DATA-DRIVEN CONSTRUCTION AND OPERATING COST DECISION SUPPORT THROUGH TECHNO-ECONOMIC ANALYSIS: RESIDENTIAL CASE STUDY

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ABSTRACT: *Construction and operating costs of residential buildings are important. Because, it can help designers, builders, owners, and renters make informed decisions about where and what to buy or rent. One of the most significant operating costs of residences is energy cost. More specifically, heating, ventilation, and air conditioning account for as much as 35% of the overall energy consumption of buildings in the world. Thus, the problem that this research paper addresses is the decision trade-off of construction costs vs. operating costs. Therefore, this paper aims to perform a techno-economic analysis of exterior residential wall-type alternatives in a warm-humid climate. The research followed a quantitative methodology using a virtual case study with multi-objective analysis. The results of this study show the significant importance of the building's infiltration on the operational savings and the return on investment (ROI) of the different types of exterior residential walls. and emphasizes the importance of a holistic approach to energy conservation regulations. The novelty of this study is the emphasis on the importance of infiltration in pre-construction decision-making. The broader impact of this result is that the International Energy Conservation Code (IECC) and similar standards could be revised to reduce energy consumption and reduce greenhouse gas emissions produced during energy generation.*

KEYWORDS: *Residential, Building Performance, Construction Cost Estimating, Insulation, Infiltration, Return on Investment, Decision Support.*

1. INTRODUCTION/OVERVIEW

Buildings are a major consumer of energy, accounting for approximately 40% of all energy demands for many countries (Farhanieh & Sattari, 2006; Ogulata et al., 2002; Vine & Kazakevicius, 1999). Likewise in the U.S., the building sector accounts for about 40% of all primary energy use, and 76% of electricity use, and is responsible for the significant associated greenhouse gas (GHG) emissions. The major areas of energy consumption in buildings are heating, ventilation, and air conditioning (HVAC) which account for approximately 35% of total building energy. (Department of Energy, 2015)

Various elements affect the energy consumption of buildings. The most important element is the thermal envelope which includes all building components separating conditioned spaces from unconditioned spaces or outside ambient conditions and through which heat is transferred (IECC, 2015). The thermal envelope assembly can have a positive or a detrimental impact on the overall building performance and therefore on the HVAC energy consumption. Although the insulative properties of exterior walls and windows are commonly regulated, with a minimum R-value or maximum U-value, other parameters are not normally considered. A higher insulative value of a wall is not always advantageous, and can also increase the heating or cooling loads, in some cases, despite complying with the legislative requirements for each location (D'Agostino et al., 2019). Another significant parameter that could hurt the performance of buildings is infiltration. Infiltration is airflow into and out of buildings through unintentional leakage in the thermal envelope due to pressure differences induced by wind, indoor-outdoor temperature differences, and the operation of ventilation and other building systems (Persily et al., 2019.). Air infiltration has a significant influence on the energy performance of buildings and can result in excessive energy demand to maintain adequate indoor comfort levels (Ji et al., 2017; Persily et al., 2019.).

The problem that this research paper addresses is the effect that different exterior wall assemblies can have on the operating cost of a building accounting for both the insulative properties and the infiltration level of the building. Furthermore, this study also addresses the initial construction costs to provide insight into the economic viability of these construction updates. The effect of the exterior wall assembly on the building's energy use is a complex issue that depends on many parameters including climate, building use, building design, and materiality (Kaynakli, 2012). Improving the thermal performance of the building envelope can remarkably enhance the whole building's energy efficiency (Abanda & Byers, 2016; Huang et al., 2020). There are various ways of improving the building envelope. As previously mentioned, thermal insulation is one of the most valuable tools in achieving energy conservation in buildings (Ghrab-Morcos, 2005; Kaynakli, 2012; Wang et al., 2007). Furthermore, air infiltration

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improvements can potentially lead to HVAC energy savings on the order of 26% (Tian et al., 2019). The objective of this paper is a techno-economic analysis of an exterior residential wall in a warm-humid climate. The analysis focuses on the effects of the insulative properties of the exterior wall (R-value) and the infiltration rate on the HVAC energy consumption. Furthermore, this study includes a cost estimation analysis for the initial construction costs associated with these assemblies, to quantify the economic feasibility of these proposed construction updates.

2. METHODOLOGY

2.1 Overview of the methodology used

A quantitative research methodology was used in this project using a virtual case study. The virtual case study consisted of a residential building with different wall types and infiltration levels. Each of the wall systems was modeled and the construction cost as well as the energy consumption/operating were determined. This was achieved in three stages: 1- Data Collection, 2- Energy Performance Modeling, and 3- Results Analysis as shown in Figure 1.

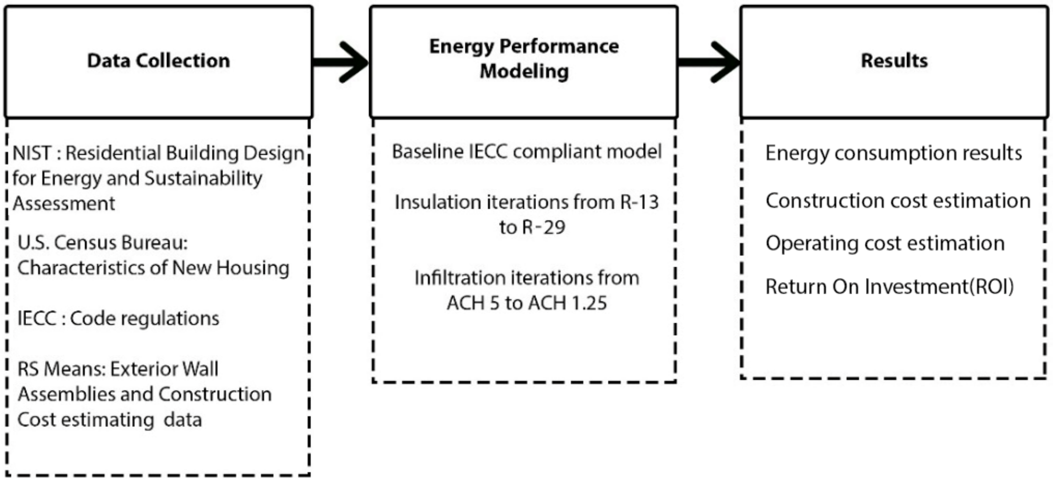

Figure 1: Methodology Diagram

2.2 Data collection process

The data collection was done from multiple sources to design and model the residential building that accurately represented the energy consumption standard and building code in the case study area.

NIST: The general building characteristics were based on the "Prototype Residential Building Design for Energy and Sustainability Assessment" which was published by the National Institute of Standards and Technology (NIST) (Kneifel, 2012).

U.S. Census Bureau: The exterior wall framing type appropriate for this study was selected based on the U.S. Census Bureau's database on residential buildings (*U.S. Census Bureau*, n.d.). As can be seen in Figure 2, for many years wood-frame construction has been the predominant type of exterior wall framing for all residential construction in the U.S. The latest available data shows that out of the 970 thousand new single-family houses built in 2021, 875 thousand were built with a wood-frame method which translates to approximately 90%. For that reason, this study focused on wood-frame-type exterior wall assemblies. Furthermore, because of the nature of wood-frame type wall assemblies, compared to mass-wall type assemblies, this study did not include thermal inertia as a parameter of the performance analysis study.

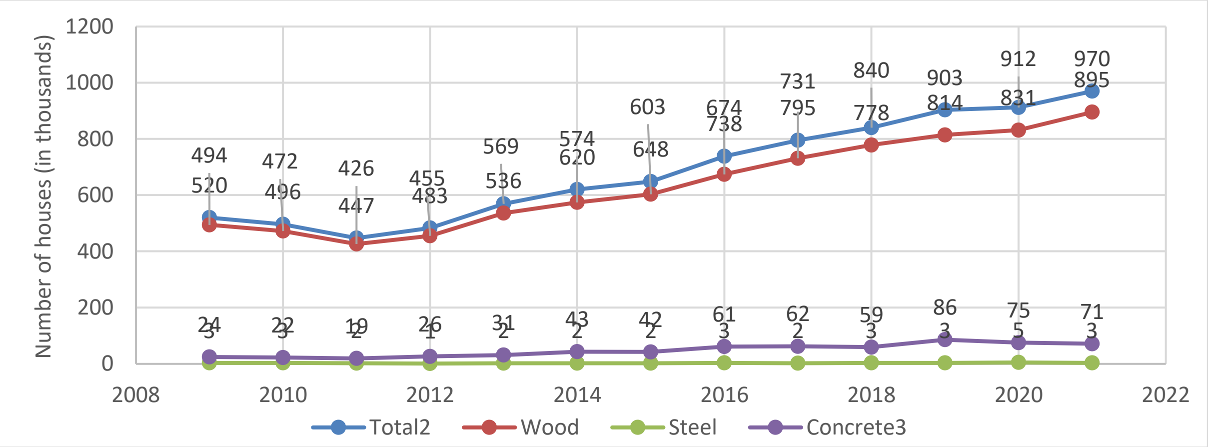

Figure 1: Type of Framing in New Single-Family Houses Completed in the U.S

IECC: The model for this case study was created to be compliant with the IECC codes for climate zone A2 which includes the Bexar County area in Texas, U.S. (See Table 1). To identify the technical characteristics (R-values, U-values) that are necessary for the building to be code-compliant, data was obtained by the International Energy Conservation Code (IECC). Because the case study of this work is placed in San Antonio, Texas, the IECC values for Zone 2 were used to determine a baseline for the energy performance modeling. Specifically, for the baseline model, an R-13 wall was implemented in the Energy+ software. Furthermore, the floor R-value was also R-13, and the ceiling was R-38. The windows used had a U-factor of 0.40 and a Solar Heat Gain Coefficient (SHGC) of 0.25.

Table 1: IECC requirements table for Texas climate zones.

	Windows			**Insulation**				**Foundation**		
	Fenestration U-Factor	Skylight U-Factor	Glazed Fenestration SHGC	Ceiling R-Value	Wood Frame Wall R-Value	Mass Wall R-Value	Floor R-Value	Basement Wall R-Value	Slab R-Value and Depth	Crawl Space Wall R-Value
Zone 4	0.32	0.55	0.4	49	20 or 13+5	8/13	19	10/13	10, 2ft	10/13
Zone 3	0.32	0.55	0.25	38	20 or 13+5	8/13	19	5/13	0	5/13
Zone 2	0.4	0.65	0.25	38	13	4/6	13	0	0	0

Regarding infiltration rates, the IECC code requires a maximum of 5 Air Changes per Hour (ACH) when tested at a pressure of 50 pascals for climate zone 2 (See Table 2). Therefore, for this study, the baseline simulations model infiltration rate was set at 5ACH.

Table 2: IECC requirements table for air leakage rates.

Air Leakage Rate	**Climate Zone**	**Test Pressure**
≤ 5 ACH	1-2	50 Pascals
≤ 3 ACH	3-8	50 Pascals

RS Means: Data on the specific characteristics of each wall assembly tested in this study and the associated costs of these assemblies were collected from the RS means publications, the industry's leading standard for construction practices, and cost estimates (John Wiley & Sons., 2012). To identify the industry standard of exterior wall assemblies, the RS means database was used. This database of standard construction practices was used to determine the wood-frame assembly design and all the construction costs associated with these wall assemblies. It can be seen in Figure 3, how the standard wood-frame exterior wall has many layers in which it can be designed and constructed. The wall variations, and their associated thermal properties, were used as simulation iterations of this study.

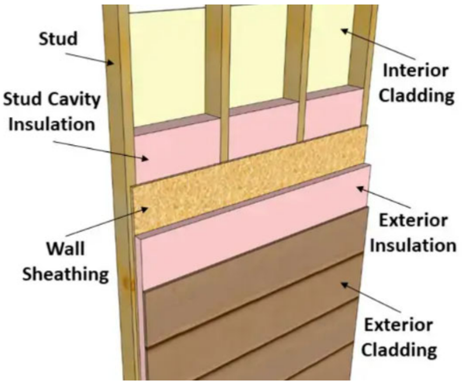

Figure 3: RS means, industry-standard exterior wood frame wall assembly (Builder's C., 2023)

2.3 Energy performance modeling

The energy performance modeling was done using the Design Builder software. Design Builder includes Energy Plus (*Energy Plus*, n.d.) which allows us to quantify the energy consumption and therefore the energy savings of the building. EnergyPlus is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), and managed by the National Renewable Energy Laboratory (NREL)

The building models were designed to be identical with the exception of the construction of their external walls' insulation (from R-13 to R29) and the infiltration level of the building (From ACH 5 to ACG 1.25). The "baseline" model was designed to be compliant with the IECC code for the climate zone of Bexar County (A2) which includes San Antonio.

In order to perform the EnergyPlus simulation analysis for this study, first a 3D model of a residential house was designed in the DesignBuilder software (Figure 4). The general building design characteristics followed the "Prototype Residential Building Design for Energy and Sustainability Assessment" which was published by the National Institute of Standards and Technology (NIST) (Kneifel, 2012). The weather data required for the EnergyPlus energy simulations were downloaded internally via the DesignBuilder software for the geographical area of San Antonio, Bexar County, Texas.

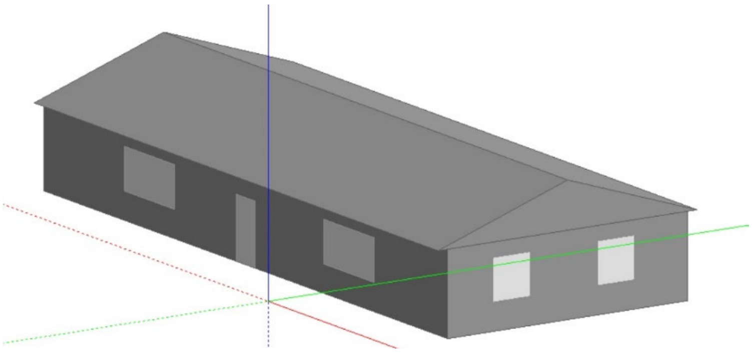

Figure 4: 3D axonometric view of wood frame building, in Design Builder software.

3. ANALYSIS AND RESULTS

3.1 Energy consumption results

Figure 5 depicts the monthly energy consumption for heating and cooling for the baseline model (IECC compliant) of the energy simulation analysis. For the summer months of June, July, and August, energy consumption for heating was minimal. This result was expected for the Warm-humid climate of this case study. Following a similar pattern, the cooling loads for the colder months (December, January, and February) were also minimal.

In the warm-humid climate of this case study, it is expected that the energy consumption for heating during the summer months of June, July, and August would be minimal. This is because warm-humid climates typically experience high temperatures and high humidity levels during the summer, reducing the need for heating. Therefore, the baseline model's energy consumption for heating during these months would be negligible.

Similarly, the cooling loads for the colder months of December, January, and February were also minimal in this case study. This can be attributed to the fact that colder months in warm-humid climates tend to have milder temperatures, reducing the need for cooling. As a result, the energy consumption for cooling in the baseline model during these months would be minimal.

These patterns of minimal energy consumption for heating in summer and cooling in winter align with the expected behavior in warm-humid climates. It indicates that the simulated baseline model's design, in terms of heating and cooling systems, is appropriately responding to climate conditions.

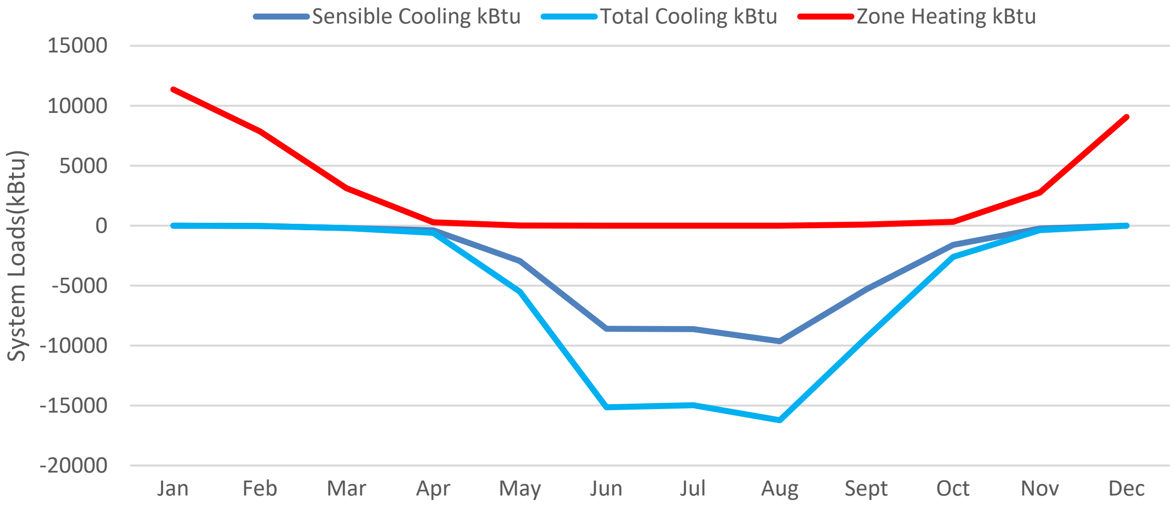

Figure 5: Monthly heating and cooling loads for the modeled house

Figure 6 showcases the effect different exterior wall iterations (R13 to R-29 and ACH 5 to 1.25) have on the cooling (shown in red) and heating (shown in green) of the house. As expected, because of the climate of this study, the cooling energy demands are overall higher than the heating energy demands, following a very similar ratio for all the wall iterations. Furthermore, Infiltration rates show a significant effect on the HVAC energy consumption compared to the Insulation levels.

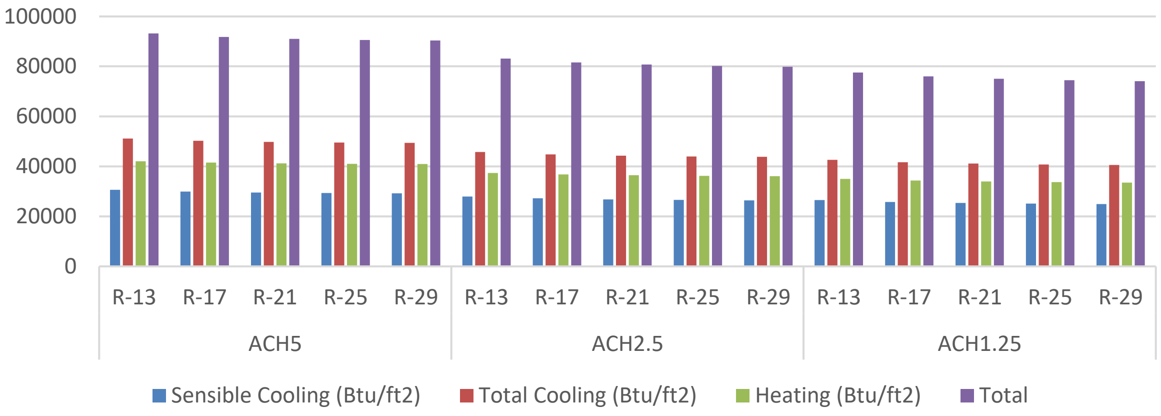

Figure 6: HVAC loads per square foot for different R-Value wall iterations

Figure 7 is a 3-dimensional graph that showcases the relationship between exterior wall R-value, building infiltration (ACH), and the overall energy consumption normalized by square foot (BTU/FT^2). As expected, a higher R-value lowers the energy consumption and a lower infiltration rate lowers the energy consumption. The colored strips of the graph represent energy consumption levels. This type of analysis allows us to easily identify and comment on the relationship between these 3 parameters, insulation, infiltration, and energy consumption. For example, the most effective level of lowering energy consumption is depicted with a light blue color at the bottom of the graph, and it represents a consumption rate of 75-77.5 kBTU/FT^2 for the building of our case study. It is apparent that a lower infiltration rate allows for this higher efficiency, even with the standard, minimum-compliant R-13 insulation. On the opposite spectrum of this graph, the inverse is also true- the building with a high, code-compliant infiltration rate is performing relatively poorly, despite the upgraded R-29 insulation. These findings quantify and validate the anecdotal rule of thumb of the residential building industry that *a good air sealing job with marginal insulation* is *far better than a good insulation job with poor air sealing.*

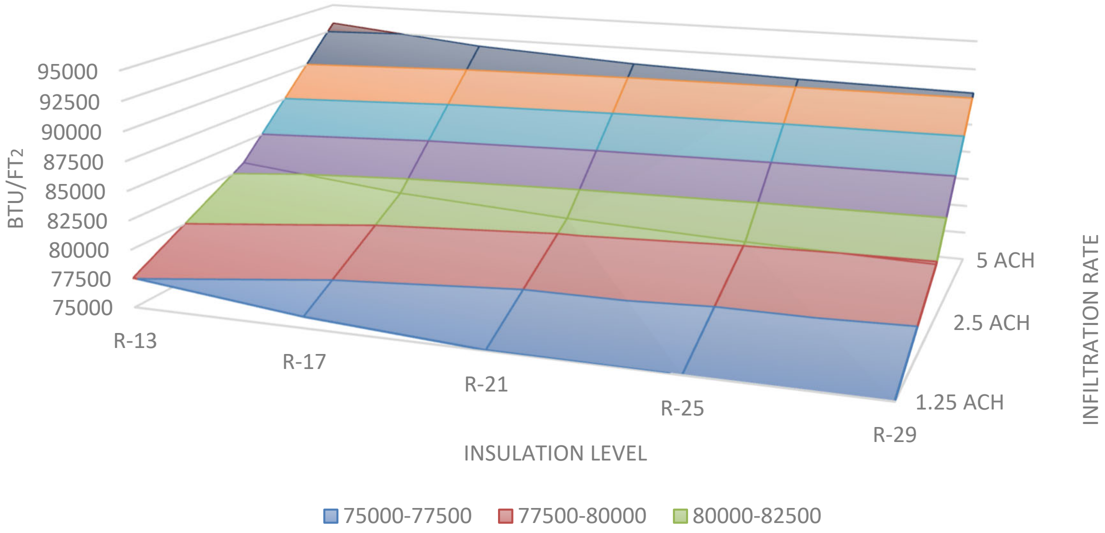

Figure 7: The effects of infiltration and insulation on energy consumption.

3.2 Cost Estimate and Return on Investment Results

The goal of this study is to provide an example of a valuable and applicable decision-making tool for many construction professionals in the pre-construction phase. Therefore, the energy consumption analysis of the previous chapter is supported by a cost analysis to evaluate the financial feasibility of these different wall assemblies. The cost analysis is presented in three parts. The first part of the cost analysis presents the cost estimating data, which includes the material and labor costs for the construction of these wall assemblies. This cost-estimating data was collected by the most recently published RS Means database(RS Means, 2023.). The second part consists in determining the operating cost analysis, where the energy consumption is converted into a monetary amount, based on the current average kWh cost of 0.14c for the area of Texas (electricityplans.com, 2023). The third and final part of the cost estimation analysis compares the initial construction costs with the operating cost savings to calculate the return on investment (ROI) and the payback period for each of these different construction updates.

3.2.1 Construction Cost Estimation

In order to properly quantify the construction cost of the different wall assemblies of this study, RS Means data was used, which includes both the material cost and the labor cost. There are a number of exterior wall construction methods that can be used to reach the R-values considered in this study. However, only the most commonly used methods of insulation practices were used for this analysis. The two most common types of insulation are Batt insulation and rigid board foam insulation. Furthermore, as mentioned before, this study focuses on the most common framing type for the U.S. market, the wood-frame wall. Therefore, the geometric limitations of the wood frame wall also affected the cost estimation analysis. Specifically, the maximum R-value that can “fit” inside a 2x4 framing wall using Batt insulation commonly found in the market is R-13 or R-15. That results in an increase of stud thickness from 2x4 to 2x6 in order to reach the values of R-25 and R-29. The cost associated with the thicker stud wall is taken into account for the cost estimate. Furthermore, a combination of Batt insulation and rigid board insulation is used to reach the specified R-values. This is a common construction practice in the industry. The last two rows of Table 3 show the total cost of insulation as well as the cost differential between the enhanced insulations (R-17 through R-29) with respect to required insulation per IECC Code (R-13).

Table 3: Cost Estimating data for exterior wall framing and insulation.

	R-13	**R-17**	**R-21**	**R-25**	**R-29**
Framing type	2X4,	2X4	2X4	2X6	2X6
Batt Insulation	3.5”, R13	3.5”, R13	3.5”, R13	6”, R21	6”, R21
Exterior Board Insulation	-	1”, R4	2”, R8	1”, R4	2”, R8
Framing type cost (L.F.)	24.5	24.5	24.5	31	31
Batt Insulation cost (S.F.)	1.24	1.24	1.24	1.48	1.48
Board Insulation Cost (S.F.)	-	1.3	1.61	1.3	1.61
Total Cost / Linear foot	34.42	44.82	47.3	53.24	55.72
Total Cost for the house (U.S. $)	**4,268.08**	**5,557.68**	**5,865.2**	**6,601.76**	**6,909.28**
Additional cost from IECC code (U.S $)	**Baseline**	**1,289.60**	**1,597.12**	**2,333.68**	**2,641.20**

In the U.S., the common construction method used to reduce air leakage is the use of sealing tape (Building Energy Codes Program, 2018). Other methods can be used to reduce air leakage, the method used in this research project was Liquid Flash which can be applied in the building envelope (i.e.: bottom and top of the walls, around windows and doors, etc.) It was assumed that to reduce the ACH from 5 to 2.5 the Liquid Flash should be applied at the bottom and top of the walls and that to reduce the ACH from 2.5 to 1.25 the Liquid Flash should also be applied to windows and doors perimeter in addition to the walls. The last row of Table 4 shows the cost differential between the enhanced leakage (ACG 2.5 & 1.25) with respect to the required air leakage requirement per IECC Code (ACH 5) in the climate zone of the study.

Table 4: Cost Estimating data for air leakage sealing

		Cost		
	Length/Perimeters	**ACH 5**	**ACH 2.5**	**ACH 1.25**
Length of Wall on the Bottom (in contact with Slab)	178 FT	--	356.00	356.00
Length of Wall on Top (in contact with Roof)	178 FT	--	356.00	356.00
Windows	8 Windows (4’x’4) = 128 FT	--	--	256.00
Exterior Doors	2 Doors (3 x 6.5’) = 38 FT	--	--	76.00
Additional cost from IECC code (U.S $)		**--**	**712.00**	**1,044.00**

3.2.2 Operating Cost Estimation

Figure 8 presents the energy saving result differential for each R-value step increase and for each of the 3 infiltrations (ACH 5, 2.5 & 1.25) categories tested. As expected, a higher R-value leads to more savings and a lower ACH level also leads to more energy savings. Furthermore, the operational savings in the case of poor infiltration rate (ACH5) are marginal. Specifically, for a greatly updated insulation to R-29, the operational savings are only 127 U.S. dollars, yearly, for the entire house of the case study. On the contrary, the improvements in infiltration rate, while maintaining the same R-13 insulation on the walls, lead to $ 453 and $ 702 in annual savings for ACH 2.5 and ACH 1.25 respectively.

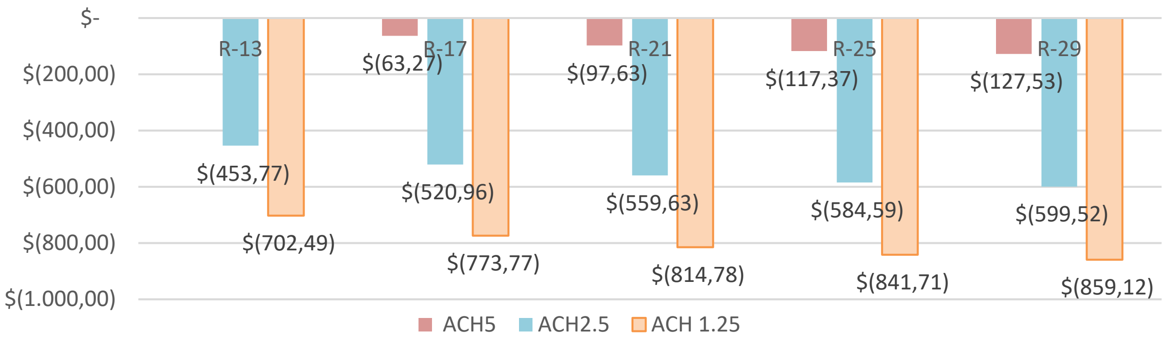

Figure 8: Annual Savings in U.S. dollars for the 1076 square foot house.

3.2.3 Return on Investment and Payback Period

The Return on Investment (ROI) and payback period analysis of this study showcases the importance of this type of methodology as a pre-construction decision tool. Figure 9 shows the ROI in bars and the payback period in lines. As shown in Figure 9, improving the R-value from R-13 to R-17 without improving the ACH results in an ROI of 4.9% and a payback period of 20.4 years (R-17 blue bar and line in Figure 9), while if the R-value from R-13 to R-17 is improved and the ACH is also improved from ACH 5 to ACH 1.25 the ROI is 33.2% and the payback period is 3.0 years (R-17 orange bar and line in the Figure 9). The same pattern showing a significantly better ROI and Payback period with lower ACH appears in all the other tester wall iterations of this study. The highest ROI was estimated to be 67.3% for improving the building's infiltration from ACH5 to ACH 1.25, without altering the insulation (R-13) of the exterior walls.

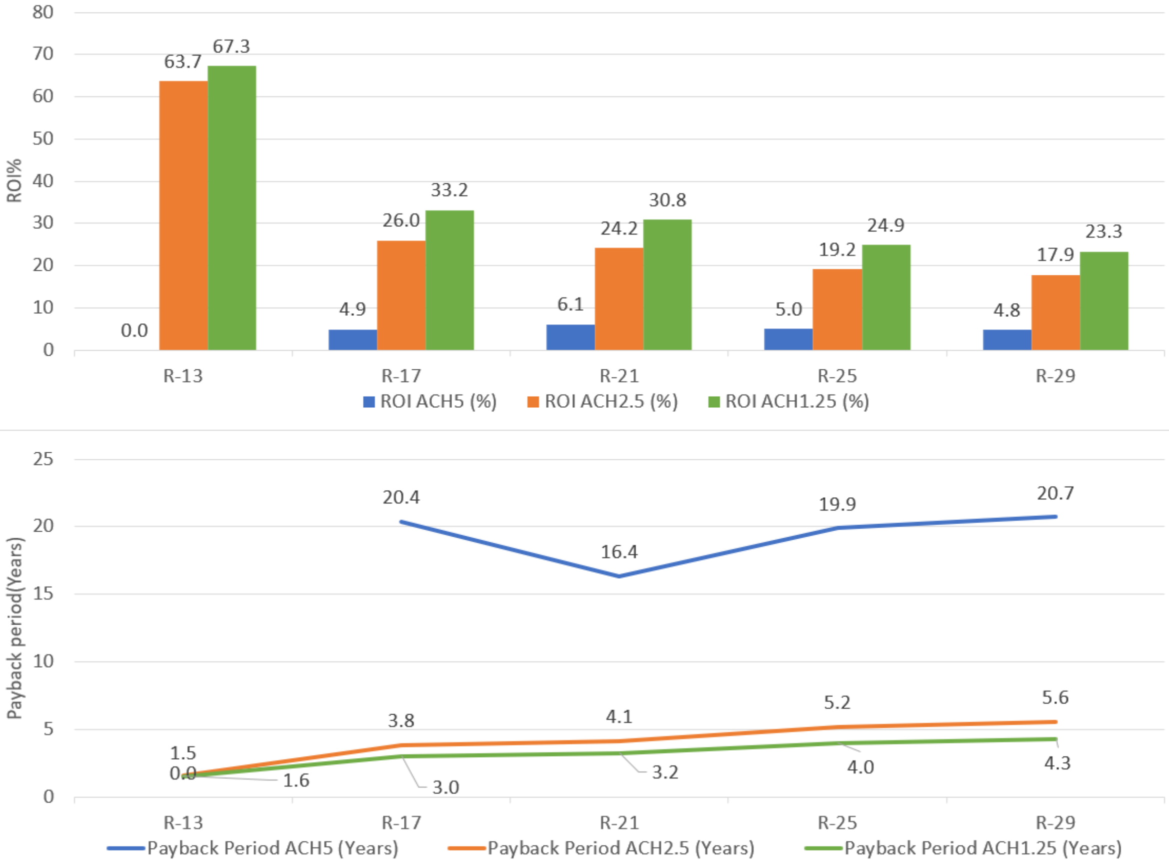

Figure 9: ROI and Payback Period

4. INTELLECTUAL MERIT

The intellectual merit of this work is to provide a greater understanding of the effects of the insulative level and the infiltration level on a residential building's performance. Furthermore, this analysis, combined with the construction characteristics and costs of the different wall assemblies can be used as a valuable decision-making tool during the pre-construction phase of a residential project. This work compared the energy-saving capability of upgraded exterior wall assemblies. Furthermore, the "upgraded" walls were tested under 3 different conditions of infiltration of the envelope of the case study. The results showcase the importance of infiltration levels for the overall performance of the residential case study. Furthermore, the methodology of this study can be replicated and scaled by construction professionals, in order to increase the economic competitiveness of a real project. Last but not least, a better understanding of the energy-saving capabilities of a better-built wall and the financial incentives presented in this study can promote a future of higher-standard construction methods for a myriad of houses across the globe.

5. SUMMARY AND CONCLUSIONS

This study highlights the importance of considering the construction and operating costs of residential buildings, with a focus on energy costs. Heating, ventilation, and air conditioning (HVAC) contribute significantly to a building's energy consumption. The research paper aims to analyze the trade-off between construction costs and operating costs by studying different exterior residential wall types in a warm-humid climate. The study uses quantitative methodology and a virtual case study to assess the impact of insulation and infiltration on energy consumption. The results highlight the importance of building infiltration on operational savings and return on investment (ROI) for different wall types. The study suggests that energy conservation regulations, such as the International Energy Conservation Code (IECC), could be revised to reduce energy consumption and greenhouse gas emissions.

In the study's climate, cooling energy demands are generally higher than heating energy demands, with a consistent ratio across different wall designs. Additionally, the infiltration rates, or the amount of air leakage, have a more significant influence on HVAC energy consumption compared to insulation levels.

Higher R-values and lower infiltration rates result in lower energy consumption. It is evident that a lower infiltration rate contributes to higher efficiency, even with the standard R-13 insulation. On the other hand, a building with a high infiltration rate, despite having upgraded R-29 insulation, performs relatively poorly. These findings support the industry belief that good air sealing with minimal insulation is superior to good insulation with poor air sealing.

The differential energy savings for each step increase in R-value and for each of the three tested infiltration categories. As expected, higher R-values result in greater energy savings, and lower air changes per hour (ACH) levels also lead to more savings. It is noted that the operational savings are minimal when dealing with poor infiltration rates (ACH5). Specifically, for a significant insulation upgrade to R-29, the yearly operational savings for the entire house in the case study amount to only $127. In contrast, improvements in infiltration rates, while maintaining the same R-13 insulation on the walls, result in annual savings of $453 for ACH2.5 and $702 for ACH1.25.

The results of the study highlight the significance of utilizing the ROI (Return on Investment) analysis as a decision-making tool during the pre-construction phase. The data presented in the study demonstrates the impact of different factors on ROI. For instance, with a consistent R-value wall of R-17, the ROI is calculated to be 4.91% for a poorly air-sealed example (ACH5), while it significantly increases to 33.13% for an improved air-sealing example (ACH1.25). This pattern is observed across all the tested wall iterations in the study. The study also identifies the highest ROI, estimated at 186.93%, for enhancing the building's infiltration rate from ACH5 to ACH2.5 without making any changes to the insulation of the exterior walls. These findings emphasize the importance of considering air sealing measures in order to maximize the return on investment, as it can have a substantial impact on energy savings and overall financial benefits. The study's distinctive contribution lies in its exploration of the typically overlooked aspect of infiltration rates in pre-construction building considerations, shedding light on the benefits of including these rates for a more holistic analysis of a building's performance.

Future work to build upon this research includes conducting a comparative study in different climate zones and with multiple building types and geometries to analyze the trade-off between construction and operating costs; conducting long-term monitoring of building performance to assess the actual performance of different wall designs over time; investigating the impact of occupant behavior on energy consumption; conducting a Life Cycle Costing (LCC) to evaluate the economic viability of different wall types; exploring the integration of renewable energy systems into residential buildings; focusing on retrofitting existing buildings to improve energy efficiency; and conducting a sensitivity analysis of parameters to determine their influence on energy consumption and ROI. Additionally, analyzing energy conservation regulations and providing policy recommendations for improving energy efficiency in residential buildings.

REFERENCES

Abanda, F. H., & Byers, L. (2016). An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling). *Energy*, *97*, 517–527. https://doi.org/10.1016/j.energy.2015.12.135

Building Energy Codes Program, D. (2018). *BUILDING ENERGY CODES www.energycodes.gov BUILDING ENERGY CODES PROGRAM Residential Provisions of the 2018 International Energy Conservation Code*. www.energycodes.gov

D'Agostino, D., de' Rossi, F., Marigliano, M., Marino, C., & Minichiello, F. (2019). Evaluation of the optimal thermal insulation thickness for an office building in different climates by means of the basic and modified "cost-optimal" methodology. *Journal of Building Engineering*, *24*. https://doi.org/10.1016/j.jobe.2019.100743

Department of Energy, U. (2015). *AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES Chapter 5: Increasing Efficiency of Building Systems and Technologies*.

electricityplans.com. (2023). *Average cost of electricity in Texas*. https://electricityplans.com/average-electricity-bill-in-texas/#:~:text=The%20average%20cost%20of%20electricity%20in%20Texas%20is%2014.63%20cents,both%20electricity%20and%20delivery%20costs.

Energy Plus. (n.d.). Retrieved March 19, 2023, from https://energyplus.net/

Farhanieh, B., & Sattari, S. (2006). Simulation of energy saving in Iranian buildings using integrative modeling for insulation. *Renewable Energy*, *31*(4), 417–425. https://doi.org/10.1016/j.renene.2005.04.004

Ghrab-Morcos, N. (2005). CHEOPS: A simplified tool for thermal assessment of Mediterranean residential buildings in hot and cold seasons. *Energy and Buildings*, *37*(6), 651–662. https://doi.org/10.1016/j.enbuild.2004.09.020

Huang, H., Zhou, Y., Huang, R., Wu, H., Sun, Y., Huang, G., & Xu, T. (2020). Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate. *Sustainable Cities and Society*, *52*. https://doi.org/10.1016/j.scs.2019.101840

IECC. (2015). *IECC DIGITAL CODES SECTION R402 BUILDING THERMAL ENVELOPE*. IECC DIGITAL CODES. https://codes.iccsafe.org/s/IECC2015/chapter-4-re-residential-energy-efficiency/IECC2015-Pt02-Ch04-SecR402#:~:text=The%20building%20thermal%20envelope%20is,leakage)%20requirements%20of%20the%20code

Ji, Y., Duanmu, L., & Li, X. (2017). Building air leakage analysis for individual apartments in North China. *Building and Environment*, *122*, 105–115. https://doi.org/10.1016/j.buildenv.2017.06.007

John Wiley & Sons. (2012). *RSMeans cost data student edition*.

Kaynakli, O. (2012). A review of the economical and optimum thermal insulation thickness for building applications. In *Renewable and Sustainable Energy Reviews* (Vol. 16, Issue 1, pp. 415–425). https://doi.org/10.1016/j.rser.2011.08.006

Kneifel, J. (2012). *Prototype Residential Building Designs for Energy and Sustainability Assessment*. https://doi.org/10.6028/NIST.TN.1765

Ogulata, T., Tug, R., & Ogˇulata, O. (2002). Sectoral energy consumption in Turkey. In *Renewable and*

Sustainable Energy Reviews (Vol. 6). www.elsevier.com/locate/rser

Persily, A., Ng, L., Dols, W. S., & Emmerich, S. (n.d.). *Techniques to Estimate Commercial Building Infiltration Rates*.

RS Means. (n.d.). *RS Means data from Gordian*. 2023. Retrieved July 8, 2023, from https://www.rsmeans.com/info/contact/about-us

Tian, Z., Yang, J., Lei, Y. P., & Yang, L. (2019). Sensitivity Analysis of Infiltration Rates Impact on Office Building Energy Performance. *IOP Conference Series: Earth and Environmental Science*, *238*(1). https://doi.org/10.1088/1755-1315/238/1/012019

U.S. Census Bureau. (n.d.). Retrieved March 19, 2023, from https://www.census.gov/construction/nrc/index.html

Vine, E. L., & Kazakevicius, E. (1999). Residential energy use in Lithuania: the prospects for energy efficiency. In *Energy* (Vol. 24). www.elsevier.com/locate/energy

Wang, Y., Huang, Z., & Heng, L. (2007). Cost-effectiveness assessment of insulated exterior walls of residential buildings in cold climate. *International Journal of Project Management*, *25*(2), 143–149. https://doi.org/10.1016/j.ijproman.2006.09.007