behavior can be seen in the Geometry-Slab interaction plot. House 3-V has much more north-facing glazing than the other houses. Following passive solar design principles, this should lead to more thermal heat storage to the slab, and the better insulation under the slab should enable more heating energy reduction. When comparing House 3-V to the rest of the houses in the Geometry-Slab plot, the trend of energy usage reduction with increasing slab insulation shows a lesser heating reduction than the other houses. House 1-J has no north-facing glass, and very little to the east or west, and yet shows more energy saving than House 3-V.

Comparison of Heating Energy Usage between EnergyPlus and TRNSYS

Despite the common components between the two energy models, EnergyPlus and TRNSYS calculated noticeably different energy usage amounts for each scenario. EnergyPlus consistently calculated energy usage at 30-40% less than TRNSYS given the same input parameters. The results from the base model with RDP-representative construction are shown alongside each parameter’s highest insulation value in Figure 4.5. The dotted lines indicate the TRNSYS results, while the solid lines indicate the EnergyPlus results. The difference between the results of the two programs is quite clear. The root of the difference may be from the differing methods of calculating convection coefficients, as discussed above. It may also be from the different ways that the two programs account for thermal mass storage in envelope components such as the massive walls.

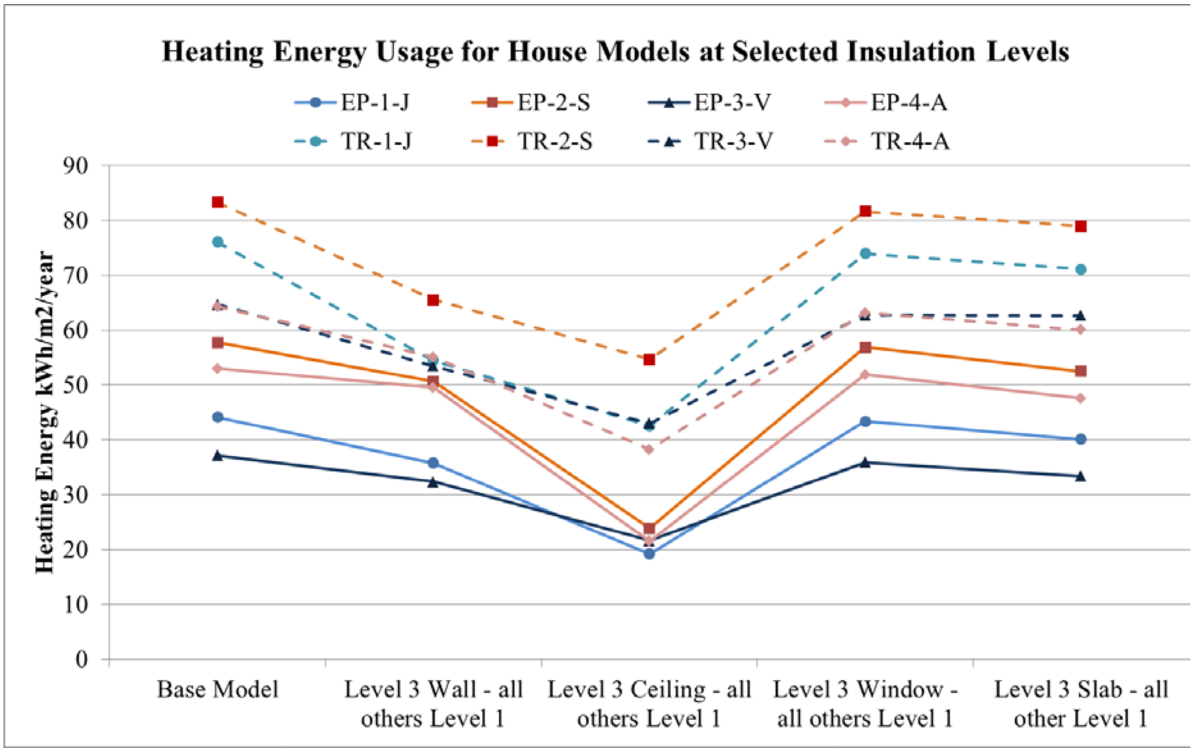


Figure 4.5. Total calculated heating energy usage comparison between EnergyPlus and TRNSYS.

While the absolute numbers are different between the two software programs, the trends in reduction are largely the same. With the exception of the additional wall insulation being more effective in the TRSNYS simulation, the sensitivity of both models to the changing parameters is very similar. To show the energy reduction if each component was added individually to the base model, the results for each of the four parameters in both simulation programs are shown in Figure 4.6. Each data point represents a single simulation where the labeled component was set to the Level 3 properties while all other components are kept at the baseline.

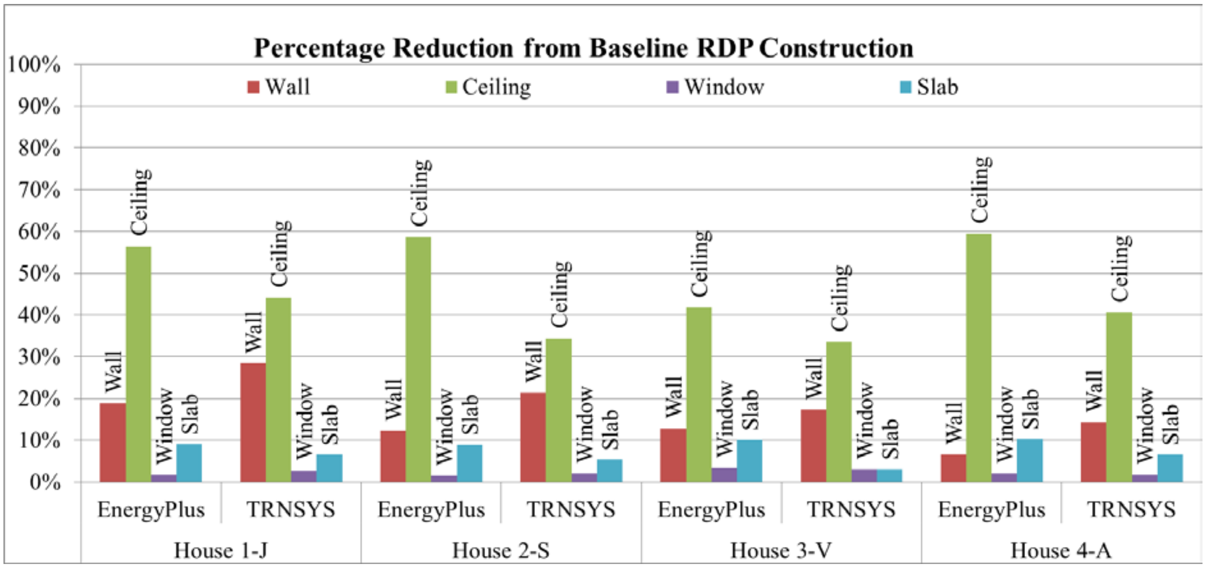


Figure 4.6. Energy reduction magnitude for each parameter varied individually.

In both simulations, it is clear that the effect of adding insulation under the roof is the most significant. To investigate this effect further, the temperatures inside the baseline RDP construction house, House 1-J, can be viewed over the course of the year. The temperatures can be compared to the same house with insulation added under the roof. Figures 4.7 and 4.8 show the two temperature distributions. The data points for the "recorded" lines are from temperature measurements taken on actual RDP houses. In table 4.7, the three lines for each data set represent the mean +/- one standard deviation of the data at each exterior temperature reading. The recorded data for Figure 4.7 is for the physical counterpart to House 1-J. The overlap between the two sets of data, simulated and recorded, shows that the EnergyPlus model is accurate in representing the balance between internal loads and solar gains and the envelope components, because the simulated data shows a very close temperature delta to the actual data across much of the temperature range. By contrast, the TRNSYS simulation resulted in a lower difference in interior and exterior temperatures and simulated a higher heating energy usage throughout the year. Because of this, the EnergyPlus results are believed to be more accurate for these simulations.

The recorded data for Figure 4.8 is for the physical counterpart to House 2-S, which is located across the street from House 1-J. The houses are nearly identical except that House 2-S has a ceiling with some insulation retrofitted to it. By changing only the insulation levels under the roof, the behavior of the house interior temperatures changes dramatically. With lower exterior temperatures, a larger interior temperature differential is maintained, meaning that the interior of the house is kept closer to the comfort zone. When the exterior temperatures become warmer, the temperature differential drops. Eventually, it is cooler inside at exterior temperatures above 25°C. This data also shows that adding insulation under the roof, as was done in the simulations, has the same effect as adding a ceiling with insulation above it. It is unknown how much insulation is present in the actual House 2-S, but the effect is clear: adding either an insulated ceiling or insulation under the roof will shift the interior temperatures such that it will be warmer in the winter and cooler in the summer.

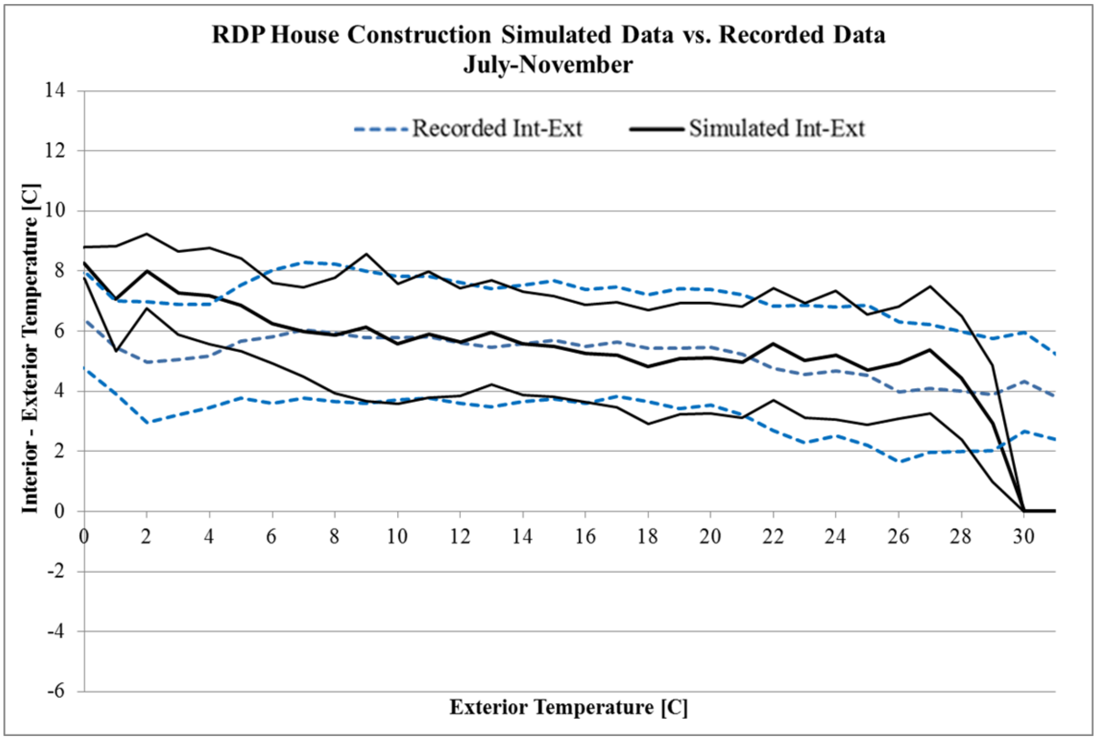


*Figure 4.7***.** Interior versus exterior temperatures for the RDP house.

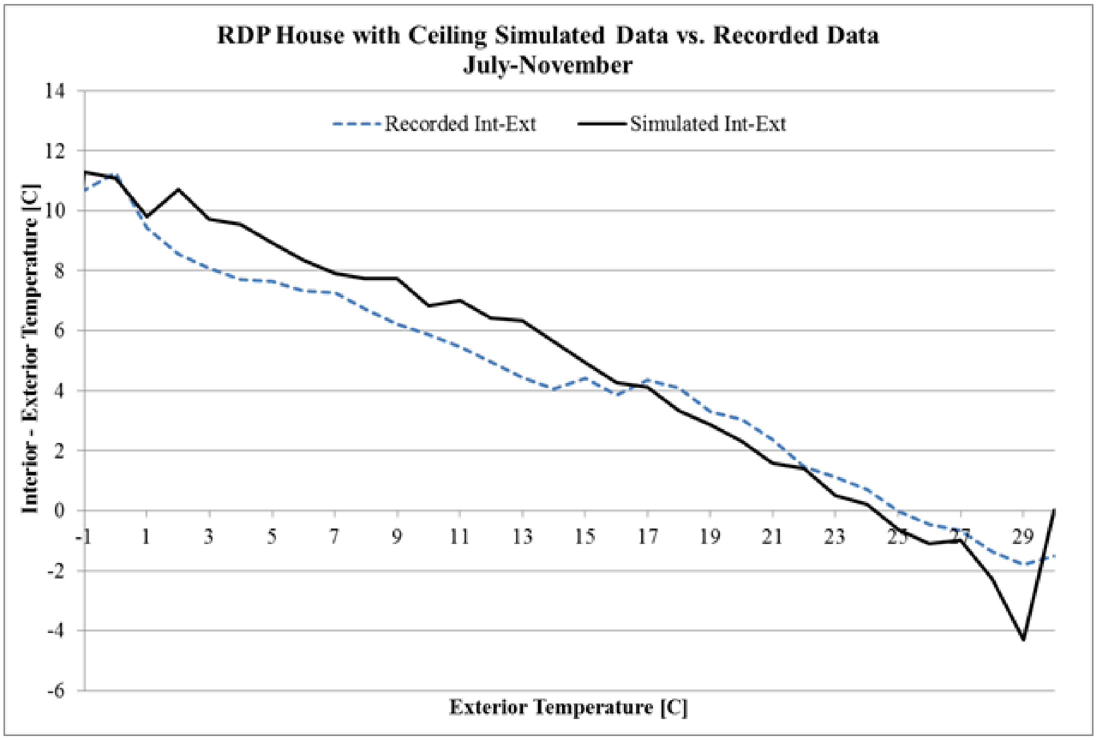


*Figure 4.8***.** Interior versus exterior temperatures for the RDP house with ceiling insulation.

Life Cycle Cost Analysis for Selected Scenarios

Using data from the life cycle cost analysis developed by Ramsdell et al. (2012), a thirty year cash flow model was developed for House 1-J, which is most representative of the typical RDP construction. The simulation data from EnergyPlus was used, because it represented the actual house behavior more closely than TRNSYS in this case. The material costs were estimated using 2012 market pricing, as well as mortgage interest rates of 8.75% for twenty years and annual electricity rates from a local utility (Eskom) that uses a tiered pricing system averaging ZAR1.07/kWh ($0.152/kWh). The mortgage lending rate reflects typical lending rates from South African banks in 2012. Electricity rates inflate at the 20-year average rate of 8.35%. The results of the cash flow analysis are shown in Table 4.8. The results from the previous life cycle analysis by Ramsdell et al. (2012) are shown for comparison in Table 4.9. The previous study was performed using Autodesk® Ecotect®. The geometry for the house is unchanged, as are material types and insulation improvements. The major difference is that in Ecotect the heating system was set up as an unlimited capacity heating system which kept the interior temperatures at 18°C at all times, while in EnergyPlus and TRNSYS the heating system had a defined maximum capacity. Because of this, the heating energy usage was much higher in that study. Annual heating energy usage for House 1-J with current construction materials in Ecotect was simulated as 3632kWh, while the EnergyPlus simulation resulted in a heating energy usage of 1854kWh per year. The large difference in energy usage decreases the absolute energy savings by adding insulation materials in EnergyPlus, as the energy usage for the base model was much lower already.

The EnergyPlus model has a more representative heating system because an electric space heater does not have unlimited capacity to keep the interior temperatures at a set point, as shown in the correlation of simulated versus actual temperatures in Figure 4.7 on page 78. For this reason, the EnergyPlus simulation results and the results from the life cycle cost analysis using those results is a more representative model of the savings that can be expected by implementing energy efficiency measures to the RDP houses.

Table 4.8. *Life Cycle Cost Analysis of House 1-J with EnergyPlus Results*

House 1-J EnergyPlus	Added Cost (~7ZAR= $1)	30-yr Cost	30-yr Savings [kWh]	30-yr Cumulative Savings	Monthly Mortgage Addition	Break Even Year
Base Model	ZAR116,590	ZAR460,415	0	ZAR -	ZAR -	1
Cavity Wall	ZAR -	ZAR428,392	7440	ZAR 32,023	ZAR -	1
EPS Wall	ZAR 6,865	ZAR428,115	10530	ZAR 32,299	ZAR 49	21
Code Ceiling	ZAR 7,752	ZAR344,767	30300	ZAR 115,647	ZAR 55	4
DP Window	ZAR 9,616	ZAR474,802	900	ZAR (14,387)	ZAR 68	30+ yrs
EPS Wall + Ceiling	ZAR14,617	ZAR317,283	39720	ZAR 143,131	ZAR103	8

Table 4.9. *Life Cycle Cost Analysis Performed in 2012 Using Ecotect® Simulation software*

House 1-J - Previous Study	Initial Cost (~7 ZAR= $1)	30-yr Cost	30-yr Savings [kWh]	30-yr Cumulative Savings	Monthly Mortgage Addition	Break Even Year
Base Model	ZAR 116,590	ZAR689,880	0	ZAR -	ZAR -	1
Cavity Wall	ZAR -	ZAR643,155	10854	ZAR 46,725	ZAR -	1
EPS Wall	ZAR 6,865	ZAR618,570	19594	ZAR 71,310	ZAR 49	7
Code Ceiling	ZAR 7,752	ZAR672,790	7389	ZAR 17,090	ZAR 55	24
DP Window	ZAR 9,616	ZAR678,131	6979	ZAR 11,749	ZAR 68	25
EPS Wall + Ceiling	ZAR 14,617	ZAR579,666	32085	ZAR 110,214	ZAR 103	11

Table 4.8 further indicates that the addition of a ceiling with insulation under the metal roof is a financially advantageous option to save significant energy—30,300kWh per house over 30 years—and has a positive Net Present Value (NPV) after 4 years and totaling ZAR 20,152 over 30 years using an 8.75% annual discount rate. The annual internal rate of return (IRR) for the case with a South Africa code ceiling is 41.26%. For the case of adding both the ceiling and wall insulation, the IRR is 25.58%/year, and the NPV is ZAR21,966. Since the NPV is greater than the initial capital cost of the improvements (ZAR14,617), the improvements should be regarded as a sound investment when building the house. These results also mean that the NPV of the insulation under the roof, ZAR20,152, is nearly three times the cost of installing the insulation, indicating a worthwhile investment.

Chapter Five: Conclusions

This study sought to answer two questions. The first was: How effective are energy-efficient construction techniques when incorporated into the design of low-income, masonry-based, single-family South African homes to optimize life-cycle costs, considering both construction and energy costs? Second, what are the comparative results of two energy models developed to address the first question, using the energy simulation programs EnergyPlus and TRNSYS?

Life Cycle Cost Analysis Conclusions

A selection of scenarios was put through a life cycle cost analysis model, with results shown in Table 4.8 on page 80. The analysis shows that the wall and ceiling insulation improvements are worthwhile in that they save more in energy costs than the initial capital cost of adding extra material. One particular improvement worth investigating with physical experimentation is implementing an air gap between the two layers of brick in the walls. The heating energy savings can be significant, and the cost to implement the improvement requires minimal extra material. This practice is currently used in the coastal regions of South Africa where cooling is necessary, so the construction experience should be available for this type of construction.

According to these simulations, the most effective measure for reducing heating energy usage in the RDP houses is to add a ceiling or insulation under the roof. This improvement greatly reduces the required energy to keep the house at a comfortable temperature, mitigates the risk of freezing inside the house during the winter, and prevents very high temperatures during the summer. The additional cost of the insulation during construction is balanced by the energy savings within the first few years of inhabitance and saves significant energy and money for the owners of the house. The total energy demand and peak demand are lowered, meaning less strain on the electricity and fuel infrastructure in South Africa, which is an increasing problem due to higher standards of living. Improvements in the design, through the addition of energy efficiency measures such as those highlighted in this study, can save the government money in infrastructure costs and the home owner in energy costs.

By thinking of the housing situation in South Africa as an opportunity to develop a more sustainable housing environment for all citizens, real benefits can be achieved on a large scale throughout the country. The housing and energy authorities can work together to create a design for housing and communities that could turn the struggle of finding adequate housing into an opportunity for raising the standard of living further, without costing the government or the citizens more money in the long run.

A continuation of this research could be to create a sample of houses that implement the energy efficiency measures highlighted in this study and then to monitor their performance over a few seasons. By having a number of houses built with different insulation values, the true difference in energy usage and interior comfort can be analyzed more closely. The impact on the citizens, when able to compare the two houses side by side, will also be shown more definitively than from the results of this study alone. This study serves as a critical first step to convince the people of South Africa that a more energy efficient house, although the capital costs may be slightly greater, can be a less expensive and more comfortable house in the long term.

Comparison of Software Programs

The two software programs used for energy modeling, EnergyPlus and TRNSYS, were used to create representative models of the typical houses found in central South Africa. By utilizing common parameters shared between the models, and investigating calculation methods for various heat transfer principles between the models, a comparison was made between the energy calculation techniques of both EnergyPlus and TRNSYS. EnergyPlus was found to have a more detailed method of calculating certain components of the model, such as convective/radiative space heaters and convection heat transfer coefficients; even with those differences, the trends of parameter effects on energy usage are similar between the two programs. Both showed significant reductions in energy usage when adding insulation to the walls and roof. Adding insulation under the concrete slab did not have as large an effect and depended more on the geometry of the house in terms of floor area to envelope area. Improvements to the windows provided minimal energy savings for all cases, which is likely due to small window areas and the poor envelope components around the windows in these homes. The results of the EnergyPlus simulation correlated well with temperature measurements taken on actual houses, indicating an accurate and representative energy model. The small size of the houses, as well as the very different types of materials used such as brick and metal, makes for a challenging model to create; but with a thorough analysis of calculation procedures by the modeling programs, an accurate representation can be created.

The different calculation methods and procedures to implement model parameters affected the output results in different ways. For example, the convection heat transfer coefficients can be calculated in a variety of different ways in EnergyPlus, each having a particular application where it suits the environmental conditions best. By reading the Engineering Reference document and other EnergyPlus documentation, the proper method can be selected for the particular simulation. In this case, the small size of the houses modeled increased the sensitivity to choosing an accurate representation of the convection coefficients. The large surface-to-volume ratio of the models, coupled with the low insulation values for the current construction parameters, made these convection heat transfer coefficients very important in the calculation of total heat transfer through the envelope surfaces. For this reason, the difference between the two programs' methods was highlighted in the energy usage results. While it was possible to calculate the inside face convection coefficients in TRNSYS, it was not possible for the outside face, where the convection coefficient can change dramatically based on exterior temperatures and wind speed, surface temperatures affected by solar irradiance, and so on. The default value in TRNSYS for the exterior convection coefficients was much different than what EnergyPlus calculated using more input parameters with an equation that aligns well with ASHRAE data, so the value was overwritten with the EnergyPlus calculated average. The constant value is still not representative of the true convection coefficients. In a larger building, and as more insulation is added and the overall conductivity of the envelope component decreases, the convection coefficients become less critical to estimate properly, but that was not the case for the models used in this study. With an additional calculation parameter input in TRNSYS, it could be possible to develop a more realistic convection model, but that was not explored in this study, as equations would need to be developed for the variety of surface conditions—vertical, horizontal, tilted, heated, and colder than ambient—for each house individually, and they would need to be modified as the insulation levels increased throughout the study.

The benefit of TRNSYS in this study is that the model starts with little set by default, and it is up to the user to input the parameters as they become pertinent. This generally makes for an easier model to create and debug. Especially in the case of a simple model such as those used in this study, the input file is much more manageable because the parameters are created and adjusted to the proper levels. The OpenStudio plugin, by contrast, starts by creating many default items including construction, HVAC systems, internal loads, and schedules. The model is immediately very complex. This is perfectly acceptable for a model which can be completely created in the OpenStudio application, because the graphical user interface hides much of the complexity from the user and provides an easy modeling interface to work with. The difficulty in OpenStudio arises when there is a component which cannot be created in OpenStudio. There is no way to add it without exporting the data file and working from then on with the EnergyPlus file alone. In this study, the item that was not available was the convective space heater that was necessary to properly represent the small houses' heating system. Once the OpenStudio application is exited, the complexity it creates must be dealt with in text format. At this point, the file must be significantly cleaned up (the models for this study decreased in size by 75% to their final state from the OpenStudio-exported file) before the file becomes as easy to handle as the TRNSYS input file. This may not be the case in the future, as the OpenStudio application is still in the early stages of development and will likely incorporate more features and components which are available in EnergyPlus. To create a simple model from scratch, it is still easier to go through the TRNSYS procedure.

Although the programs have different approaches to modeling a building in some aspects, both are very capable of creating representative models of a very wide variety of building structures. For the structural types modeled in this study, and with the training in the two different software programs, EnergyPlus simulations more accurately represented the actual houses. Further education and study of the software programs can go a long way towards eliminating the gaps between the programs. In the end, the modeling software that can create the most representative model is the one that the modeler has a better grasp of, which involves knowing what assumptions are made and what assumptions can be made.

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Vita

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