Comparing the Effects of a Building's Glass Type, Size, and Location on Its Average Annual Energy Usage Through BIM Software

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Abstract

Studies have utilized Building Information Modeling (BIM) software to understand a building's peak energy times and to predict a building's future energy consumption. While BIM software can help optimize the energy savings of an individual building, it has not been used to simulate the effects on a building's energy loads at the global scale. This study investigated the effects of a building's glass type, size, and location on its annual energy usage. Using Autodesk Revit, ten, twenty, and thirty story office buildings were modeled and simulated in 141 cities. In Autodesk Insight, each building's facade was changed between Single Clear, Double Clear, Double Low-E, and Triple Low-E glass and the building's energy unit intensity (EUI) was recorded in kBtu/sq.ft/yr. The study found that there was a strong relationship between the latitude of the building and the building's energy saving potential from using more thermally resistant glass. The results included that buildings located inland had greater EUIs than buildings in coastal cities. Additionally, the research discovered that for buildings North of about 53° N, the energy saving potential of replacing Single Clear glass with Double Clear glass surpassed the energy saving potential of using Triple Low-E glass instead of Double Low-E glass. The results can help building professionals and governments around the world understand how to develop or retrofit buildings that are more energy efficient, contributing to a reduction in global energy use, the need for resources, and the emission of carbon dioxide into the atmosphere.

1. Introduction

The global urban population is projected to increase from 3.1 billion in 2010 to 5 billion by the year 2030 (Seto et al., 2011). This growth in population, time spent indoors, demand for building functions and indoor quality, and global climate change have all led to an increase in energy consumption (Cao, Dai, & Liu, 2016). Buildings largely contribute to this issue; they are responsible for 40% of the global energy demand (Ahmad et al., 2016) and 70% of the main energy in cities (Hong & Luo, 2018). This has led to an increase in attention to sustainability and rating schemes for building efficiency during the past decade (Chegut, Eichholtz, & Kok, 2013), with designers and policy makers searching for energy efficient strategies for sustainable development (Raji, Tenpierik, & Dobbelsteen 2015).

Many factors contribute to a building's energy performance. Examples include ambient weather conditions, building structure and characteristics, the operation of sub-level components, such as lighting and HVAC systems, and occupant behavior (Zhao & Magoulès, 2012). Additionally, a building's energy use intensity (EUI) is correlated with its thermal envelope parameters (Wate & Coors, 2015). According to Dorey, an energy efficient building should have a simple geometry and the largest volume for the smallest surface/envelope area (Dorey, Valinejadshoubi, & Bagchi, 2019).

To construct buildings that are highly energy efficient, conducting energy analyses during the conceptual design stage is important to select optimal building components (Nguyen & Amoah, 2019). In recent years, Building Information Modeling (BIM) has been a useful platform to analyze buildings (Salimzadeha, Vahdatikhaki, & Hammad, 2018) and predict their performance (Latif et al., 2019). According to Autodesk, "BIM is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructures" (www.autodesk.com/solutions/bim, 2016). To simulate a building's energy demands, programs make simplified calculations with monthly or seasonal average outdoor temperatures (Vollaro et al., 2015), using the typical meteorological year (TMY) data format (Reinhart & Davila, 2016).

The Autodesk Revit BIM software is capable of modeling virtual environments (Oerter et al., 2013) and simulating building performance (Gerrish et al., 2017). Autodesk Insight 360, which is a plug-in for Revit, simulates daylighting (Ergün et al., 2019), heating, cooling, solar radiation, and whole building energy optimization (Huang, 2018). Optimizing the components of a building can be beneficial during an early design stage, as well as in retrofitting. Autodesk Insight 360 generates annual and monthly data of a building's EUI in energy and monetary units (Keskin & Salman, 2018).

Previous research utilized BIM software to simulate the energy use of a single family residential house and compared its energy usage in different cities in the Middle Eastern and North African (MENA) region (Al-Saeed & Ahmed, 2018). The study focused on creating a nearly zero energy buildings (nZEB) standard. Khoshbakht et al. analyzed the energy savings of an office building with a double skin facade in two different climates. They also measured heat losses and gains and discomfort degree hours. Novelli tested if the Modelica simulation environment could understand the behavior of a dynamic solar building envelope system. The parameters of the Integrated Concentrating Solar Facade (ICSF) were inputted from real-life data of the prototype, and integration with a building energy model (BEM) was proposed. Yarbrough analyzed energy peaks of different university buildings. Similarly, Gul compared a university building's energy patterns to the occupancy behavior. There is a gap in comparing the variables of a building's energy usage at the global scale. The goal of this study was to investigate the effects of a building's size, location, and glass type on its annual energy usage and compare the energy saving potential of implementing more thermally resistant glass in buildings with different volumes and locations.

2. Hypothesis

It was predicted that the ten story building would have the greatest EUI compared to the twenty and thirty story buildings in the same geological locations. This hypothesis was based on the premise that buildings with a larger surface area to volume ratio are more responsive to fluctuating temperatures and weather conditions, thus having greater heating and cooling loads and overall energy consumption to support occupant thermal comfort.

3. Materials and Methods

Using Autodesk Revit Version 2018, a thirty story office building with a level of detail (LOD) of 200 was modeled. The first floor was the lobby (Figure 1), and each additional level was dedicated to office spaces identical to each other. An office level was allocated for two companies and consisted of sixteen elevators, two elevator lobbies, a corridor, two emergency exit staircases, a men's room, a women's room, two waiting rooms, four conference rooms, eighteen private offices, and two open floor plan office spaces for cubicles. Service spaces included: a corridor, telecom room, mechanical room, electrical room, elevator, and closet. This layout is depicted in Figure 2. The spaces within each level were then divided, and a schedule was created to identify the function of each individual space. Because there was no option for an elevator in Revit's pre-set space types, a mechanical/electrical room was selected.

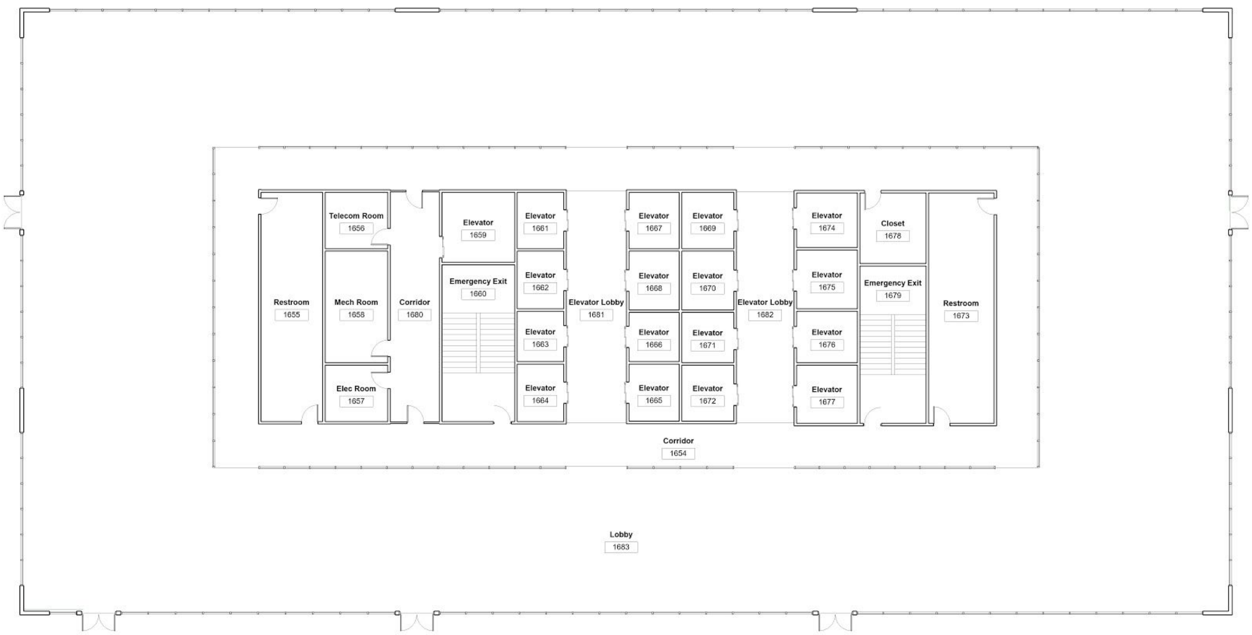

Figure 1. Floorplan of the first level lobby in the 20 and 30 story buildings.

Figure 2. Floorplan of the office levels in the twenty and thirty story buildings.

The thirty story model was then duplicated to two additional Revit files. The two new models were modified to be twenty and ten stories, respectively, by removing the top levels of the building. The ten story building was adjusted so that eight of the sixteen original elevators were specified as storage spaces rather than mechanical/electrical rooms. The interior core and service components have been adjusted according to the service needs of each building. Figure 3 shows the thirty, twenty, and ten story office buildings (from left to right) that were modeled in Revit.

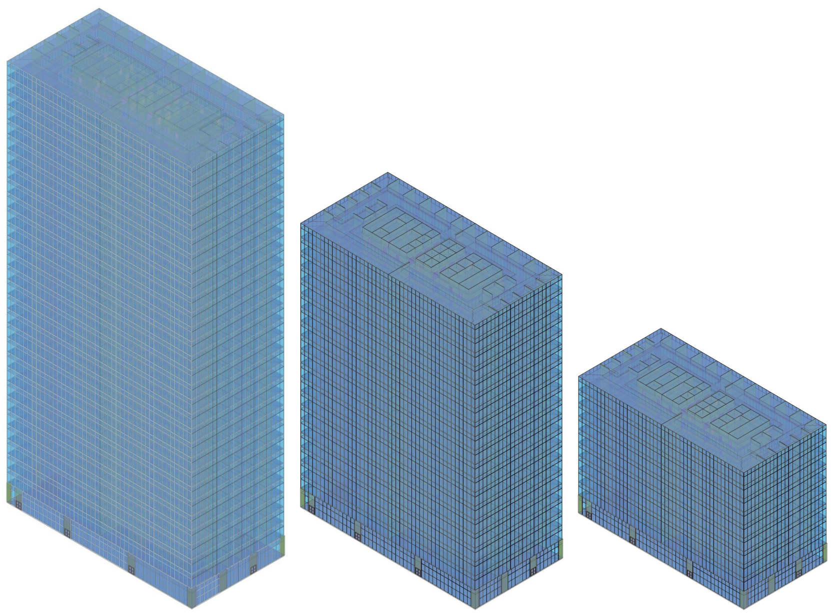

Figure 3. Office building models in Revit. From left to right, are the thirty, twenty, and ten story building.

Each of the three Revit files were duplicated 141 times, then labeled by a geographic location. The cities analyzed in this study were located in the North and South Americas, Europe, Asia, Africa, and Oceania and have a human population of over 1 million. In each Revit file, the location of the building was identified, and an energy model was generated, which was exported as gbXML and IFC files to visualize in Autodesk Insight (Khan, Ghadge, 2019).

3.1 BIM Simulation

The Insight program offered different building parameters to be input, such as glass type, shading, HVAC system, plugin loads, and orientation. However, this study only explored the effects of glass type from Insight and location and building size from Revit. For each building size and location, the glass type of all four sides of the building had to be changed to Single Clear, Double Clear, Double Low-E, and then Triple Low-E glass (Figure 4). The Single Clear glass had one pane, both Double Clear and Double Low-E had two, and the Triple Low-E had three. Also, Low-E glass differed from Clear glass by having an extra thin layer for low-emissivity. This prevented infrared from penetrating the building, while allowing sunlight to enter. After the glass type was changed on all four sides for a particular building size in a certain location, the predicted annual EUI was recorded in a Google Docs spreadsheet.

After recording all of the energy data, a subtraction function was input into the spreadsheet to calculate the energy difference of using Double Clear rather than Single Clear glass and Triple Low-E instead of Double Low-E glass. The difference in EUI for a building with Double Low-E and Double Clear glass was not calculated because neither significantly outperformed one another. Finally, different averages were taken of the data and the locations' latitudes were recorded from Revit, which are described with their appropriate figure.

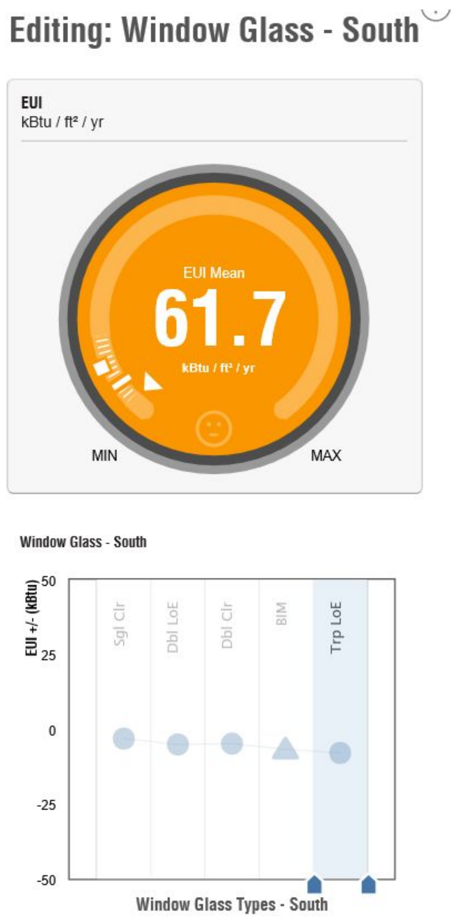

Figure 4. Inputting glass parameters in Autodesk Insight 360. From left to right, Single Clear, Double Low-E, Double Clear, and Triple Low-E glass were selected for each side of the building. The triangle and BIM option represent the building's pre-existing glass type from Autodesk Revit, which was ignored. Towards the top, the building's predicted EUI is indicated in kBtu/sq.ft/yr based on the selected glass type.

4. Results

Figure 5 shows the EUI of an office building with Single Clear Glass in various cities. For each location, the energy value is an average of the ten, twenty, and thirty story buildings. Figure 6 represents the building's EUI with Triple Low-E glass. The two glass types were chosen because they are the least (Single Clear) and most (Triple Low-E) thermally resistant glass-types in this study. Comparing both graphs, the data in Figure 4 had a greater color range. Therefore, buildings with single clear glass were predicted to consume more energy than Triple Low-E Glass. Observing the depreciation in energy usage, buildings in cities closer to the equator required less energy. Additionally, buildings in cities with similar latitudes required less energy if they were in a coastal region.

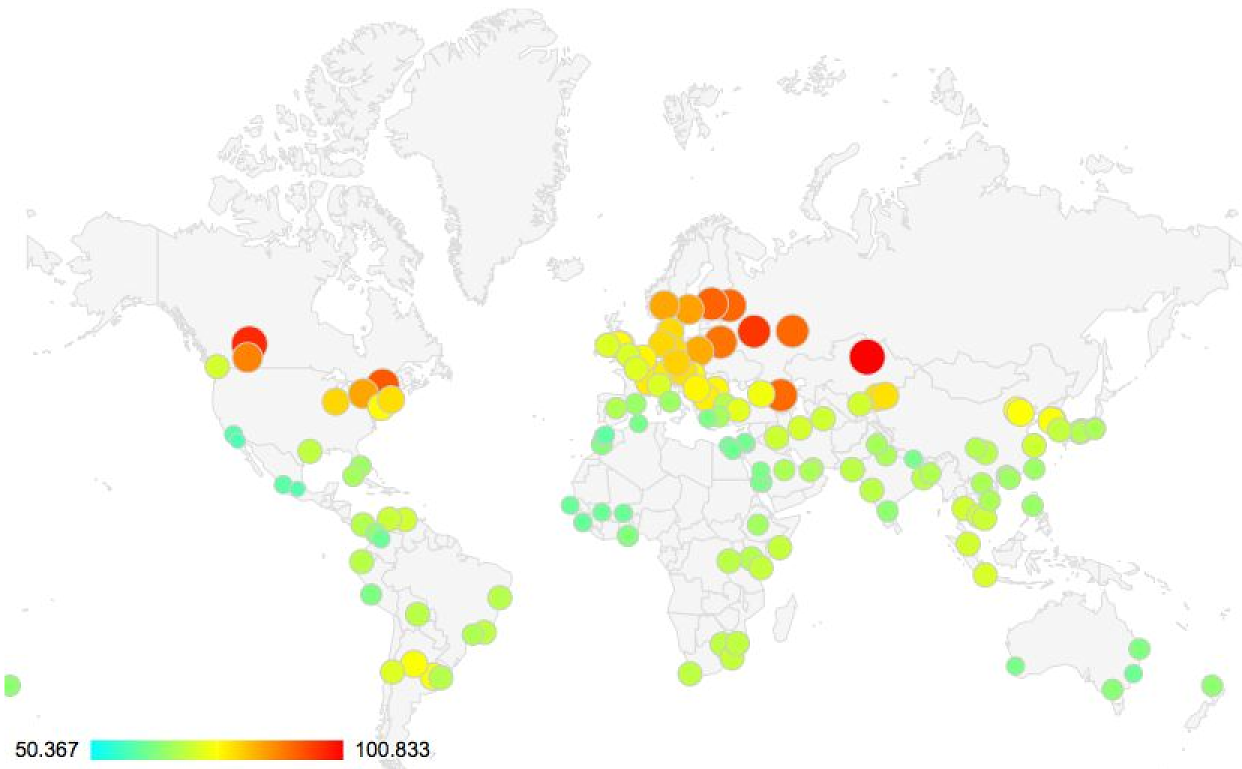

Figure 5. The effect of location on energy unit intensity (EUI) of an office building with Single Clear Glass. The color spectrum represents the building's annual energy usage in kBtu/sq.ft., with blue indicating the lowest energy load and red indicating the highest energy load.

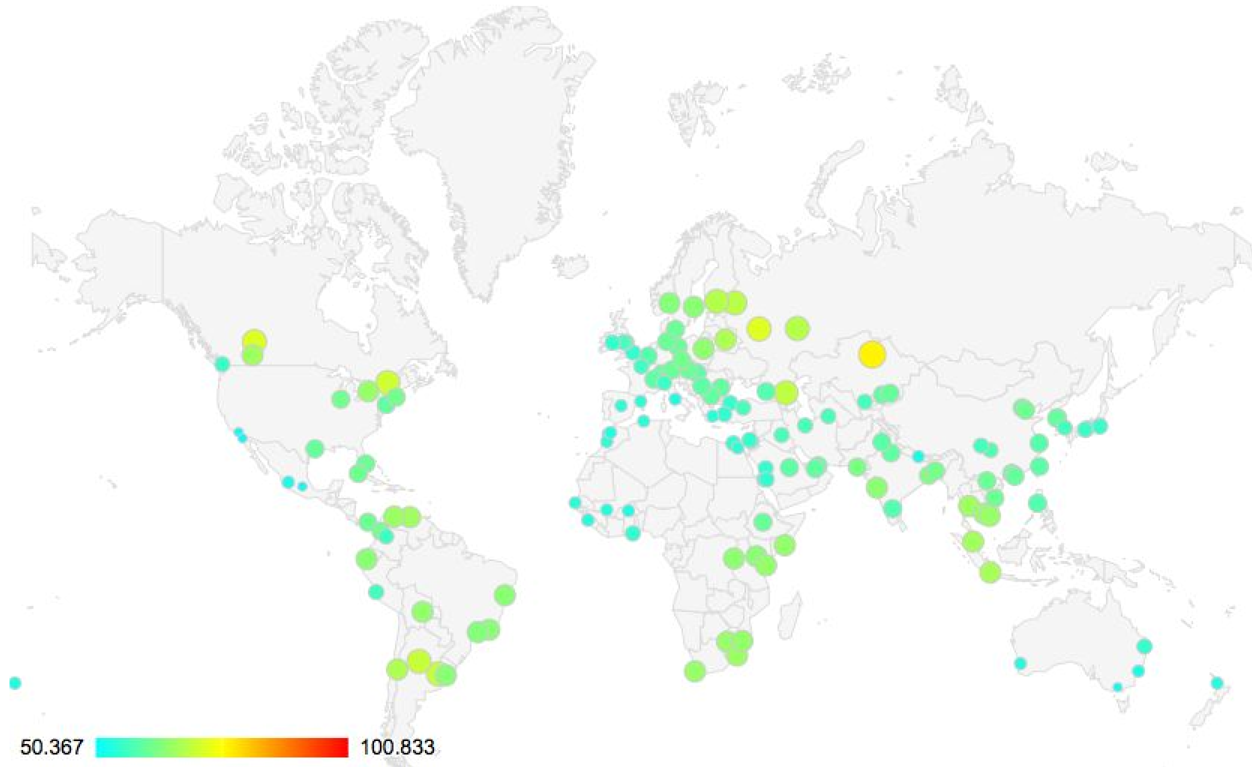

Figure 6. The effect of location on energy unit intensity (EUI) of a building with Triple Low-E Glass.

The difference in EUI from implementing a more thermally resistant glass type in the building was then observed. Figure 7 depicts how using Triple Low-E glass rather than Double Low-E glass would cause different amounts of energy savings around the world. This shows a different trend than analyzing the building's energy consumption alone (Figures 5 and 6); the more North the building is located, the greater the energy savings outcome.

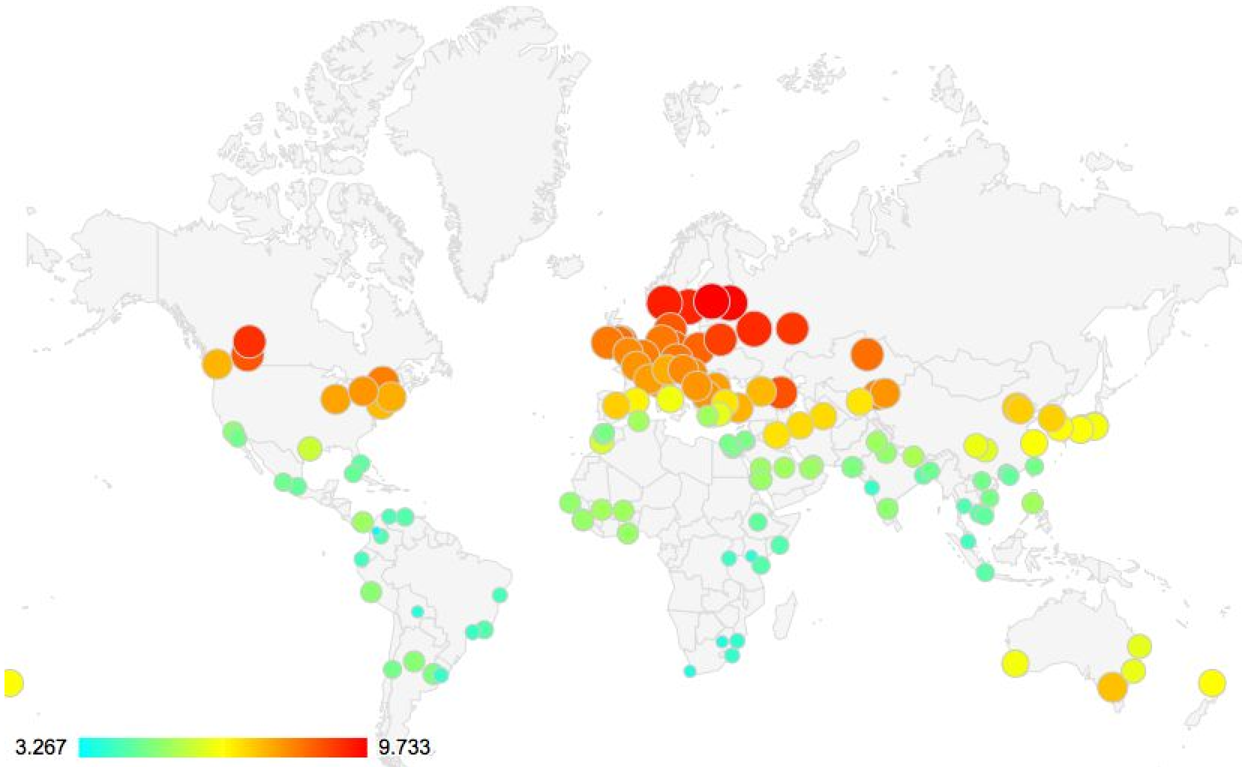

Figure 7. The effect of building location on energy savings from implementing Triple Low-E rather than Double Low-E glass. Each dot represents an average of the differences in EUI between using Triple Low-E and Double Low-E glass for the ten, twenty, and thirty story buildings. The color spectrum represents the building's potential annual energy savings in kBtu/sq.ft., with blue indicating the lowest energy difference and red indicating the highest.

The effects of a building's size and glass type on its energy consumption were then analyzed. Figure 8 shows a decrease in EUI from Single Clear Glass to Triple Low-E Glass. Also, the chart displays that with all four glass types, the building's energy usage decreased as building size decreased. This did not support the original hypothesis that the ten story building would consume the most energy due to its larger surface area to volume ratio.

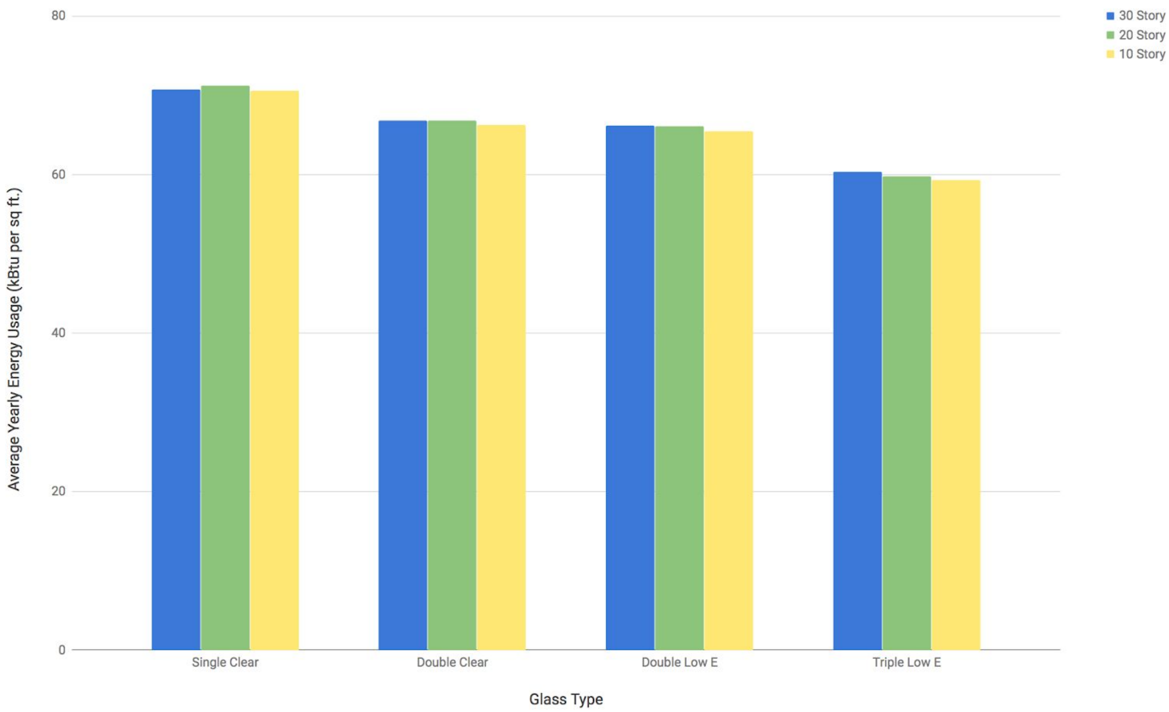

Figure 8. The effects of a building's glass type and size on its annual energy unit intensity (EUI).

The 141 cities in the study were then ranked based on EUI and energy difference from implementing a different glass type. Figure 9 shows the three cities with the highest and lowest EUI. Nur-Sultan, Kazakhstan; Edmonton, Canada; and Moscow, Russia had the greatest energy unit intensity and Los Angeles, United States; Tijuana, Mexico; and Mexico City, Mexico had the lowest. A unique relationship was found between building size and EUI; the smaller the building, the greater the EUI in the Northern Hemisphere, and the larger the building, the greater the EUI in the southern hemisphere.

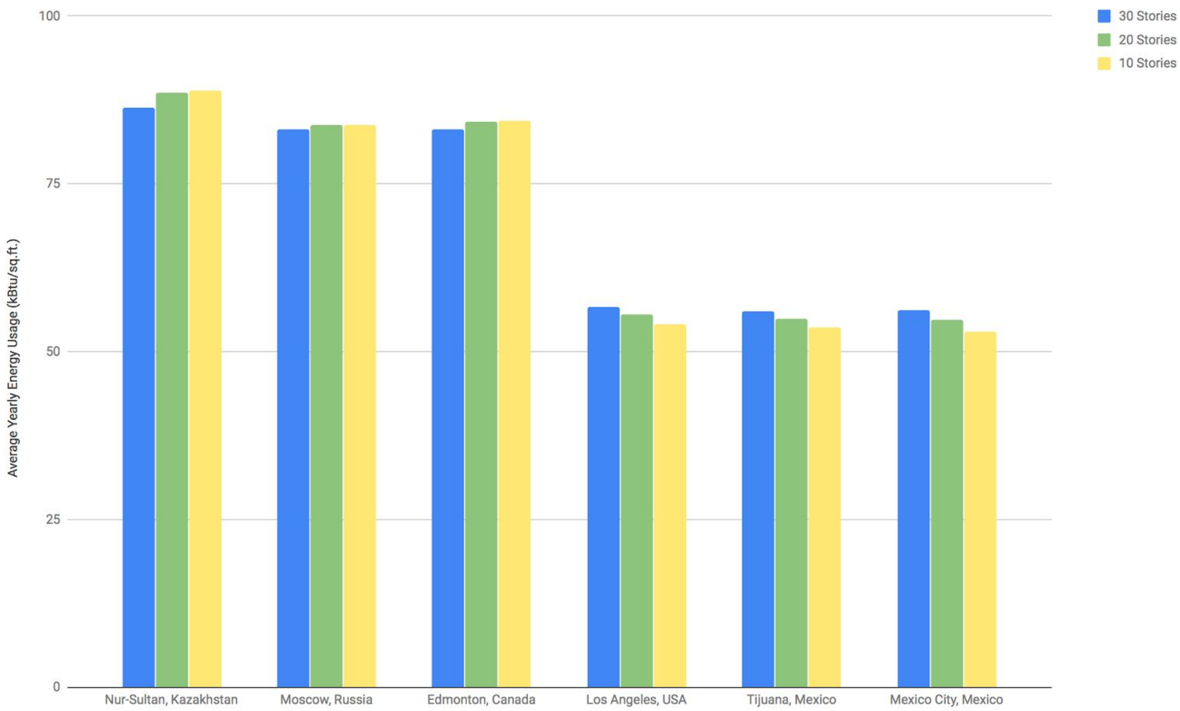

Figure 9. The effect of building size on energy unit intensity (EUI) for the top and bottom three cities. The graph depicts the three cities with the highest and lowest annual EUI.

Figure 10 shows the three cities with the highest and lowest energy difference between using Double Low-E or Triple Low-E glass. This scenario was chosen because it is more common than replacing Single Clear glass with Double Clear glass. Overall, Helsinki, Finland; Saint Petersburg, Russia; and Oslo, Norway had the highest energy saving potential. Johannesburg, South Africa; Capetown, South Africa; and Medellín, Columbia represented the lowest energy savings from changing the glass.

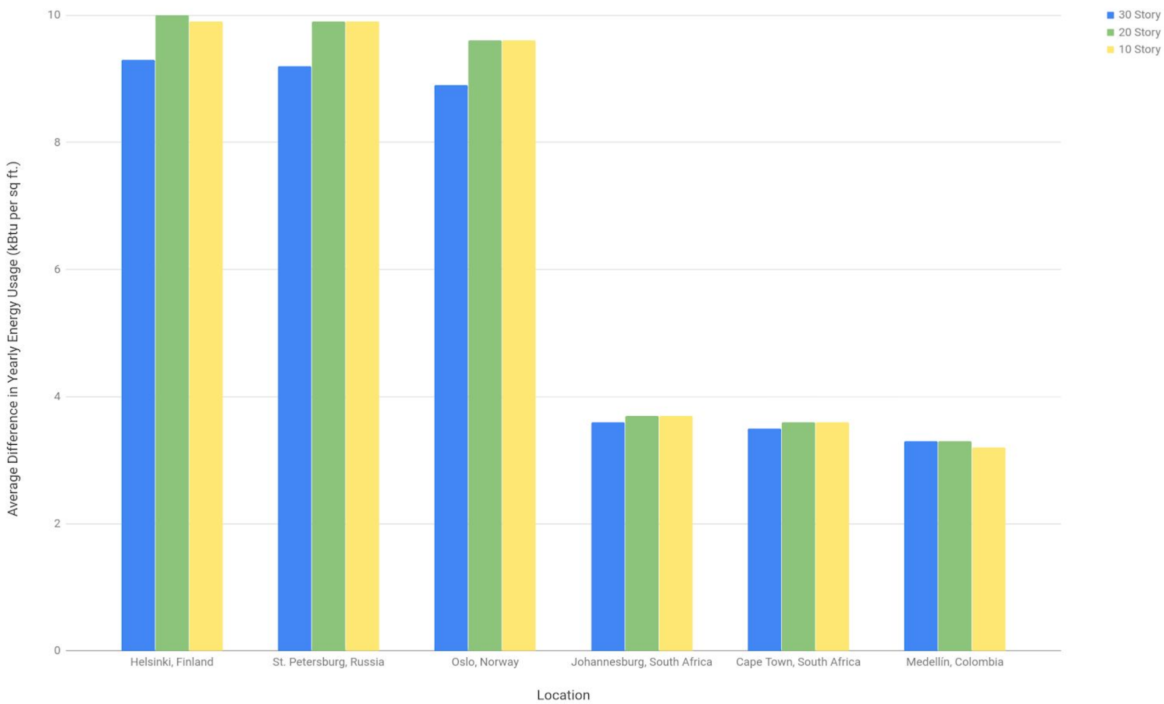

Figure 10. The effect of building size on energy savings for the top and bottom three cities. The graph depicts the three cities with the highest and lowest potential energy savings after calculating their difference in EUI with Double Low-E and Triple Low-E glass.

Afterward, the building's energy savings for each building size were averaged in each location. Figure 11 shows that replacing Double Low-E glass with Triple Low-E glass produced more energy savings than changing Single Clear glass to Double Clear Glass. This relationship was especially significant in the three cities with the lowest overall energy savings.

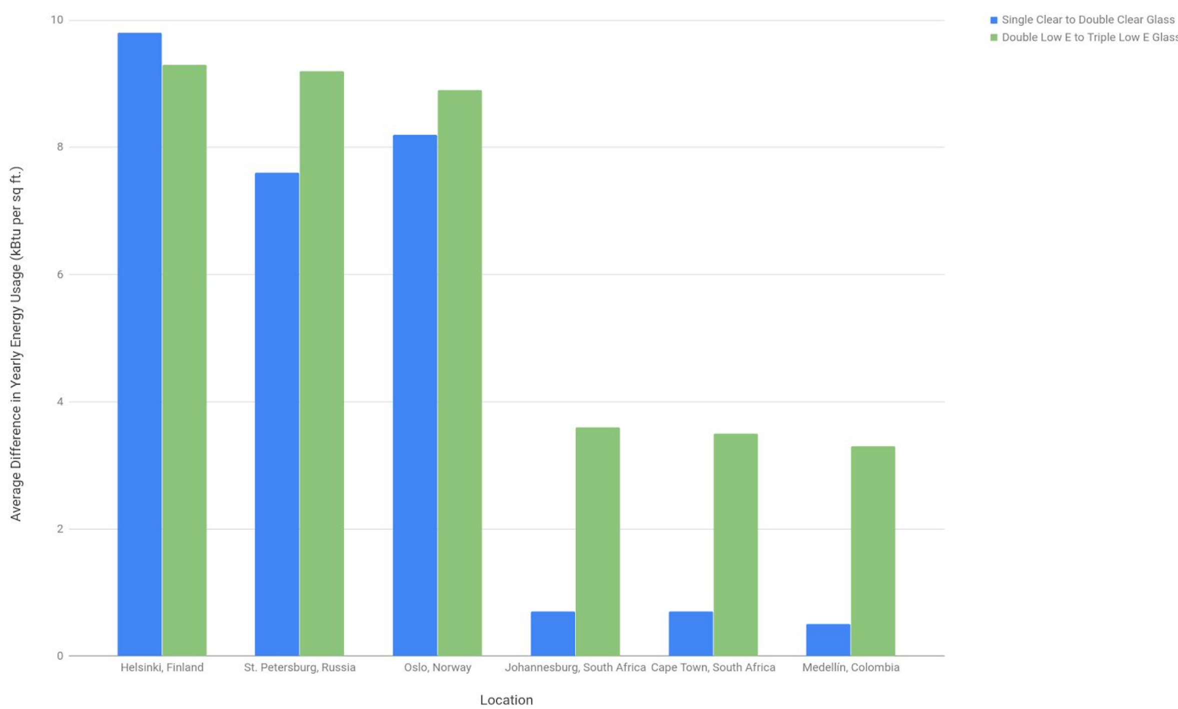

Figure 11. The effect of changing glass type on energy savings for the top and bottom three cities. The graph depicts the three cities with the highest and lowest potential energy savings and compares a building's energy savings between changing Single Clear to Double Clear glass and changing Double Low-E to Triple Low-E glass.

4.1. Building Latitude

The correlation between the latitude of the building's location and the building's EUI was then analyzed. For accuracy purposes, the latitude that was used for each location was the one provided by Revit when the location was identified. The latitudes used were actually of the weather stations within each city. Figure 12 showed a curved trend of EUI, however there was a weak relationship at latitudes beneath the equator. The only interpretations of this result were that either there were not enough cities analyzed in the Southern Hemisphere or buildings required more energy in areas with cold weather than warm weather.

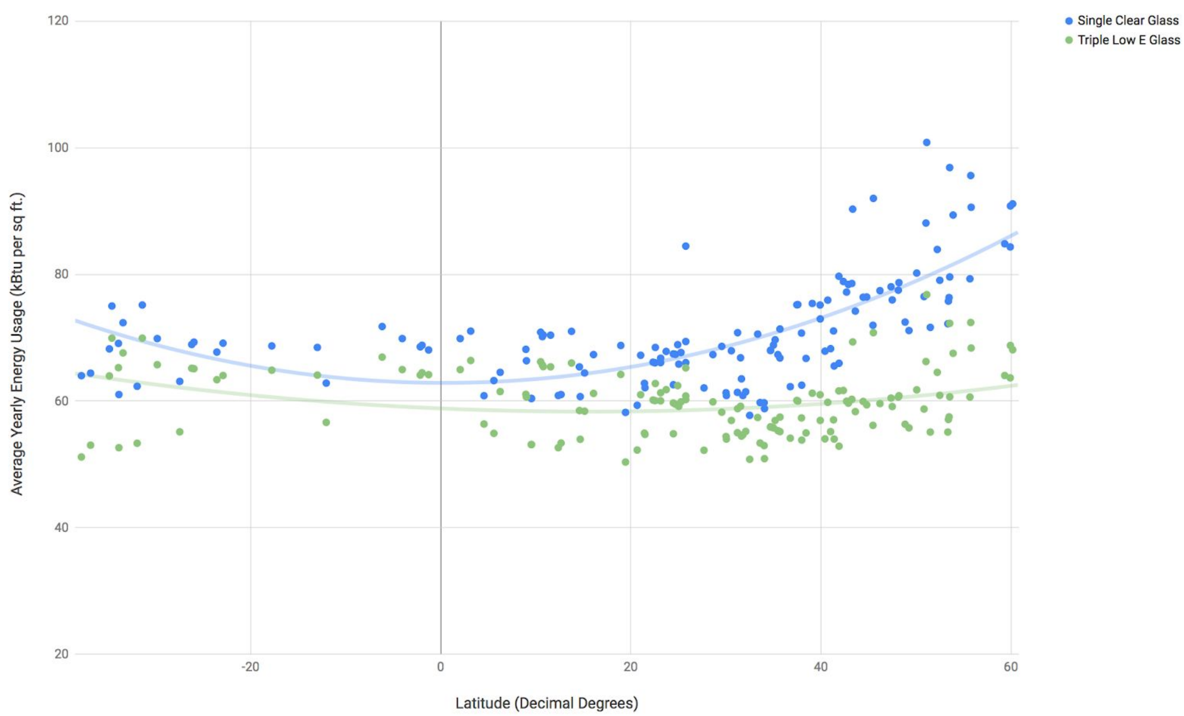

Figure 12. The effect of a building's latitude and glass type on its EUI. The 0 line represents the equator, at 0°, and the right half of the chart is the Northern Hemisphere, while the left half is the Southern Hemisphere. For each glass type, the data was derived by averaging the EUI across the different building sizes.

The relationship between the building location's latitude and yearly energy savings from using more thermally resistant glass was then observed (Figure 13). Compared to EUI, the effect of latitude on potential energy savings was much more dramatic. The graph also supported the relationship discovered in Figure 11. However, at about 53° N, the energy savings of using Double Clear glass instead of Single Clear Glass surpassed the energy savings of using Triple Low-E glass over Double Low-E glass.

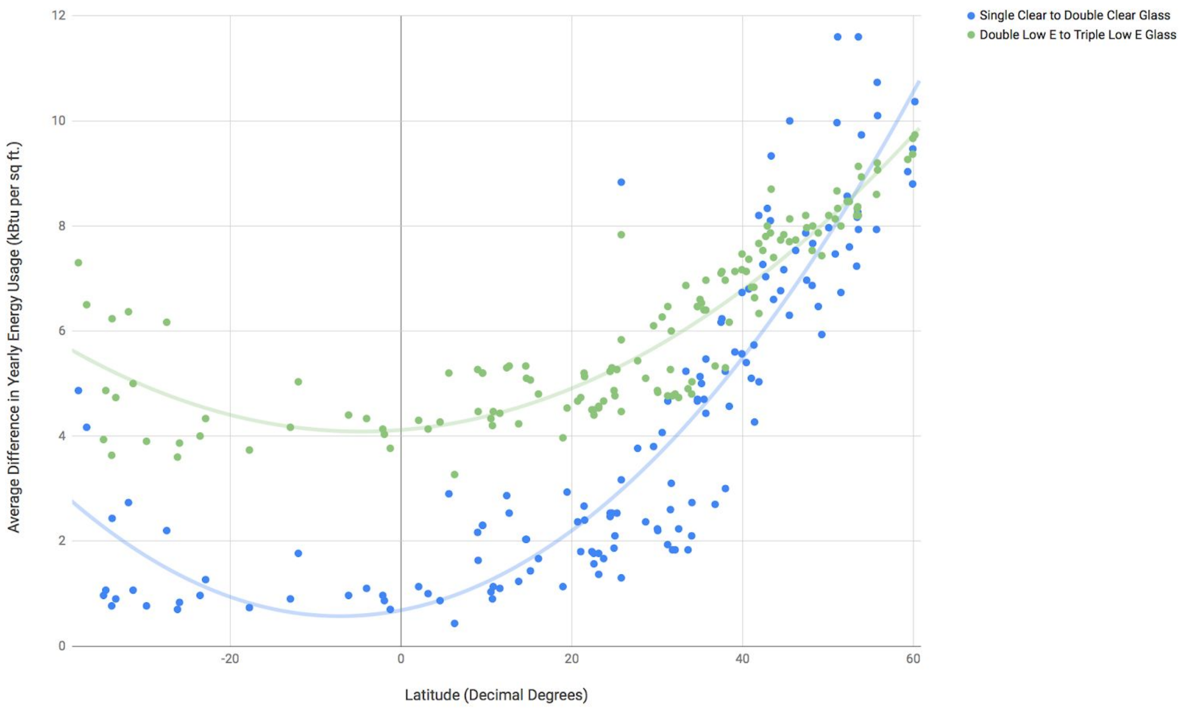

Figure 13. The effect of a building's latitude on its difference in EUI from implementing more thermally resistant glass. This data was generated from calculating the average difference in energy usage from using different glass types between the ten, twenty, and thirty story buildings for each location.

Finally, the correlation in Figure 9 was tested with all of the locations to determine if the relationship between building size and EUI was inverse in the Northern Hemisphere and direct in the Southern Hemisphere. Figure 14 shows that, for the most part, the larger building had a greater EUI until about 42° N.

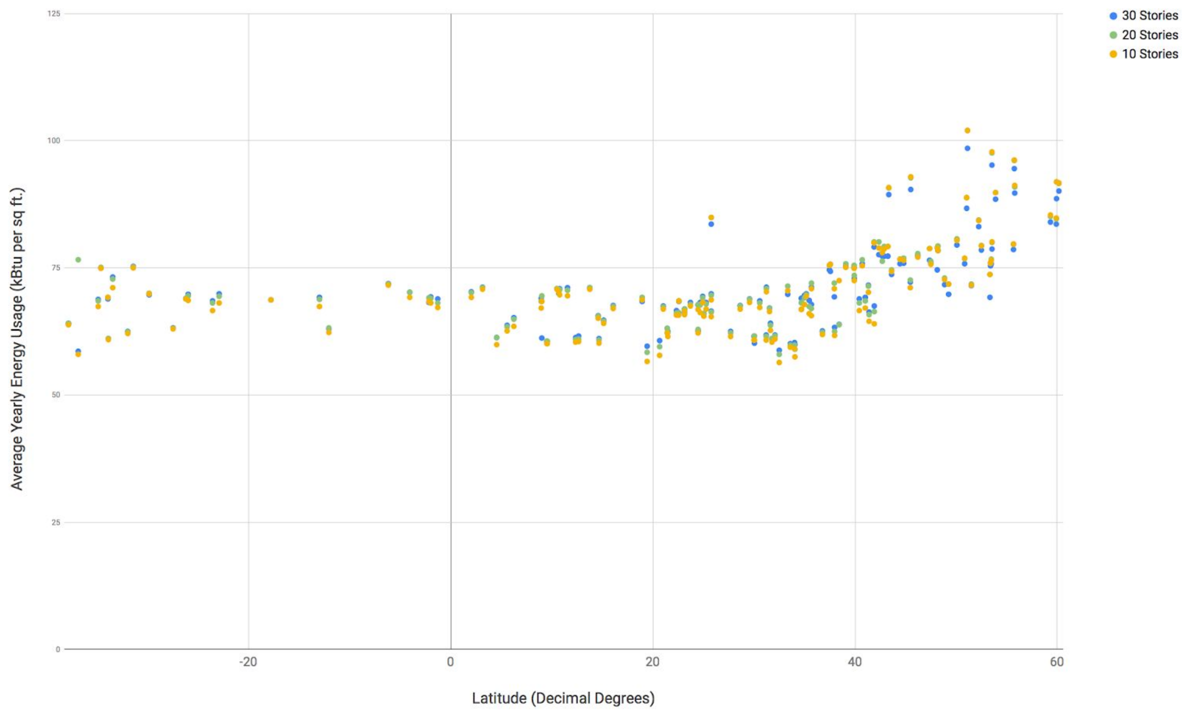

Figure 14. The effect of a building's latitude and size on its EUI. For each building size, the EUI of the building was averaged using the data of implementing each glass type.

5. Discussion

The results in this paper suggest multiple relationships between a building's glass type, size, and location on its EUI. First, Figures 5 and 6 show that buildings with Triple Low-E glass had less energy loads than buildings with Single Clear glass. This is supported by the fact that the more thermally resistant glass will block outdoor weather conditions from penetrating the inside of the building, thus maintaining occupant thermal comfort. Additionally, it was found that there was a higher potential for energy savings by using more thermally resistant glass in cities farther from the equator, especially in the Northern hemisphere (Figures 7 and 13). This makes sense because cities farther from the equator experience fluctuating temperatures and weather conditions. As a result, using thicker glass will have a greater effect in regions that have a greater range of weather or cold weather year-round. After comparing the effects of building glass type and size on EUI in Figure 8, there was a direct relationship between building size and EUI. Moreover, this did not support the hypothesis that smaller buildings would have a greater EUI. An explanation for this result could be that by adjusting the function of the spaces in the ten story building, the EUI was significantly reduced. However, in Figure 9, the three cities with the highest and lowest EUIs were compared. Nur-Sultan, Kazakhstan; Edmonton, Canada; and Moscow, Russia had the greatest EUI, and Los Angeles, United States; Tijuana, Mexico; and Mexico City, Mexico had the lowest. The graph suggested that the cities north of the equator supported the original hypothesis, while the cities in the southern hemisphere supported the findings in Figure 8. To test this relationship further, Figure 14 concludes that the hypothesis was unsupported until about 42° North of the equator. The locations with the highest and lowest potential for energy savings by replacing glass type were then observed in Figure 10. Helsinki, Finland, Saint Petersburg, Russia, and Oslo, Norway had the greatest potential for saving energy while Johannesburg, South Africa, Capetown, South Africa, and Medellín, Colombia had the lowest. The three cities with the highest energy saving potential also had the highest latitudes in the Northern Hemisphere, while the other three cities were some of the farthest from the equator in the Southern Hemisphere. Therefore, the latitude of the building significantly affected its energy saving potential, even more so than the building's EUI. Figures 12 and 13 supported this interpretation, as the line of best fit was much more curved when comparing latitude and energy savings. One possible reason is that using a more thermally resistant glass will be effective in almost any location to save energy. However, the impact of using thicker glass will be much greater in cities farther from the equator because it will impede the various weather conditions. In Figure 11, it was clear, especially in the cities South of the equator, that the change from Double Low-E to Triple Low-E glass will save more energy than the change from Single Clear to Double Clear glass. This was also supported in Figure 13, where there was a greater gap between the blue and green data points left of the 0° line. Also, at about 53° N, the energy savings of using Double Clear glass over Single Clear glass surpassed the energy savings of using Triple Low-E glass instead of Double Low-E glass. An explanation for this is that using triple pane glass will greatly reduce a building's EUI, however, in extremely cold regions, just changing single pane glass to double pane glass had a greater effect.

6. Conclusions

With the increase in attention to sustainability (Chegut, Eichholtz, & Kok, 2013), conducting energy analyses during the conceptual design stage is important for selecting optimal building components and creating highly energy efficient buildings (Nguyen & Amoah, 2019). This study tested the relationships between a typical office building's glass type, size, and location on its energy unit intensity (EUI). Using the Building Information Modeling (BIM) software, Autodesk Revit, a building was modeled with three variations: ten, twenty, and thirty stories. Then, the usage of each space was identified to understand their energy loads. In the ten story building, the function of some rooms was changed to match the building's needs. The three building files were duplicated 141 times for each location. In each file, the city was identified and an energy model was generated, which was exported to Autodesk Insight. After choosing between Single Clear, Double Clear, Double Low-E, and Triple Low-E glass, the yearly EUI was recorded. Following the collection of data, the difference in EUI was calculated between implementing Double Clear instead of Single Clear glass and Triple Low-E rather than Double Low-E glass.

The results of the study supported that using more thermally resistant glass will reduce a building's EUI. They also suggested that buildings in cities of higher latitudes will have a greater EUI. Additionally, a building in a coastal city will have a smaller EUI than if it were located inland. This study found a curved relationship between a building's latitude and energy saving potential in using more thermally resistant glass, which was stronger than the correlation between latitude and annual EUI. Based on the results of this research, the hypothesis was incorrect, and larger buildings have greater EUI's. However, the hypothesis correctly described buildings above the latitude of 42° N. The data may not have supported the hypothesis because of the adjustments made to the ten story building's room functions.

The research also found that a building in Nur-Sultan, Kazakhstan; Edmonton, Canada; or Moscow, Russia had the greatest energy unit intensity and a building in Los Angeles, United States; Tijuana, Mexico; and Mexico City, Mexico had the lowest. After analyzing the difference in EUI from changing glass type, Helsinki, Finland; Saint Petersburg, Russia; and Oslo, Norway had the highest energy saving potential. A building in Johannesburg, South Africa; Capetown, South Africa; or Medellín, Colombia will save the least energy from using more thermally resistant glass. Another discovery was that replacing Double Low-E with Triple Low-E glass saved more energy than changing Single Clear for Double Clear glass, especially for a building that was further South of the equator. This relationship was concluded to be consistent until about 53° N.

This study used BIM software to test different variables on an office building's energy unit intensity. However, it was limited in scope, in that it did not consider the building's energy cost because of the price fluctuation and purchasing power in various parts of the world. While an individual building was simulated (with three variations), future research can generate an urban building energy model (UBEM) for each city to more accurately predict a building's energy usage through the building's proximity to surrounding buildings. For example, shadows from adjacent buildings can impact the intensity of sunlight on the building, affecting the energy needed to maintain occupant thermal comfort. The findings in this paper can be used by building professionals and government officials to optimize energy savings in buildings throughout different cities. Because 141 cities from around the globe were included in this study, other cities can consider the results for improving the energy efficiency of their buildings. Overall, the implementation of these findings can lead to a decrease in energy used in cities, contributing to a reduction in the need for resources and diminished carbon emissions.

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