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BIM-based Sustainability Analysis of Small-Scale New Construction in Florida Climatic Zones: Tallahassee, FL and Miami, FL

Siera Sylvester, Dr. Clayton J. Clark II
Department of Civil and Environmental Engineering,
FAMU-FSU-College of Engineering,
Tallahassee

Abstract- During recent years, Green building information modelling technology is currently gaining substantial attention in the sustainable engineering sector since a rapidly changing climate has made traditional design methods, time-consuming and inefficient processes. Reducing excess material waste, construction improvement, and promotion of urban sustainability are three main advantages of Building Information Modelling technology development, which intersects with the residential building sector, using approximately 21% of total operational energy in the United States. Previously, studies evaluated data interoperability between Building Information Modelling technology and environmental impact assessment software, while simultaneously investigating sustainability analysis capabilities. Linking proposed parametric models to building performance analysis tools allows for energy utilization evaluation, aiding critical sustainable construction decision-making processes during the conceptual design phase. However, gaps in current research emphasize the need for green design sustainability analyses conducted on multi-family residential buildings prior to construction in Florida. This study focuses on small-scale new construction energy analysis amalgamated during the sustainable design phase, for humid subtropical and tropical monsoon, two climatic regions in Florida.A sustainability analysis highlighting the benefits of a common building information modelling method was utilized to assess the impact of lighting efficiency, glazing, and window-wall ratio on thermal energy efficiency. Autodesk Revit and Green Building Studio software, interoperable tools developed to aid in building performance analysis, displayed results showing that lighting efficiency improvement decreases annual energy demand, directly lowering annual energy costs and carbon emissions significantly. It was observed that heating energy consumption was negatively affected by an increased window to wall ratio, which could be attributed to the model's building orientation. Proper window glazing, a factor that literature describes as critical for successful Window to Wall Ratio implementation, should be utilized as an alternative design option, specifically low-E hot climate glazing for the Southeastern U.S. region. Further research considering total life cycle energy consumption i.e. material manufacturing process and transportation will be a next step in sustainable building investigation.

Keywords:-Building Information Modeling, Sustainability, Green Building Studio, Energy Performance Analysis.

I. INTRODUCTION

Florida, a state known for its tourism, growing population and infrastructure, has been progressively vulnerable to climate change induced events including increased temperature and increased intensity and frequency of extreme weather events, partly attributed to carbon emissions through the

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burning of fossil fuels for electricity generation. Climate change mitigation includes increasing environmental and economic sustainability efforts in the built environment. Statistics show that the residential sector is responsible for 26% of the total carbon emissions from energy utilization alone. [6], [11]

It is imperative for construction teams in Florida to be proactive while investigating the impact of green design options, consequently, decreasing environmental impact of the residential sector. According to the Southeast Florida Regional Action Plan, carbon emission mitigation strategies are being implemented to reduce greenhouse gas concentration levels.

A recommendation of the climate compact includes advancing energy efficiency through technological solutions, which can also include BIM sustainability assessments.

Adaptation measures are necessary for greenhouse gas reduction and sustainable building design methodology development, aligning with government objectives to achieve carbon neutrality by 2050. [18] The construction industry could assist in emission reduction effort by implementing green building strategies for major metropolitan areas.

Integration of building performance and GHG emission reduction strategies into new and existing structures is relevant for industry stakeholders and the future of sustainable infrastructure development.

This paper assesses Green Building Studio's capabilities to perform an energy analysis of a multi-family residential structure, while comparing energy analysis results amongst various design alternative options to observe the most sustainable building design parameter for two major climatic regions in Florida.

1. Florida Climate:

In the present paper, Tallahassee and Miami are selected as representative cities for these climatic regions, considering the addition of apartment, townhome, and condominium developments within these specific areas categorized below respectively. A summary of location characteristics is presented in Table 1, accompanying the Köppen-Geiger Florida climate zone map, Fig. 1.

Table 1. Characteristics of Representative Cities.

City	Climate	Latitude (°N)	Longitude (°W)	Elevation (ft)
Tallahassee, FL	Humid Subtropical	30.4383	84.2807	18
Miami, FL	Tropical Monsoon	25.7617	80.1918	5.4

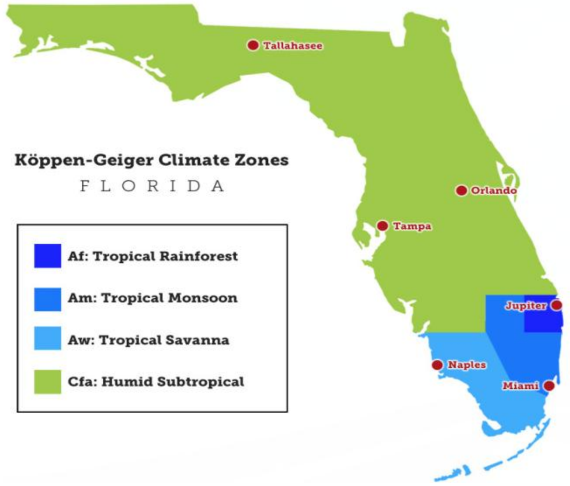


Fig 1. Köppen-GeigerClimate Zone Map. [13]

2. Parameters' Impact on Energy Efficiency:

During a building's life cycle, there are several factors influencing building energy efficiency. Studies suggest lowering energy consumption is a direct correlation to efficient building element implementation including building envelope efficiency increase, lighting efficiency, window-wall ratio, glazing, shading, occupancy sensors, and orientation. [15], [19]

Occupants' behavior is known to have a significant impact on the level of energy required for heating indoor spaces. Based on energy consumption analysis, (Mitra et al., 2020) found that a building's orientation is an energy conservation technique during the life cycle. [1], [16]

(Pacheco et al., 2012) claims energy efficiency building design and changes in building orientation can increase sustainability and a decrease in energy demand. (Ghoshal et al., 2014)observed the critical role of glazing in energy conservation.[8] Previous research studies have examined the impact of glazing on energy consumption and comfort, due to observed poor insulation value leading to detrimental environmental impacts. [4], [24].

Lighting systems in built environments consume 5-15% of the total electricity in modern society. [22]

Day lighting controls, occupancy controls, and dimming are common lighting control methods. Day lighting is a key green building design strategy conserving energy, while providing a healthier indoor environment, when compared to conventional building design according to Gou et al., 2020. [9]

Stakeholder interests in various building changes have led to improved energy solutions and lighting service systems. Building shape, orientation, and window-wall ratio (WWR) of the building directly affects lighting energy demand. (Pathirana et al., 2019)[20]

Utilized Design Builder simulation software to examine the impact of WWR on the lighting requirement and the thermal comfort in tropical climates. Investigation of the most sustainable design techniques in Florida is key to determine estimated annual electricity values and carbon emissions for a new construction multi-family structure.

Hence, a proper design represents energy consumption reduction as a top priority, a principal goal of public stakeholders coupled with the need to discover cost-effective solutions, while reducing environmental impacts of early design options.

3. BIM and Energy Sustainability Analysis:

The Department of Energy states building envelope components can account for approximately 30% of the primary energy consumed in residential structures. To design more efficient apartment homes with a reduced impact on energy costs, suggested sustainable alternatives implementation has a potential to significantly reduce carbon emissions. In a collaborative effort to minimize environmental impact, while maximizing energy savings, it is important for construction teams to incorporate sustainable elements in the preliminary design phase.

In addition, (Azhar et al., 2008), (Ebrahim et al., 2019), (Luziani et al., 2019), and (Solla et al., 2016) [5], [7], [23], [12] noted the benefits of building information modelling derived from a conceptual framework for BIM-based sustainability analysis, specifically displaying the results of sustainable assessment construction plans while decreasing project costs, increasing productivity, and quality. Sustainability as it relates to facility operations and management is an important application to consider for building optimization research methodologies.

A BIM-based analysis solves major problems in the sustainable engineering sector and allows practitioners to determine residential structure energy efficiency using the framework outlined below supporting early decision making. [3], [10]

Data interoperability between Revit and Green Building Studio is also a main component of current research. (Mostafavi et al., 2015) defineddata interoperability as a concept demonstrating software communication capabilities.

(Adamus et al., 2013) [2] Describes interoperability as “the ability to effectively transfer project data to different domains and platforms”. Research investigation is based on the adaptability of both applications mentioned in the framework below, applicable to various climate conditions and building elements.

4. Problem Statement:

Despite substantial theoretical research on energy efficiency and carbon neutrality, real-world application has been obstructed by the traditional building design process. Previous sustainable infrastructure studies, show building material selection has a significant impact on energy consumption and GHG emissions. Energy efficiency issues within residential structures are a result of numerous factors including construction industry reluctance to employ more sustainable technological methodologies and the lack of cost effectiveness when studying sustainable design.

However, in previous literature, the effects of lighting efficiency, and window-wall ratio, have not been sufficiently discussed for humid subtropical climate of Florida and small-scale new construction design techniques utilizing BIM technology.

Therefore, this comparative study is established by answering three research questions: (a) what is the impact of lighting efficiency, glazing, and window-wall ratio on the energy utilization of multi-family residential buildings within two climatic regions in Florida? (b) What is the observed data interoperability between BIM software and energy simulation systems for modelling green design alternatives within small-scale new construction? (c)

What are the limitations involved in a BIM-based sustainability analysis?

II. RESEARCH METHODOLOGY

To gain insights of how green building design parameters influence energy efficiency, the analysis proposed in the research utilizes two different software: Autodesk Revit and Green Building Studio. A BIM-based sustainability analysis framework displaying the methodology is shown below in Fig. 2:

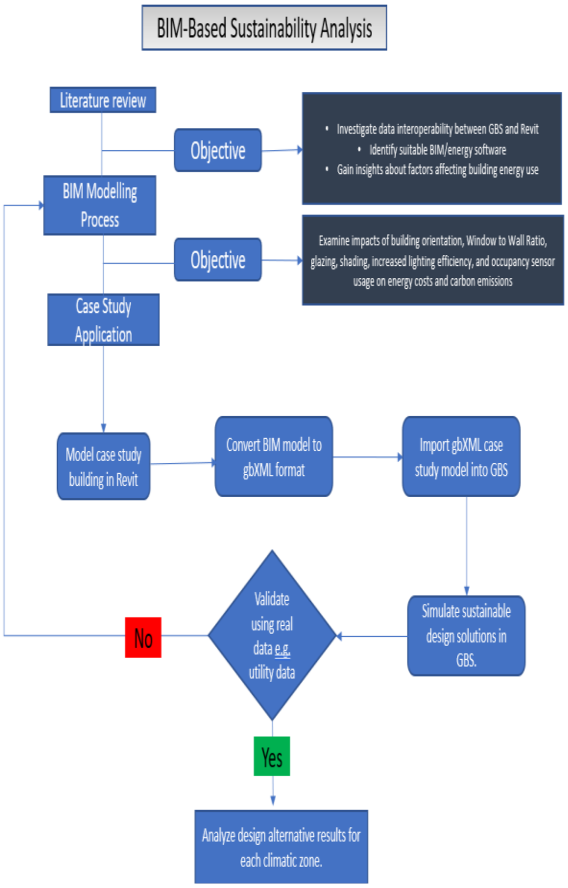


Fig 2. BIM-based Sustainability framework.

1. Case Study:

The conventional design of a three-story townhome style apartment home is employed in this paper as a case study. Table 2 displays the project details below:

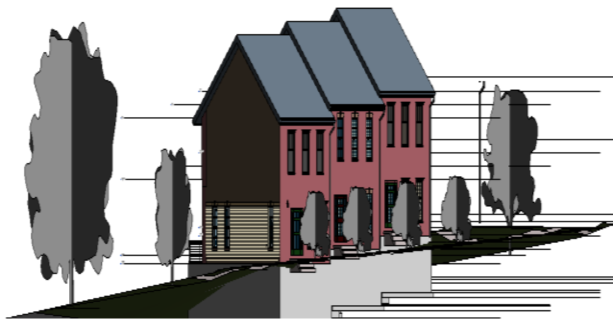
Revit Architecture, a 3-D BIM (Building information modeling) Autodesk software package, was used to define the building geometry and thermal zones. [14], [17] The model orientation is in degrees with counterclockwise direction. Green Building Studio building energy simulation models thermo-physical properties of the building envelope and building service features.

Table 2. Multi-family Project Details.

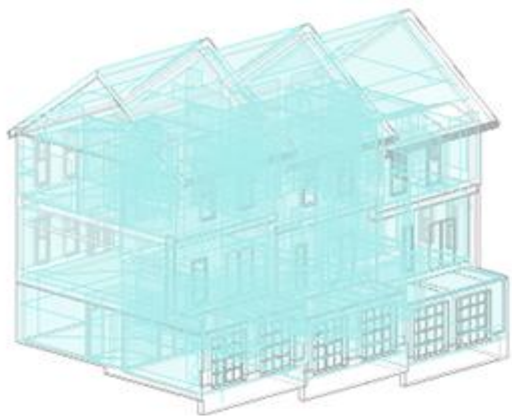
Building type	Multi-family apartment home
# of stories	3
Total gross area	5846 ft^2
Air conditioned area	5165 ft^2
Building Envelope Construction: External walls R13 Wood Frame wall	U-value = 0.09
Building Envelope Construction: Roof R20 over Roof Deck	U-Value = 0.05
Building Envelope Construction: Windows Non-North Facing Windows	U-Value = 2.86 W/m^2k
Constructions of internal structure: R0 Wood frame carpeted floor	U-Value = 0.20
Constructions of internal structure: Ceiling	R45 ceiling U-value = 0.02
Constructions of internal structure: R0 metal frame	U-value = 0.45
HVAC Average Lighting Power Density: 1.00 W/ft^2 Average Equipment Power Density: 1.30 W/ft^2	HP 14 SEER, 8.3 HSPF, Electric Heat, 68F economizer, Residential

2. Energy Model Creation:

Autodesk Revit, a software package allows the user to create an architectural template, define building geometry, thermal zones, and occupancy number, within the energy model, dependent on HVAC zone designation.



(a) 3-Dimensional BIM Model.



(b) "Conceptual Mass" Model.
Fig 3.

Fig. 3(a) depicts the 3-dimensional model of the multi-family floor plan created within Autodesk Revit.

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The developed method mentioned in the framework above is applied to all thermal zones within the multi-family town home structure to investigate the impact of sustainable residential building modifications in the climatic regions of Florida.

Two options for generating a simulation model for Energy analyses exist in Revit, based on the user's preference, one being during the conceptual stage of a project, with an alternative analysis performed during the building stage by adopting "Building Elements".

The option "Conceptual Elements" was selected as the analysis basis since the floor plan and additional building project details were readily available with Fig. 3(b) displaying this model above.

The model is then exported to GBS as a gbXML (green building extensible Makeup Language) file format for further analysis, including the entire building and carbon emissions analysis, and then design alternatives are compared to determine the most sustainable building solution.

3. Energy Simulation in Green Building Studio:

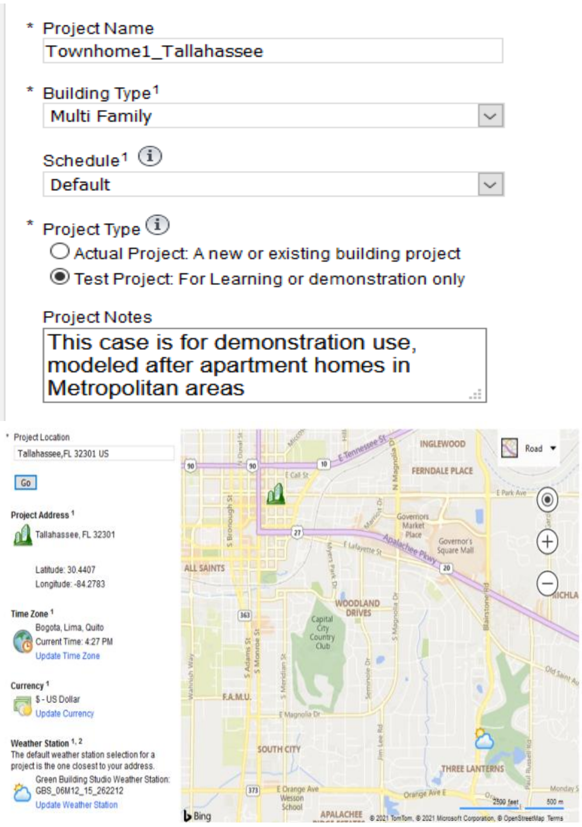

Fig 4. Project information- Multi-family building in Tallahassee, FL.

Within a Green Building Studio web interface, each new project for both Miami and Tallahassee, FL was created by specifying the project name, building type, operational schedule, and location. Green Building Studio automatically selects the projects nearest weather station to simulate the most accurate climatic conditions.

Fig. 4(a) and Fig. 4(b) display all specific project information. Current utility rates displayed in Table 3 are chosen for energy performance evaluation.

Furthermore, current utility rates representative of the location were entered into Green Building Studio, including electricity costs of $0.07/kWh and a gas price of $0.97/Therm.

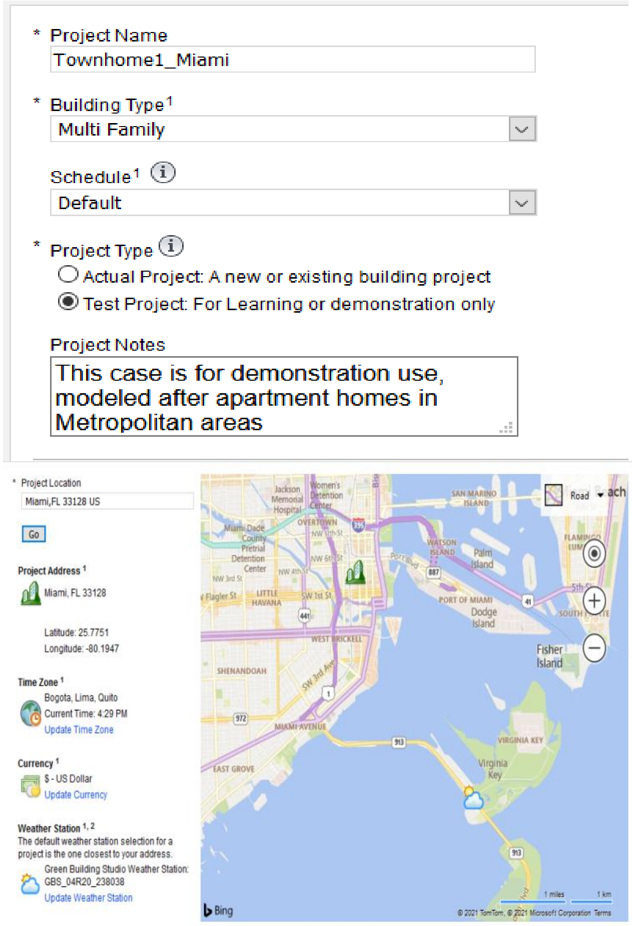

Fig 5. Project information- Multi-family building in Miami, FL

Table 3. Current utility rates.

Usage Rates	
Energy Rate (non-fuel)	$0.07631 per kWh
Fuel and Purchase Power Charge Rate (ECRC)	$0.03329 per kWh
Effective Billing Rate	$0.10960 per kWh

Investigation of lighting efficiency, glazing, and window-wall ratio design options on energy use, required the addition of design alternatives during the building performance analysis process, completed by selecting the design alternatives tab in Green Building Studio.

Following project creation in Autodesk Revit, it is then converted into a gbXML file, followed by a submission in Green Building Studio for an initial run with current building element conditions.

In addition to a "Base Run", seventy other "Design Alternatives" for the generated model. Data created by the initial baseline scenario (no changes made in Green Building Studio) is used for test 1, test 2 incorporates a change in the HVAC system, test 3 incorporates occupancy sensors and the HVAC system, and test 4 includes all the changes mentioned previously in addition to lighting efficiency, glazing, and window-wall ratio. Similarly, changes for other scenarios are affected and outputs for each scenario are presented in scatter plots within the results section.

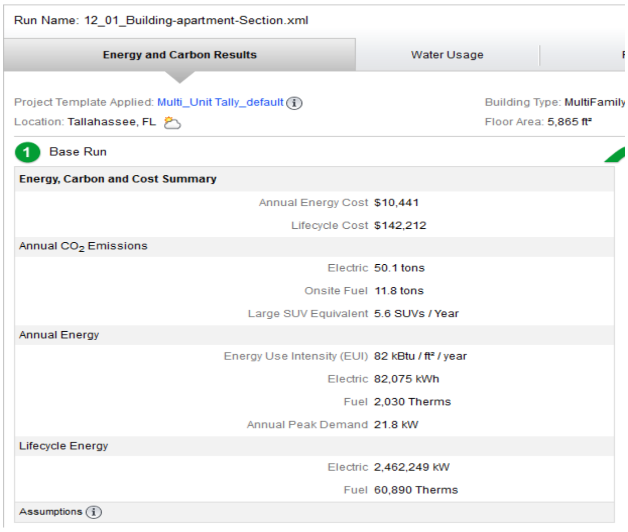

Fig 6. Energy and Carbon Results.

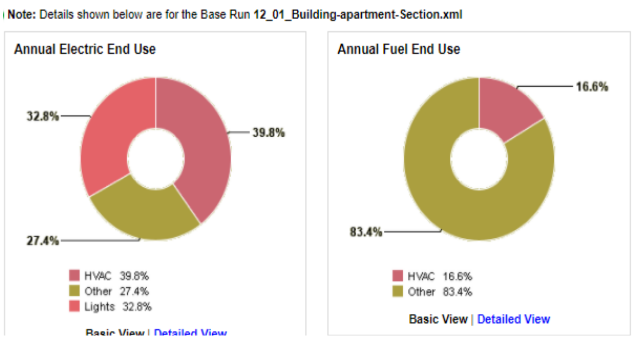

Fig 7. Annual Energy End Use (GBS).

Initial Base Run results include annual energy consumption and carbon emissions, both of which are related to the amount of electricity and fuel a building site may utilize per year. Fig. 6 represents the annual electricity usage for different purposes including appliances, space cooling, lighting etc. and annual fuel usage for space heating, hot water respectively.

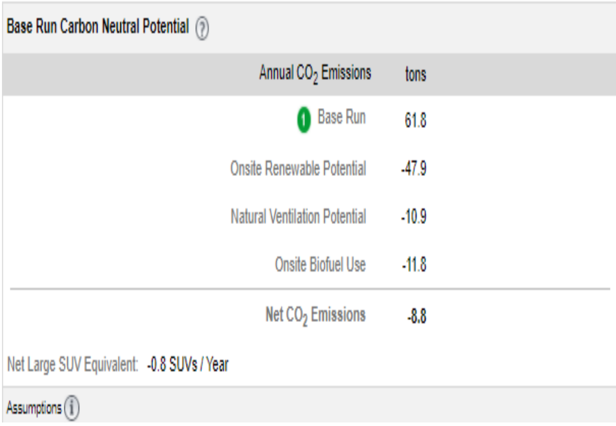

Fig 8. Base Run Carbon Neutral Potential (Tallahassee, FL)

Fig. 7 shows the Base Run Carbon Neutral Potential of the example initial test containing original building elements of the gbXML file, displaying the total sum of carbon emissions created by the multi-family project from both annual electric and onsite fuel usage. Potential carbon emissions removal by renewable energy usage is defined as Onsite Renewable Potential.

Carbon reduction from using natural ventilation for a residential building cooling alternative is represented by a negative value known as natural ventilation potential. Onsite Bio-fuel use characterizes total carbon emissions removal potential by utilizing onsite bio-fuel in the place of fuel. A net CO2 emission is the annual carbon emissions subtracted by the annual carbon emissions potentially removed by implementing green building techniques.

4. Design Alternatives:

In order to compare the impact of common sustainable residential design alternatives i.e. lighting efficiency, glazing, and window to wall ratio, a number of tests were added to the base run of the project in GBS.

The design alternatives tab is selected and changes to the base run mentioned above are made. Fig. 8

shows an example design alternative with a rotation of 0°, a HP 17.4 SEER Residential HVAC system, and 20% increased lighting efficiency.

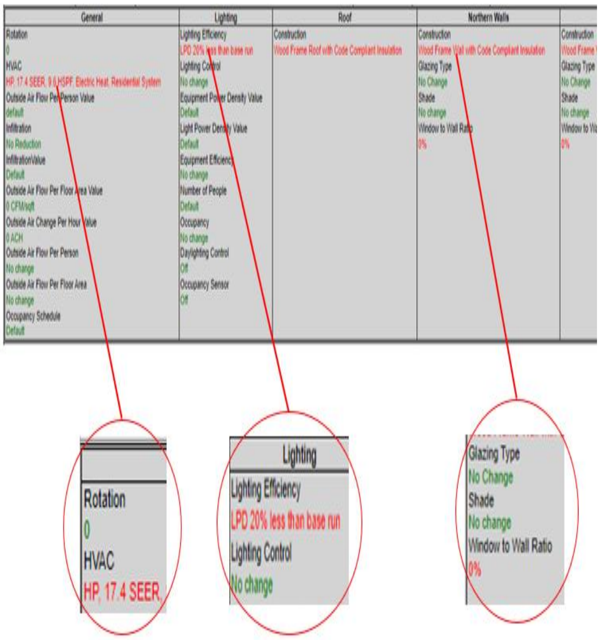

Fig 9. Design Alternatives Image Example.

Table 4 emphasizes the main research objective by displaying additional sustainable design parameters implemented for a new construction multi-family project, with an additional 28 runs being conducted to observe the impact of lighting efficiency, glazing, and window-wall ratio.

Table 4. Constant Sustainable Design Parameters.

Building Orientation	0°
HVAC	HP, 17.4 SEER, 9.6 HSPF, Electric Heat, Residential System

Validation of Computation Results

To prove model results accuracy, a validation method obtained from literature is utilized to determine result legitimacy, developed by (Reeves et al., 2012) [21].

In this section of the methodology, a common validation technique is adopted, comparing the computational results of the annual energy from Green Building Studio, with the real utility bill of a three-story townhome with a similar apartment size. The energy usage bill summary, Table 5, is compared to the annual electricity use from Green Building Studio results.

Table 5. Energy Usage Bill Summary.

5/07/2020	$208.56	$183.30	0.00	0.00	16.75	8.51	0.00
4/07/2020	$271.91	$246.65	0.00	0.00	16.75	8.51	0.00
3/06/2020	$281.48	$256.22	0.00	0.00	16.75	8.51	0.00
2/07/2020	$326.48	$301.22	0.00	0.00	16.75	8.51	0.00
1/08/2020	$269.70	$244.44	0.00	0.00	16.75	8.51	0.00
12/06/2019	$349.31	$324.05	0.00	0.00	16.75	8.51	0.00

The average electrical cost of a 3-story townhome every month is approximately $284.57, an estimate from an electric bill in 2020 from U-Club Townhomes, an apartment home built in 2016, bringing the annual cost of one apartment home to $3,414.88.

Since, this is a multi-family triplex townhome; the total annual electricity cost is $10,244.64. An annual electricity cost of the "Base Run" is $10,441, according to GBS result. The difference between the two observed annual energy costs is approximately 2%.

III. RESULTS AND CONCLUSION

A total of 28 green building design configurations were simulated and analyzed for green building energy performance.

As a sole parameter, 50% lighting efficiency had the greatest impact on energy consumption in both Miami and Tallahassee, FL with tables 6 and 7, displaying the importance of considering this green building parameter for new construction analysis.

Table 6. Building Performance Analysis Results (Tallahassee, FL).

	Tallahassee, FL	% Difference in Annual Energy Costs (+/-)	% Difference in Annual Carbon Emissions (+/-)
Building Design with Increased Lighting Efficiency			
Test 1	10% Lighting Efficiency	-1.95%	-7.12%
Test 2	20% Lighting Efficiency	-9.51%	-11.73%

Test 3	30% Lighting Efficiency	-13.3%	-16.54%
Test 4	40% Lighting Efficiency	-17.07%	-21.15%
Test 5	50% Lighting Efficiency	-21.24%	-25.77%
Building Design with Window to Wall Ratio, Low-e hot climate glazing			
Test 6	15% WWR	+4.33%	+5.38%
Test 7	30% WWR	+10.31%	+12.69%
Test 8	40% WWR	+13.7%	+16.9%
Test 9	50% WWR	+17.1%	+21.15%
Building Design with Window to Wall Ratio, Low-e hot climate glazing, and increased lighting efficiency			
Test 10	10% LE, 15% WWR	-5.02%	-5.18%
Test 11	20% LE, 15% WWR	-8.63%	-9.61%
Test 12	30% LE, 15% WWR	-12.23%	-14.05%
Test 13	40% LE, 15% WWR	-15.82%	-18.50%
Test 14	50% LE, 15% WWR	-19.42%	-23.10%

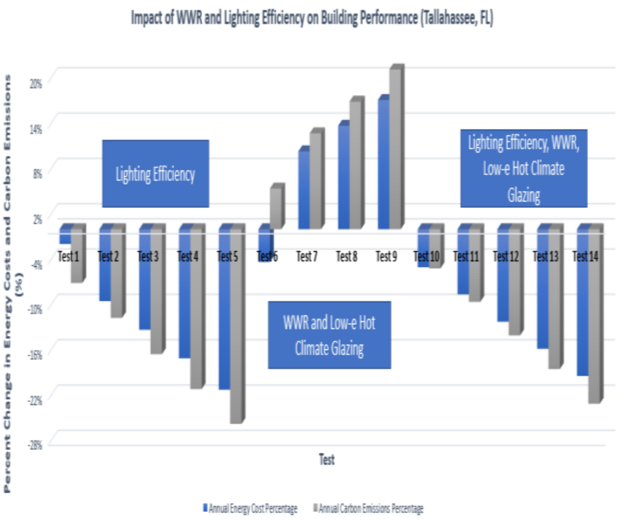

Fig 10. Percent Change in Building Performance Analysis (BPA Bar Graph), Tallahassee, FL.

Table 7. Building Performance Analysis Results (Miami, FL)

	Tallahassee, FL	% Difference in Annual Energy Costs (+/-)	% Difference in Annual Carbon Emissions (+/-)
Building Design with Increased Lighting Efficiency			
Test 1	10% Lighting Efficiency	-1.59%	-1.85%
Test 2	20% Lighting Efficiency	-5.24%	-6.47%
Test 3	30% Lighting Efficiency	-8.91%	-11.09%
Test 4	40% Lighting Efficiency	-12.6%	-15.53%
Test 5	50% Lighting Efficiency	-16.31%	-20.15%
Building Design with Window to Wall Ratio, Low-e hot climate glazing			
Test 6	15% WWR	+4.33%	+5.38%
Test 7	30% WWR	+10.31%	+12.69%
Test 8	40% WWR	+13.7%	+16.9%
Test 9	50% WWR	+17.1%	+21.15%
Building Design with Window to Wall Ratio, Low-e hot climate glazing, and increased lighting efficiency			
Test 10	10% LE, 15% WWR	-5.02%	-5.18%
Test 11	20% LE, 15% WWR	-8.63%	-9.61%
Test 12	30% LE, 15% WWR	-12.23%	-14.05%
Test 13	40% LE, 15% WWR	-15.82%	-18.50%
Test 14	50% LE, 15% WWR	-19.42%	-23.10%

Fig 11. Percent Change in Building Performance Analysis (BPA Bar Graph), Miami, FL.

Overall, energy consumption is 8.41% higher in Miami, FL and Tallahassee, FL indicating region-specific materials may be necessary to assist in improving building performance for locations closer in proximity to the equator.

As chosen parameters are implemented such as 15% WWR, 50% lighting efficiency, and low-e hot climate glazing, specifically, for the humid subtropical region of Tallahassee, FL, 19.42% savings in Annual Energy

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Costs and 23.1% reduction in carbon emissions are observed. Results in the tropical monsoon region of Miami, FL, displayed a 15.91% decrease in energy costs and a 19.77% decrease in carbon emissions. Low-e hot climate glazing decreased energy usage for each window to wall ratio by 4%.

Since windows are necessary for conventional building design, the optimal WWR is approximately 15%, a value previously supported by literature and data collected through this BIM-based Analysis. Bar graphs (Figs. 9 and 10) highlighting the impact of lighting efficiency, WWR, and glazing on annual energy costs and carbon emissions are displayed above for each region.

Lighting efficiency improvement decreases annual energy demand. Conversely, the window-wall ratio displayed a negative impact on energy efficiency, with climatic region as a non-determining factor for additional significant energy savings. It was observed that heating energy consumption was negatively affected by an increased window to wall ratio, which could be attributed to the building's orientation not being optimal for this building design to take advantage of window placement. The observed phenomenon of WWR contributing to additional energy usage in Florida is due to a correlation between window area and increased cooling load demand.

This research displayed the capability of BIM to assess the impact of various design parameters i.e. window-wall ratio, glazing, and lighting efficiency on building energy usage in Florida, offering opportunities to explore green building design alternatives, during the beginning stages of design for new construction.

1. Opportunities/Limitations in BIM-based Sustainability Analysis:

Observed errors during experimentation from building element transfer between interoperable software and occupancy model inaccuracy. A significant limitation of Green Building Studio becomes apparent during the initial run phase, leading to an overestimation of energy usage since its default setting is an HVAC single packaged system for each specified energy model zone. Building element loss during file transfer is also a common issue during the process of sustainability assessments, impacting energy performance results. Model inaccuracy due to occupancy schedule assumptions selected from energy performance simulation software options varying from real-time occupant schedules and behaviors is common when applying the sustainability framework.

Future research can include the integration of IFC (Industry Foundation Class) schema and sustainability-targeted MVDs (Model View Definition) to investigate the potential interoperability of a different file type for more accurate environmental analyses within Green Building Studio.

Cost Benefit Ratio (CBR) generation associated with the addition of previously simulated parameters and investigation of net zero water buildings to reduce annual water usage, by implementing strategies such as air-cooling condensate usage and wastewater reclamation also provide opportunities for further research. Further research considering total life cycle energy and embodied energy i.e. material manufacturing process, transportation, construction, and decommissioning will be a next step in sustainable building investigation, by utilizing a LCA (life cycle analysis) tool, SimaPro.

Additional research including occupancy sensors, glazing, shading, will be conducted to determine the impact of additional green building design options on energy efficiency for multi-family homes in Florida.

2. Major Findings:

Building Information Modeling (BIM) based sustainability analysis helps to enhance building energy performance by decreasing energy costs and reducing environmental impact through carbon emissions reduction.

- Data intercommunication and information management are executed traversing the BIM platform to solve building data integration problems. Investigation of BIM-based design tools demonstrated the exchange of thermal data, construction properties, and building geometry between applications.
- Full data interoperability between Autodesk Revit and Green Building Studio is shown, following BIM-based sustainability framework implementation.
- Implementation of BIM based sustainability analysis helps the practitioners in designing the facility, with simple energy efficient measures with least impact on the environment and promoting energy

consumption reduction. This research displayed the capability of BIM to assess the impact of two parameters, namely window-wall ratio, and lighting efficiency on building energy usage in Florida, offering opportunities to explore green building design alternatives, prior to new construction.

- Increased lighting efficiency, decreasing window to wall ratio, and applying Low-e hot climate glazing to all windows, lowers Annual Energy Costs and Annual Carbon Emissions for multi-family new construction projects in Florida, with both factors having a slightly more significant impact in Tallahassee, FL when compared to Miami, FL due to differences in weather conditions.

It was also noted that as a sole design parameter, lighting efficiency had a positive impact on operational energy usage. Proper window glazing, a factor that literature describes as critical for successful Window to Wall Ratio, should be utilized as an alternative design option, specifically low-E hot climate glazing for the Southeastern U.S. region. Therefore, it can be concluded that the advantages of BIM-based sustainability analysis align with goals related to efficient construction design, leading to a more sustainable future.

IV. ACKNOWLEDGEMENTS

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