STUDYING WINDOW ENERGY PERFORMANCE USING THERMAL CAMERA

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Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Windows, which are responsible for 45% of overall heat loss, play a major role in a building's energy performance. Therefore, it is critical to measure window energy performance for existing buildings. This study aimed to evaluate the energy performance of windows to determine if replacement of windows is necessary. The evaluation was based on window location, height, orientation, and weather condition in a high-rise residential building. A thermal camera was used for measurements and statistical analyses were performed for measured data. Analysis results showed different performance of each side and floor of the building with a significant difference at the 0.05 level due to various temperatures, wind speeds, and directions. This study suggests using more efficient windows on upper floors, particularly from the fourth floor and above is beneficial as well as considering dominant wind speed and direction for the best configuration of window design.

ACKNOWLEDGMENTS

I owe everything in my life including where I am now and this accomplishment to my God. Thanks, my dear God for such a blessing.

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At last but not least important, I owe more than thanks to my lovely husband, Ali, who always put my happiness and success in his priority. He not also motivated me in hard situations but also tried to help me to overcome any difficulties. I owe my success and confidence to him

who always says you deserve the bests. Ali, this accomplishment would not have been possible without you. I love you.

DEDICATION

To my kind husband, Ali who leads and supports me in all my steps, and my parents that whom their unyielding and unconditional love, support, and encouragement have inspired me to pursue my dreams.

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1. INTRODUCTION

1.1. Background

The building sector plays a significant role in energy consumption, responsible for 30-40% of energy use in the world (Lior 2012). On the other hand, buildings are responsible for about 36-38% of overall CO_2 emission (Ahmad et al. 2014). Therefore, reducing energy consumption will not only decrease the energy cost of buildings but also reduce the potential harm to the environment. To reduce the energy consumption of a building, it requires studying a variety of effective factors including building structure and characteristics, weather conditions, occupancy, and their behavior (Zhao and Magoulès 2012) as well as building locations (Zhang et al., 2013). Additionally, H. Kim et al., (2011) believed that the energy performance of the building is based on all components of the building: lighting, HVAC system, controls, envelope, and equipment. According to Grynning et al (2013), among building components, windows are the most significant components, which are responsible for 45% of overall heat loss in buildings (as a comparison, it is 8% for walls, 8% for roof, 9% for floor, 11% for thermal bridges, and 19% for air leakage). Further, windows account for 40% of overall cooling and heating loads of a building (U.S. Department of Energy, 2012). The stricter fenestration regulations of Florida, in energy provisions of their Building Code, mentioned the importance of windows in building energy consumption as well (Zeng et al., 2017). Therefore, optimizing the windows, as one of the main sources of energy loss, by considering the condition and features of a building as well as the area and localization of windows (Grynning et al., 2013) would have a big contribution to energy efficiency in buildings.

In order to optimize window energy performance in buildings, accurate and comprehensive assessments are necessary. Many studies have been conducted about assessing and optimizing the different types of windows' energy performance (Aydin, 2006; Buratti & Moretti, 2012; Huang et al., 2014; Jonsson & Roos, 2010; Nielsen et al., 2000; Zeng et al., 2017). The results of these studies suggested simulating, calculating, or measuring as the approaches to assess the energy performance of windows. A literature review revealed that simulation is the most common approach in window studies. However, the measurement approach is the most accurate approach to assess window energy performance. In addition, the usefulness of the measurement approach has been determined not only for existing buildings but also for new buildings as benchmarks.

1.2. Problem statement

Even though simulation and computation-based methods are more common for studying windows energy assessment, the accuracy and credibility of these methods can be weak in comparison with the measurement method, which deals with real-life conditions. Furthermore, the accuracy rate of data and results of studies for the measurement methods are more acceptable. The collected data and results of the measurement tools can be used not only for assessing the energy performance of an existing building's windows as well as window designing of new buildings. However, there are only a few studies that used measurement methods and none of them considered the best design and configuration of windows for a building. Due to the lack of precise studies in this area, comprehensive and detailed studies are required to determine an applicable and accurate measurement tool for this approach. Therefore, this study has considered all or any of the different variable factors and conditions such as window types, orientation, weather, and location for windows energy performance assessment regardless the method, in order to provide an implementable measurement method to determine if different windows are necessary to improve building energy performance. Developing a measurement approach for windows energy performance will improve applicable knowledge on building energy consumption that may yield better design and configuration of windows to reduce energy loss.

1.3. Objectives

This study hypothesized that the weather condition including air temperature, wind speed and direction, and windows' location including orientation, and height have a significant effect on window energy performance. To assess this hypothesis, the following research objectives have been conducted through this study.

1) Determine the best assessment method by reviewing various assessment methods of windows energy performance
2) Perform ANOVA analysis and post-hoc test to determine whether wind direction, speed, windows' direction, and located height affect window energy performance significantly or not.
3) Address effect of potential various factors on windows thermal performance
4) Assess the limitations of using a thermal camera as a measurement approach

1.4. Organization of the thesis

This thesis is divided into six chapters, and three appendixes to provide and meet the required information on the aforementioned objectives. Chapter 1 offers a comprehensive introduction, background, and the general scope of this research. Chapter 2 presents a summary of the methodology used for the current study. Chapter 3 includes a comprehensive literature review by addressing the available methodologies, advantages, and weaknesses of the previously used methodologies on the assessment of the window energy performance. Chapter 4 presents a case study to address the specific objectives of the current study. To do so, a high-rise building was selected and thermal information of the windows at four different sides and four floors were obtained at three-studied dates. In this chapter, a thermal camera was utilized to measure the windows' temperature. Statistical analysis was performed to understand the effect of weather condition, direction, and location of the windows on measured thermal value. Therefore, the results of this study are presented in Chapter 5. In the end, in Chapter 6, the conclusion and summary of the work are provided as well as limitations and recommendations regarding future research topics. A list of references used for the current study is presented at the end of the thesis.

2. METHODOLOGY

Energy consumption and efficiency are some of the important topics in almost all industries these days, and construction and buildings are not exceptional from that. Therefore, in order to pursue this importance, studies related to building energy performance have been reviewed. The methodology used for the current study is summarized as a flow chart in figure 2.1.

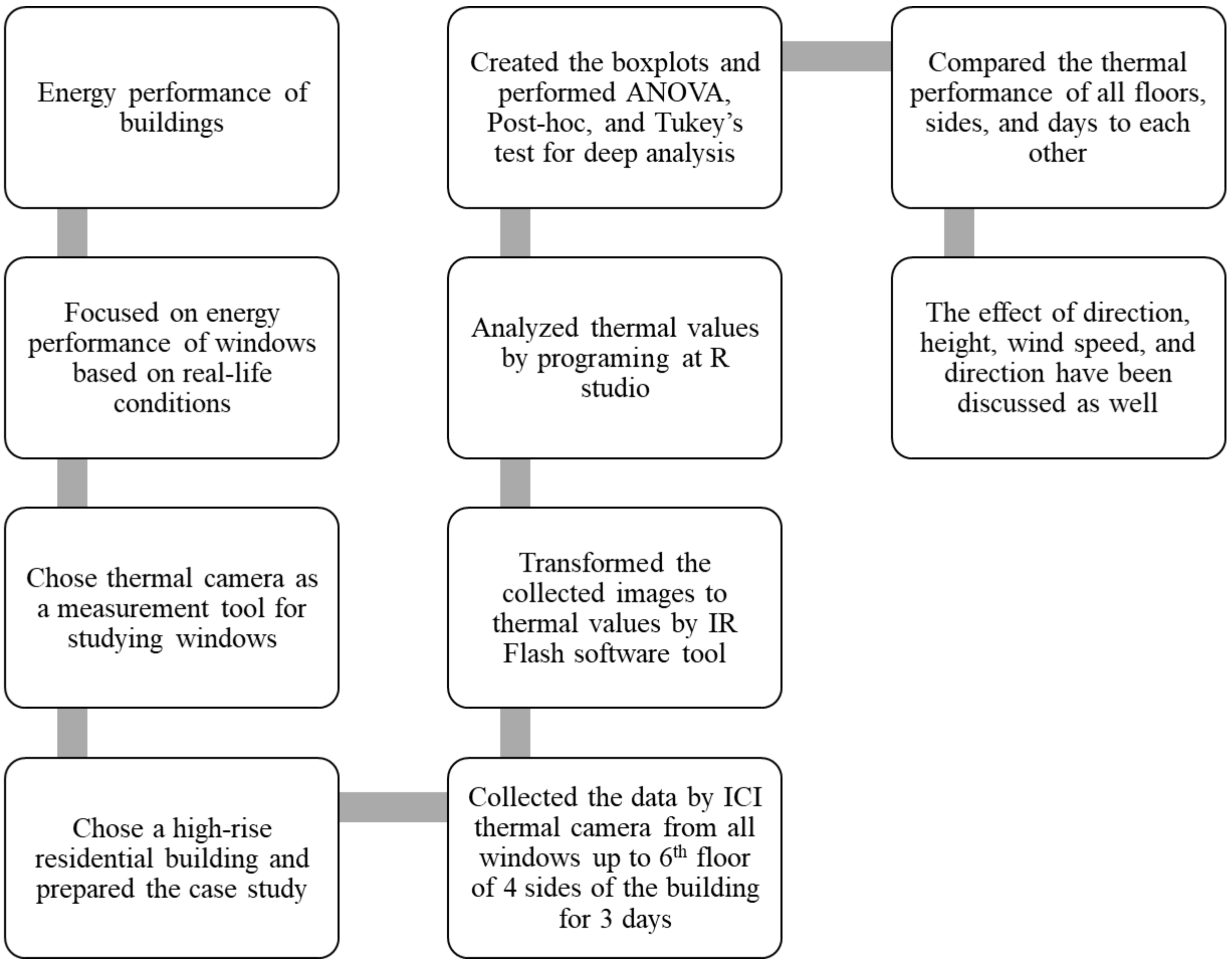

Figure 2.1. A summary flow chart of methodology.

A literature review of more detailed studies about window energy performance and their assessment method has been prepared, and different studies have been categorized in different groups. Reviewed literature is discussed with details later in the literature review section.

The literature review has three steps. First, review literature about the energy performance of buildings that includes components, features, and conditions effect. Second, review literature with keywords pertains to any kind of windows or glazing energy assessment as well as other references suggested by these papers. Third, review literature that has been done to assess windows desirable essential. In summary, a lack of measurement approach and tools in evaluating window energy performance was identified. To address the lack of measurement, thermal camera, which is one of the most common and useful detector tools in construction and has a higher accuracy rate than heat flowmeter, was selected to study window thermal performance of a building.

2.1. Study site and measurement

For a case study, a high-rise residential building was chosen, which is Thompson Hall, located at the North Dakota State University (NDSU) main campus. The building has 9 floors and 32 windows in each East and West sides and 48 windows in each North and South sides

An ICI infrared camera with a spectral sensitivity of 7 μm to 14 μm and accuracy of ±1 °C was used to capture the thermal images. Due to harsh weather condition and flight regulation, a 9 m pole was used to hold the camera instead of using a lifter or drone. Due to students' privacy and concerns, the imaging had to be done during winter break. Therefore, three study days including December 21, 22, and 23 of 2019 were chosen for data collection.

With an assistant of NDSU facilities, all rooms' temperature was set at 20 °C (68 °F) at least 24 hours before data collection dates when the outside temperature was predicted to be less than 0 °C. Besides, we asked the facility to close all curtains and remove any objectives from windows during the time of data collection. However, we observed that some of the windows remained blind by curtains and some rooms had lights on which were excluded from final data analysis.

2.2. Data collection

Imaging was started at 6 a.m. every day before sunrise to prevent the possible reflection and errors caused by sunbeams and reflection from surrounding objects of the building. Further, to reduce the possibility of reflection on the glass during a thermographic survey, several images have been taken at different viewing angles of 5°- 60° (0° is perpendicular). In addition, to achieve the actual temperature from apparent temperature measured by a thermal camera, black foam board was used to calibrate the camera.

The proper location for the camera for all sides was determined to be about 27 m (90 ft) away from the surface of the building to have consistency between data of all sides of the building. After finding the proper location on each side, more than 15 pictures were taken from each side of the building in different angles, raging 5°- 60° every day in order to have enough replicates.

2.3. Data processing

From all collected images for each side of the building during each day of data collection, three images that were covered all windows and had proper angles were picked. In order to transform the raw images to thermal values, the IR Flash software tool (Infrared Cameras Inc., Beaumont, TX) was used, and an Excel file was exported for each window, which means more than 20 Excel files have been produced for each picture. So, to analyze the collected data as well as performing the statistical analysis, and R program was developed in R Studio (Version 1.2.5033). After removing invalid data such windows with blind curtain or light on have been removed from the data set, the average, maximum, minimum, and standard deviation of all exported files for each window were obtained. Besides, the “ggplot2” package was used for plotting, and various boxplots were created for each side, day, and floor of the building in order to compare the trend of temperature changes. ANOVA model was performed to understand the effect of different factors. Tukey’s post-hoc test with a 95% confidence level was used in R using “Agricole” package to reveal the interaction effect of various factors and differences between various factors in terms of measured thermal values.

3. LITERATURE REVIEW

The literature review section includes three steps: (1) review of the studies on building energy performance, including any of components, features, and conditions; (2) review of windows or glazing (e.g. thermographic, Low-E) energy assessments; and (3) further review of essential studies for windows-related assessments (e.g. simulation, thermographic) that have been conducted. The detailed review methodology is illustrated in Figure 3.1.

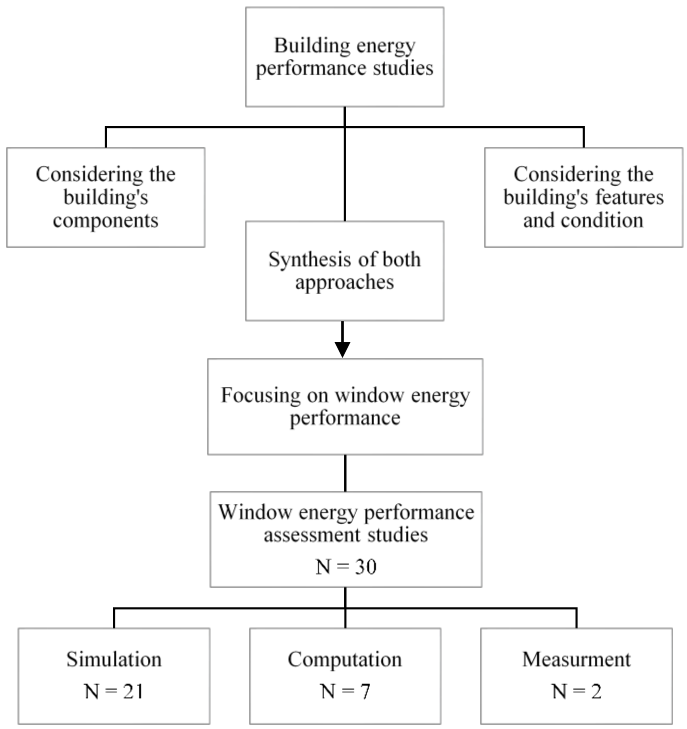

Figure 3.1. Flow chart of the review methodology and number of approaches (N) that have been used for assessing the thermal performance of a group of windows.

The studies of building energy consumption can be divided into three groups:

(1) Studying the overall effect of different factors on building energy performance such as building characteristics, weather condition, and building's orientation. For example, Abanda & Byers (2016) assessed the effect of orientation on energy consumption of a small building by Building Information Modeling (BIM);

(2) Studying the energy performance of building components individually, such as wall, roof, windows, control system, HVAC system, and insulation. For example, Buratti and Moretti (2012) studied the performance of innovative glazing systems with silica aerogel;

(3) A synthesis of the two approaches above, in which components of the building are studied with considering the features of the buildings. For example, Jonsson & Roos (2010) studied four mechanisms of switchable electrochromic windows considering the occupancy of the room, daytime usage, lower need for cooling and heating, and limiting the perpendicular component of solar radiation. Zeng et al. (2017) introduced photonic crystals glazing (PCG) as the most energy-efficient system for decreasing cooling and heating loads compared to other glazing systems considering the weather. El Fouih et al., (2012) studied the performance of a heat recovery ventilation (HRV) system based on cooling, heating, and primary energy consumption for diverse climatic zones in both commercial and residential buildings.

3.1. Windows assessment methods

Table 3.1 shows a summary of past and current window energy consumption assessment methods. According to the literature review, which will be discussed later in this chapter, the most frequently used window assessment method is simulation, along with two infrequently used methods, computational (numerical) and measurement. For the current review, each of these methods has been reviewed for their accuracy, efficiency, limitations, advantages, disadvantages, and potential sources of errors. The simulation focuses on analyzing the windows by designing different models based on variable factors including building features, location, and climate

(Jonsson & Roos, 2010; Saeli et al., 2010; Zeng et al., 2017). For the Computation-based method, models are created by applying variable factors and building features to calculations or diagrams (Arici et al., 2015; Aydin, 2006; Grynning et al., 2013; Nielsen et al., 2000). In comparison to these two approaches, the Measurement method collects real data by focusing on a real project (Buratti & Moretti, 2012). Each of these three methods is discussed further below.

Table 3.1. Summary of past and current methods for consumption assessment of window energy.

Objectives	Methods		
	Simulation[1]	Computation[2]	Measurement[3]
One/Different configurations of a window	13	4	2
Different types of windows	11	4	
Window's size/ratio to wall	5	1	
Window's frame	2	1	
Plan size/type	3	1	
Climate	8	2	
Orientation	14	1	
Latitude and/or location	3		
Daylight and/or solar radiation	6	2	1
Occupants comfort		2	1
Comparing methods for accuracy purpose		2	

3.1.1. Simulation

The simulation methodology has been widely used to study the energy performance of different types of windows, to optimize potentials, and to assess the effect of climate and

[1] Jonsson & Roos, 2010; Huang et al., 2014; Tian et al., 2010; Van Den Bossche etal., 2015; Zeng et al., 2017; Saeli et al., 2010; Kim et al., 2016; Ochoa et al., 2012; Alwetaishi, 2019; Tsikaloudaki et al., 2012; Gasparella et al., 2011; Poirazis et al., 2008; Bojic et al., 2002; Singh & Garg, 2009; Sadrzadehrafiei et al., 2011; Yaşar & Kalfa, 2012; Persson et al., 2006; Tavares et al., 2014; Fasi & Budaiwi, 2015; Yao & Zhu, 2012; Zhang et al., 2016.

[2] Nielsen et al., 2000; Grynning et al., 2013; Arici et al., 2015; Aydin, 2006; Menzies & Wherrett, 2005 (partly); Karlsson et al., 2001; Chaiyapinunt et al., 2005.

[3] Buratti & Moretti, 2012; Menzies & Wherrett, 2005 (partly); Hammarberg & Roos, 2003

orientation on their performance (Huang et al., 2014; Jonsson & Roos, 2010; S. Kim et al., 2016; Saeli et al., 2010; Tian et al., 2010; Van Den Bossche et al., 2015; Zeng et al., 2017). For simulation purposes, a model of any existing or new building can be created using simulation software, in which windows can be considered with all building's conditions and features. Different scenarios can be created by changing conditions and features of the windows for further studies (S. Kim et al. 2016). For example, Jonsson & Roos (2010) studied four control mechanisms by combining either solar control or Low-E glazing with electrochromic windows considering the occupancy of the room, daytime usage, lower need for cooling and heating, and limiting the perpendicular component of solar radiation. Saeli et al. (2010) compared the energy savings made by thermochromic glazing coatings to standard products for different climates. Zeng et al. (2017) introduced photonic crystals glazing (PCG) as the most energy efficient glazing system for decreasing cooling and heating loads. Huang et al. (2014) evaluated the impacts of latitudes and orientation on the windows' performance and their cost-effectiveness in cold climates by a series of simulation studies. Van Den Bossche et al. (2015) identified typical approaches to improve the thermal performance of several kinds of window frames such as wooden, aluminum, and vinyl frames. Tian et al. (2010) prepared a window energy rating system for office buildings by considering the daylight and thermal performance. Sadrzadehrafiei et al. (2011) evaluate the energy performance of advanced glazing in a mid-rise office building in Malaysia. S. Kim et al., (2016) studied the impact of windows' size, orientation, and position on their energy performance by creating 65 different design scenarios.

3.1.2. Computation

A computation method involves computation-based rating systems to evaluate the energy performance of windows (Arici et al., 2015; Aydin, 2006; Grynning et al., 2013; Nielsen et al., 2000a). Different researchers used the computation method to assess the window energy performance and each used different approaches to achieve their goal. For instance, Grynning et al. (2013) introduced the different types of computation-based rating systems such as Danish, Spanish, Italian, and Canadian methods. Arici et al. (2015) studied heat transfer of three different windows with two, three, and four panels by continuity, momentum, and energy equations considering different outdoor temperatures and different gap widths of panels for both excluding and including radiative heat transfer. Aydin (2006) studied a double panel window's conjugate heat transfer by using a finite difference technique for four different climates in order to identify the optimum air layer thickness between the panels. Nielsen et al. (2000) produced diagrams of windows' energy performance by heat loss and solar gain equations based on the g-value, the U-value, the tilt, and the orientation.

3.1.3. Measurement

Measurement is a rarely used method in window studies. This methodology requires a precise tool to measure the real data of windows energy performance. For example, Buratti and Moretti (2012) studied four samples of innovative glazing systems with silica aerogel. The study was conducted using a spectrophotometer to measure the optical properties and measured real data were used to calculate the energetic and luminous parameters.

3.1.3.1. Thermal camera

Infrared cameras are one of the most common and useful tools in construction to detect deficiencies in a different part of the construction buildings. More importantly, the infrared thermography technique (IRT) has become popular in construction and buildings to identify thermal irregularities since 1987 (Balaras and Argiriou 2002). According to Dall'O' et al. (2012), the accuracy of the infrared thermography technique (ITT) is higher than the heat flowmeter method.

Thermography and thermal camera have been widely used for different purposes as well as construction engineering and building thermal performance. For instance, in order to identify the subsurface structural deficiencies, Clark et al. (2003) found the failure point of a concrete bridge in the UK by thermographic analysis. Lucchi (2018) believes the thermal camera is one of the useful methods to study the thermal characterization of glazing and windows. Ariwoola et al. (2016) identified some diverse insulation defects of campus buildings' envelop using Fluke TI25 infrared hand-held camera and an ArduCopter 3DR Hexa-C drone. Mauriello and Froehlich (2014) generated the 3D reconstruction and discovered poor insulation and heat leakage of a building of Maryland university in a time-efficiently manner using a FLIR e4 camera and Parrot AR. Drone 2.0. Krawczyk et al. (2015) used multirotor hexacopter UAV with an IR camera to study the thermal performance of a new detached house. Marino et al. (2017) obtained the external and internal surface temperatures of the building's facades by infrared thermography to measure the heat loss through the envelope of the building. They showed that the air boundary layers' thermal resistances vary during the day, and it's also, greater than the suggested value by local regulation. Lehmann et al. (2013) quantified the influence of parameters such as solar irradiation, wind, air and sky temperature, emissivity, and thermal transmittance (U-value) on the evaluation of thermal images by a numerical study. They determined that the minimum climatic history is needed to accurately interpret the thermal images.

According to Fox et al. (2014) and Fox et al. (2016) to study the buildings thermal performance, there can be two approaches: active thermography, which inspects building defects closely and focuses on analyzing the detail areas, and passive or statistic thermography, which examine unknown defects to realize the location of the problem. Due to the important role of windows in a building energy performance and lack of measurement approaches in windows assessment studies, active thermography can be considered as a practical tool to study the thermal performance of windows, quantitively.

3.2. Summary

The simulation method is the most commonly used for assessing the energy performance of windows. The application of computation-based methods for window assessment is less frequently used. These two approaches can be used to quickly analyze the performance of windows. Further, it will be possible to study different scenarios based on different conditions and design and determine the most energy-efficient configuration using these two approaches (S. Kim et al., 2016; Ryan & Sanquist, 2012). However, one of the major problems of using these methods for energy performance assessment is the lack of comprehensive and detailed verification and validation. Even when validated models have been designed specifically for idealized cases, real-life conditions may be excluded (Ryan & Sanquist, 2012). Grynning et al. (2013) showed that the results of three different rating methods, including simulation and computation-based method, did not agree regarding the energy performance of windows. Therefore, despite the advantages of simulation and computation-based methods, the credibility and accuracy of the results can be weak (Wang et al., 2012).

On the other hand, the measurement method is a rarely used approach for a window energy assessment. The accuracy and credibility of the data and results can be more reliable since it includes real-life conditions. Lee et al. (2007) believed simulation or computation-based methods are the only choices for new buildings, and measurement is only proper for existing building energy analysis. However, energy measurement quantification of building components such as windows can be used for new buildings as well. For example, measured data of the energy performance of an existing building's windows can be considered in designing any new building's windows, which has a very similar condition and features such as climate and location with an existing building. That way, the data and results of the existing building energy assessment can be used as a benchmark for new buildings in that area, which would be reliable. To achieve a suitable window configuration considering the performance and cost in a building, it is better to perform a techno-economic evaluation because, according to, the performances and quantities of windows are proportional to the costs Hee et al. (2015).

According to the reviewed literature, the measurement method is not very common, and it requires broader studies for developing further methods as well as determining more accurate and applicable measurement tools. In addition, none of the past studies discussed the possibility of using different configurations of windows in a building according to the weather condition, windows direction, and height. Studying the impact of the building features and conditions on window energy performance, based on real data and projects, is important and worth investigation. Therefore, the current study was conducted to understand the impact of windows' directions and height on energy performance and assess the potential factors that may affect window energy performance.

4. FIELD MEASUREMENT AND DATA ANALYSIS

4.1. Project site description

To pursue the mentioned objectives, a thermographic survey was planned. The goal of this survey was to observe the thermal behavior of a building's windows based on their location, height, orientation, and weather condition by using a thermal camera and provide an optional configuration based on the results. This building had to be a high-rise residential building due to its occupant's uniformity. To this aim, Thompson Hall at North Dakota State University (NDSU) was chosen (Figure 4.1), which has 9 floors and 32 windows in each East and West sides and 48 windows in each North and South sides, and it's located on the NDSU main campus in Fargo, North Dakota. North Dakota has a continental climate with low humidity, and nearly continuous wind (Niaghi, Jia, Steele, et al. 2019). Images were collected for windows of four sides of the building. Windows of this building are consisting of two separates frames permanently interlocked by a Termo-barrier. (Table 4.1).

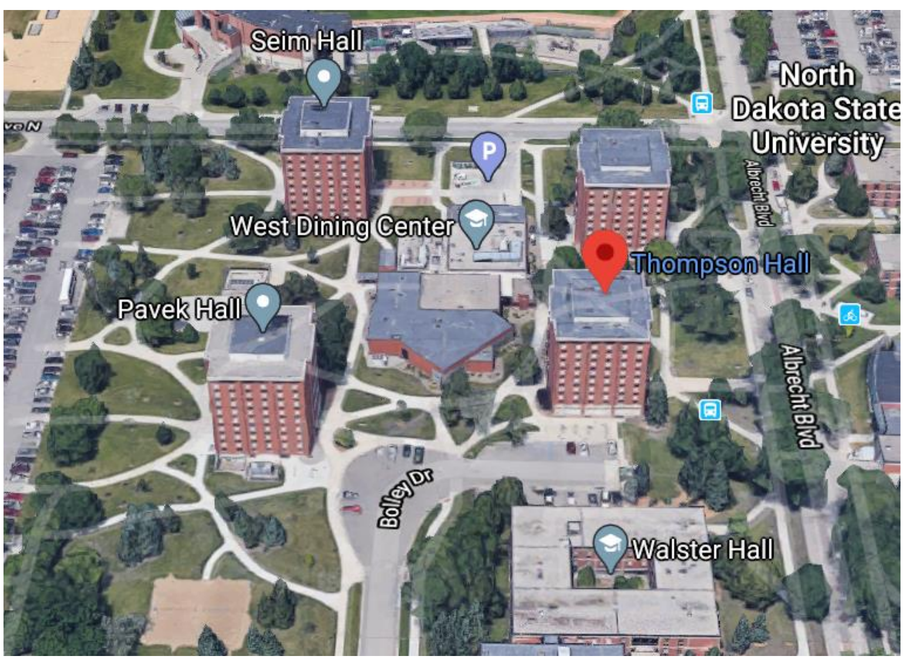

Figure 4.1. Thompson Hall, Fargo, ND (source: google map).

Table 4.1. Parameters of Case Study project (Design guidelines and specification of Thompson Hall).

Case study project	Thompson Hall
Built date	1965-1966
Windows	Architectural Window/AW class, NAFS-08
	Fixed
	Sash
	Screen
	Frame: Aluminum
Glazing	DSB sheet glass set in vinyl glazing channel
Size of window	4' x 5'(1.21 m x 1.52 m)

4.2. Measuring equipment

The equipment used in this research were:

1) ICI infrared camera with a spectral sensitivity of 7 μm to 14 μm and accuracy of ±1 ℃ (Table 4.2)
2) A black foam board to measure the emissivity of the surface, calibrate the camera, and measure the actual temperature of the windows (Dall'O' et al. 2013; Marino et al. 2017);
3) A measuring tape to measure the camera-object distance;
4) 2" PVC pipe to hold the board in each image, and;
5) A 9 m (30 ft) pole to attach the camera and raise it to the desired height.

Table 4.2. Technical specifications of the infrared camera used for this research.

Characteristics	Description
Name	ICI 9640
Detector Array	UFPA (VOx)
Pixel Pitch	17 µm
Pixel Resolution	640x480
Spectral Band	7 µm to 14 µm
Thermal Sensitivity (NETD)	< 0.02 °C at 30 °C (20 mK)
Frame Rate	30 Hz P-Series
Dynamic Range	14-bit
Temperature Range	-40 °C to 140 °C
Operation Range	-40 °C to 80 °C
Storage Range	-40 °C to 70 °C
Accuracy	± 1 °C
Pixel Operability	> 99 %
	75 G Shock / 4 G Vibration
Dimensions (without lens)	34 x 30 x 34 mm (H x W x D ± .5 mm)
Power	< 1 W
Weight (without lens)	37 g
	USB 2.0 for Power & Data
	Built-in Shutter
	Aluminum Enclosure

4.3. Weather condition

According to the guidebook of FLIR Systems (2011), to detect missing heat, the temperature difference between the outside and the inside of the building should be at least 10 °C.

So, late fall was the closest best time to apply this criterion easily. In addition, since taking images might disrupt the students' privacy, the imaging was done during winter break. Therefore, December 21, 22, and 23 of 2019 were chosen as dates to collect the data. The information about these days' weather conditions is provided in Table 4.3. The reason for choosing three days to collect the data was to have more consistency and accuracy in the results by increasing the number of samples for statistical analysis.

Table 4.3. Weather information for studied dates (Source: NDAWN, Fargo, ND).

Day	Air Temp (ºC)	Air Temp at 9 m (ºC)	Wind Chill (ºC)	Wind Speed (m/s)	Wind Speed at 10 m (m/s)	Wind Direction (degree)
Saturday, Dec. 21, 2019	-8.7	-8.5	-14.5	2.9	3.4	158
Sunday, Dec. 22, 2019	-3.1	-2.7	-8.7	4.1	4.7	169.6
Monday, Dec. 23, 2019	-5.6	-5.4	-11.3	3.6	4.2	14.5

Wind affects the air pressure distribution on building surfaces, which controls the heat loss. Air movement is an important cause of energy loss from buildings. For instance, variation in overall surface heat transmission between high velocities (13.4 m/s) and very low velocities (1.3 m/s) is of the order of 30% for single pane glass (Arens and Williams, 1977). Thus, wind can cause about 10% of the total heat transfer to the environment (Arens and Williams, 1977). For wind speed of 2 m/s, Tijani (2014) showed that the convection heat loss contributes 64% of total heat loss across the glass envelope whereas radiation contributes 36% of the total heat loss. In the current study, wind directions of studied dates obtained from NDAWN (https://ndawn.ndsu.nodak.edu/) weather station located at NDSU main campus for three-studied dates and are shown in Figure 4.2. In addition to the wind direction and speed, the shape of the building and its orientation to the wind strongly influence the wind velocities and flow characteristics in its vicinity and effect wind-flow pattern along each wall (Figure 4.3).

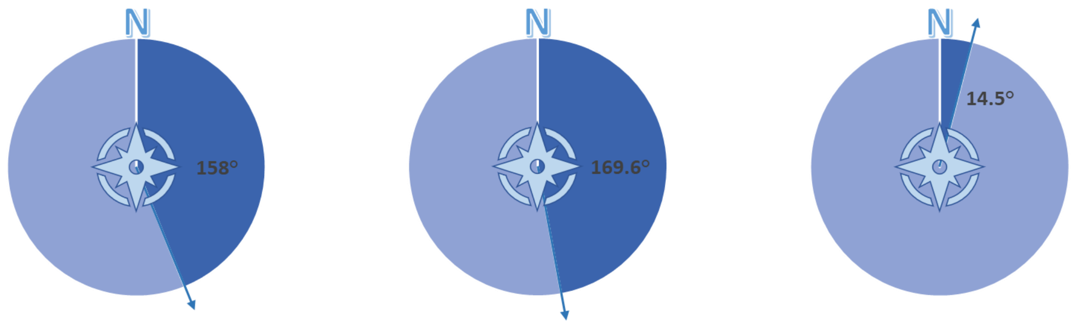

Figure 4.2. Wind direction – from left to right: December 21, December 22, and December 23, respectively.

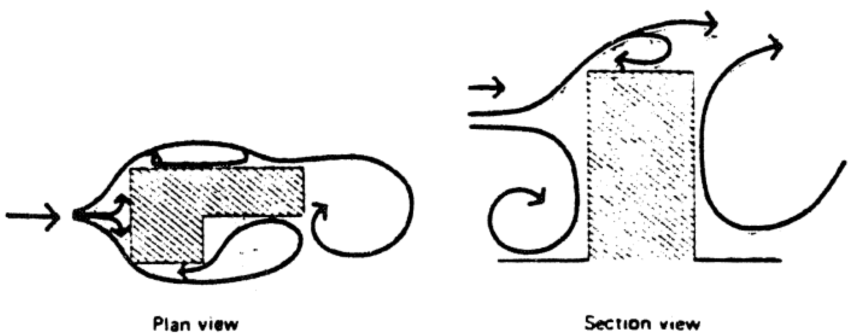

Figure 4.3. Air turbulence around the building (Arens and Williams, 1977).

4.4. Measurement criteria and procedure

The study required the temperature of all rooms to be set of the same temperature at least 24 hours prior to data collection. Besides, based on Thermal Imaging Guidebook, when using a thermal imaging camera to find irregularities in the building's thermal performance, the preferred difference in temperature between the inside of the building and the outside should be at least 10 °C. To follow this criterion, we asked the NDSU's facilities to set the temperature of all rooms at 20 °C (68 °F) at least 24 hours before data collection dates, when the outside temperature was predicted to be less than 0 °C (Table 4.3). In addition, to have an equilibrium room temperature, all windows should not be blocked by a curtain or any other object during the time of data collection. However, we observed that some of the windows remained blind by curtains and some rooms had lights on, which were excluded from final data analysis.

In order to achieve enough height to capture proper images, a drone, a lifter, and a pole were discussed as alternatives. However, using drone and lifter was not considered because of the drone flight regulation on the safety issue and weather condition (below 0 ^{o}C). Thus, a long pole was used to raise the camera to about 9 m (30 ft) high, which only allowed to capture thermal information of windows up to the 6th floor (including 5 rows of windows). Windows that were blocked by trees were not considered in analyses.

In order to have lower outdoor temperature and avoid direct radiation of the sun, Ariwoola et al. (2016) collected all infrared images early in the morning. According to FLIR Systems (2011), early morning is the preferred time to avoid sun reflection in cases the studied surfaces are highly reflective like glazing. Therefore, imaging for the current study was started at 6 a.m. every day, before sunrise, to prevent the possible reflection and errors caused by sunbeams and reflection from surrounding structures of the building. Surrounding structures of the building with different temperatures can have a reflection on the glass, which can be a source of error in thermal images and results. To reduce the possibility of reflection on the glass during a thermographic survey, a viewing angle of 5°- 60° (0° is perpendicular) is recommended as shown in figure 4.5 (FLIR Systems 2011). In order to avoid objects' reflection on glazed surfaces, Marino et al. (2017) suggested testing different angles ranging from 0° to 30° during thermal imaging. Therefore, a viewing angle of 5-60^{o} was used in the current study.

The infrared camera measures the effect of temperature, not the temperature. So, it's apparent temperature, which is the temperature value reported by the infrared camera. To make the results more comprehensible, the goal is to make the apparent temperature closer or equal to the actual temperature. To determine the actual temperature, we need to know the emissivity of the surface. To calibrate the camera and measure the reflected apparent temperature, Ariwoola et al. (2016) and Dall'O' et al. (2013) mounted a piece of black tape and aluminum foil near the target area. Then, by setting the emissivity of the black surface as 1, it would be easy to have an approximate actual temperature of the surface. Toward that end, the first step was fixing the blackboard on each side of the building in a way that it can be captured in each picture properly. Due to the harsh weather condition and the building's limitation, it was not possible to stick the blackboard on each side of the building. Instead, a 2" PVC was used to hold the blackboard for each side during imaging time. Meanwhile, the camera, which was fixed on the 9 m (30 ft) pole, was set in a proper location. The proper location was determined to be about 27 m (90 ft) away from the building (Figure 4.4) for each side to have consistency between data of all sides of the building. More than fifteen images were taken from each side of the building in different angles, raging 5°- 60° (Figure 4.5), for each studied date in order to have enough replicates for accurate data analysis.

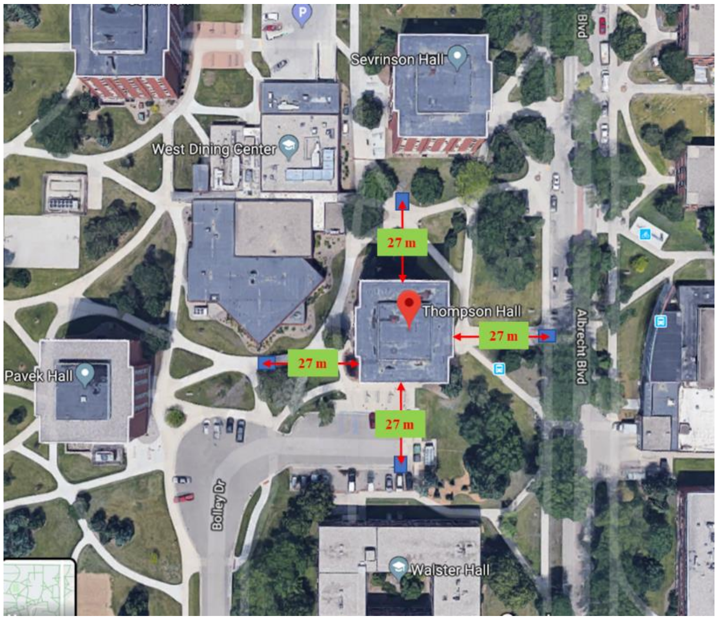

Figure 4.4. Map of the building and approximate camera locations (Source: Google Maps).

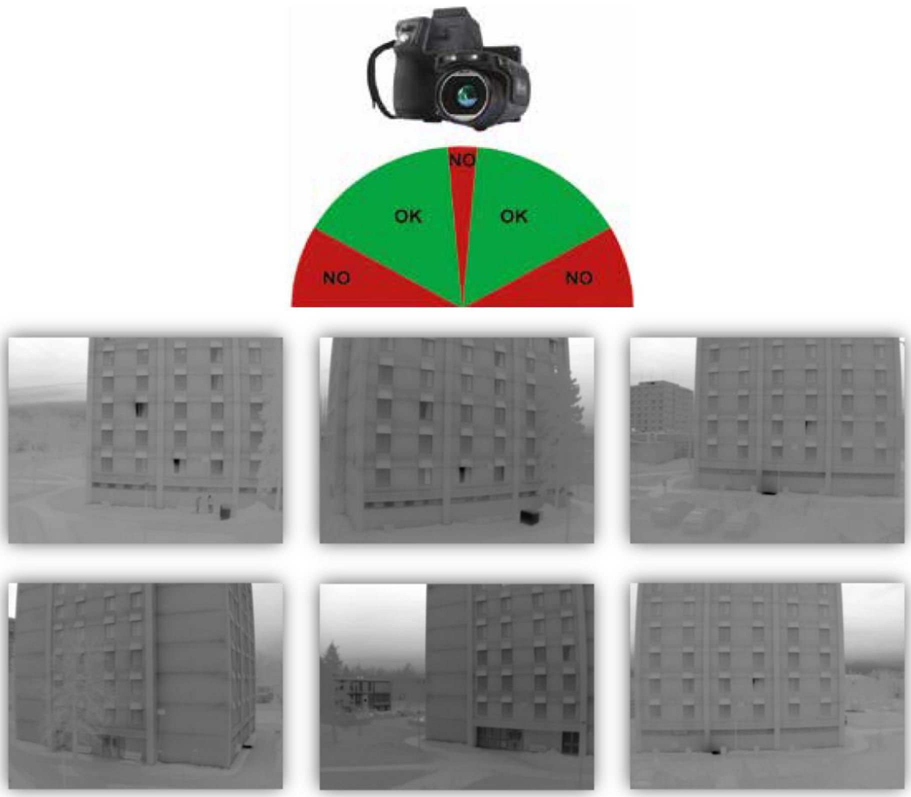

Figure 4.5. Recommended angle for thermographic inspections of reflective surfaces (FLIR Systems 2011) and images that have been taken from the study site.

4.5. Thermal images processing

Determining the temperature based upon infrared emission is related to the object that emits the energy. Surfaces with higher temperature emit a lot of infrared energy where low-temperature objects emit less infrared energy.

The emissivity is defined as the percent of infrared energy emitted by an object at any given temperature as compared to the theoretically perfect amount of infrared energy emitted by an object at the same temperature (Becker and Zhao-Liang Li 1995). The emissivity range from 0 to 1.0. In practice, the emissivity value of an object is influenced by the material, surface condition, and reflectivity (Avdelidis and Moropoulou 2003). This variability makes the temperature measurement complex. An object that emits the theoretically perfect amount of infrared energy at any given temperature is called a blackbody, which is a perfect emitter. When an infrared thermometer is manufactured it is calibrated against a blackbody emitter. In the current study, the camera was recalibrated on-site to make sure the collected data from the windows are accurate. Hence, to correct the emissivity of the measured images, from the IR Flash software toolset, a box shape was selected on the black body and the emissivity of the black body corrected to 1.

Three proper images were picked out of collected images for each side of the building and each data collection dates. The IR Flash software tool (Infrared Cameras Inc., Beaumont, TX) was used to transform the raw images to thermal values for each image. A box shape was selected and drawn for each window of the selected image, and temperature information of the window was exported as an Excel file that included temperature values of the image as a matric value for each 4 cm by 4 cm pixel of a window (Figure 4.6).

Figure 4.6. Thermal image of East side of the Thompson Hall – December 21.

Even though all six floors, which include five rows of target windows, had been asked to not be blind with curtains, some of the windows were still blind with curtains as well as most of the windows on the sixth floor with few rooms had lights on. Therefore, all sixth floor's windows and windows with either blind curtain or light have been removed from the analyzed data. In addition, the condition of the West side was not proper to get accurate data since the building was blocked by a tree; thus, the number windows used from the West side was reduced significantly in order to keep the valid data. For detailed analysis and conclusion, the West side has not been considered. However, this side has not been ignored in analyzing the average of days to have more consistency in the overall results. Besides, some removed windows' data including floor 6 have been discussed later in the dissertation to show the impact light, reflection, and curtain on the data. To process the exported Excel data from IR Flash software, analyze data, and create figures, an R program was developed in R Studio (Version 1.2.5033). The Excel file for each window from IR Flash software was imported to the R program using the "Readxl" package. The average, maximum, minimum, and standard deviation of all exported files for each window were obtained. In addition, the "ggplot2" package was used for plotting, and various boxplots were created for each side, day, and floor of the building in order to compare the trend of temperature changes. Subsequently, this boxplot made it possible to compare the temperature changes trend among floors, sides of the building, and study dates as well. In order to understand a combined effect of orientation, day, and height of the window on measured temperatures using the thermal camera, an ANOVA model was performed. To perform the ANOVA model for each day, the orientation of the building and floor and correlation between orientation and floor were considered. To build a model for all three-study dates, the day variable was added to the previously developed model. Although ANOVA is a powerful and useful parametric approach to analyze approximate normal distributed data with more than two groups, it does not provide any deeper insights into patterns or comparisons between specific groups. After a multivariate test, it is often desired to know more about the specific groups to find out if they are significantly different or similar. This step after the analysis is referred to as 'post-hoc analysis' and is a major step in hypothesis testing. One common and popular method of post-hoc analysis is Tukey's Test. Tukey's test compares the means of all treatments to the mean of every other treatment and is considered the best available method in cases when confidence intervals are desired or if sample sizes are unequal. Therefore, Tukey's multiple comparisons of means with a 95% family-wise confidence level were developed in R using Agricole package.

5. RESULTS AND DISCUSSION

5.1. Effect of blind curtain and light reflection

In any kind of thermal performance study, light and reflection cause errors in the results. To show the effect of light reflection and the blind curtain on the collected data, unfiltered data is discussed. However, having a blind curtain can be a case study itself to see the effect of the curtain on saving energy. Figure 5.1 shows the East side of the Thompson hall including the RGB image, thermal image, and boxplot for the collected thermal values on December 21, 2019. The window that had a blind curtain is shown by an orange box. The sixth floor, which also had a blind curtain, is shown with a blue box. The boxplot of measured thermal values from each window clearly shows the effect of the blind curtain for the specific floor compared to the rest of the windows in the same row. The highlighted boxplot is belonging to the 4th window of the 3rd floor (left to right), which not only had a blind curtain but also was reflecting the outside light on the glass. Therefore, the boxplot of measured thermal value shows a higher standard deviation comparing to other windows.

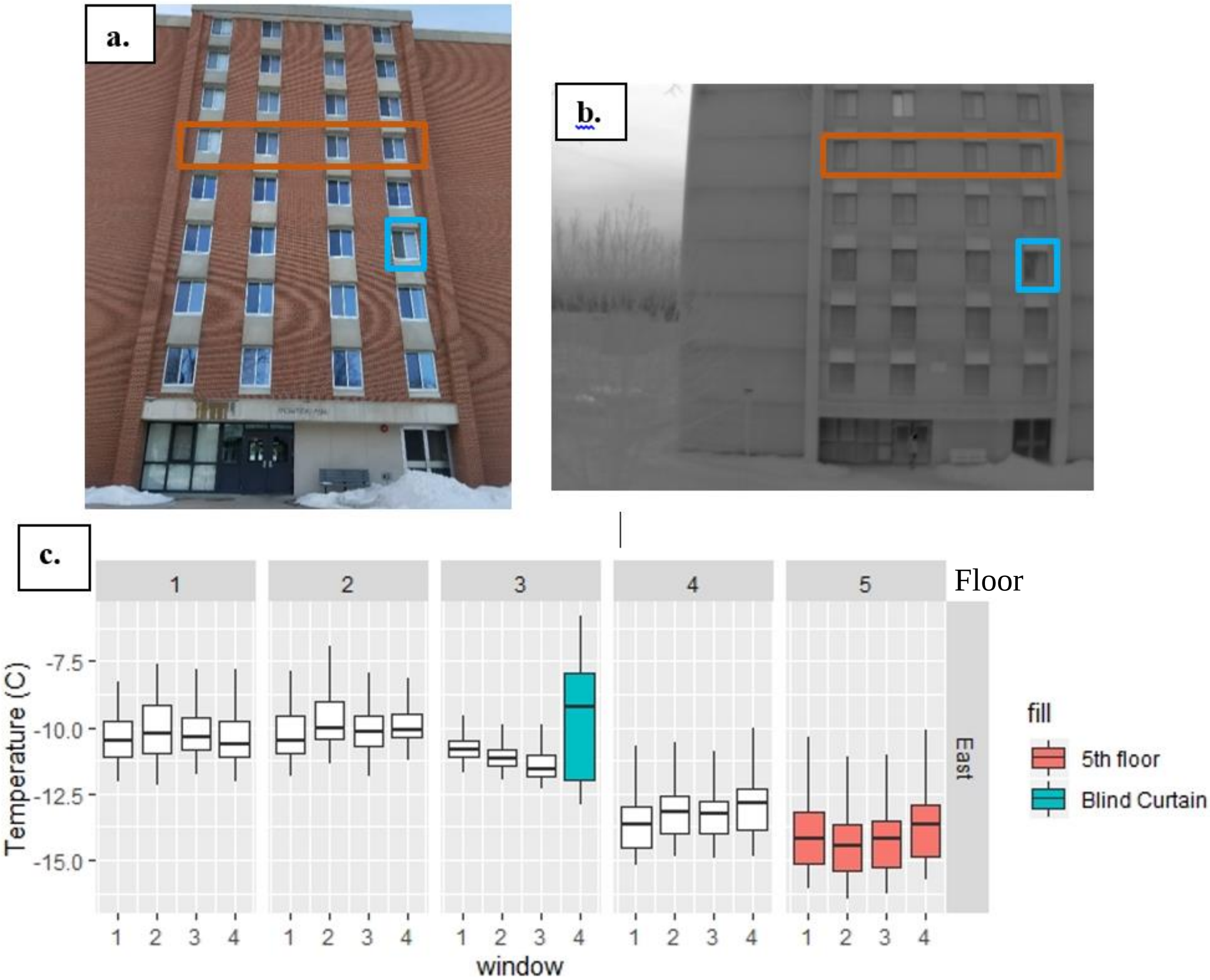

Figure 5.1. a) RGB image, b) thermal image, and c) boxplot of each window temperature range for each measured row for the East side of the building on December 21 (windows numbered from left to right).

Figure 5.2 shows the South side of the building including RGB and thermal images. The boxplot shows the variation of the measured temperature for each window. As shown in figure 5.2, the effect of the light bulb inside the room, blind curtain, and object, which acts as a curtain, is detectable. Comparing with other measured windows for the same row, the windows that had curtain or light on showed the highest range of temperature. In some cases, an anomaly in data was detected when the curtain was partially closed or window partially blocked by some object.

Hence, these anomalies were excluded from the final analysis. For the East side of the building, the curtain was blind for the fifth floor and above.

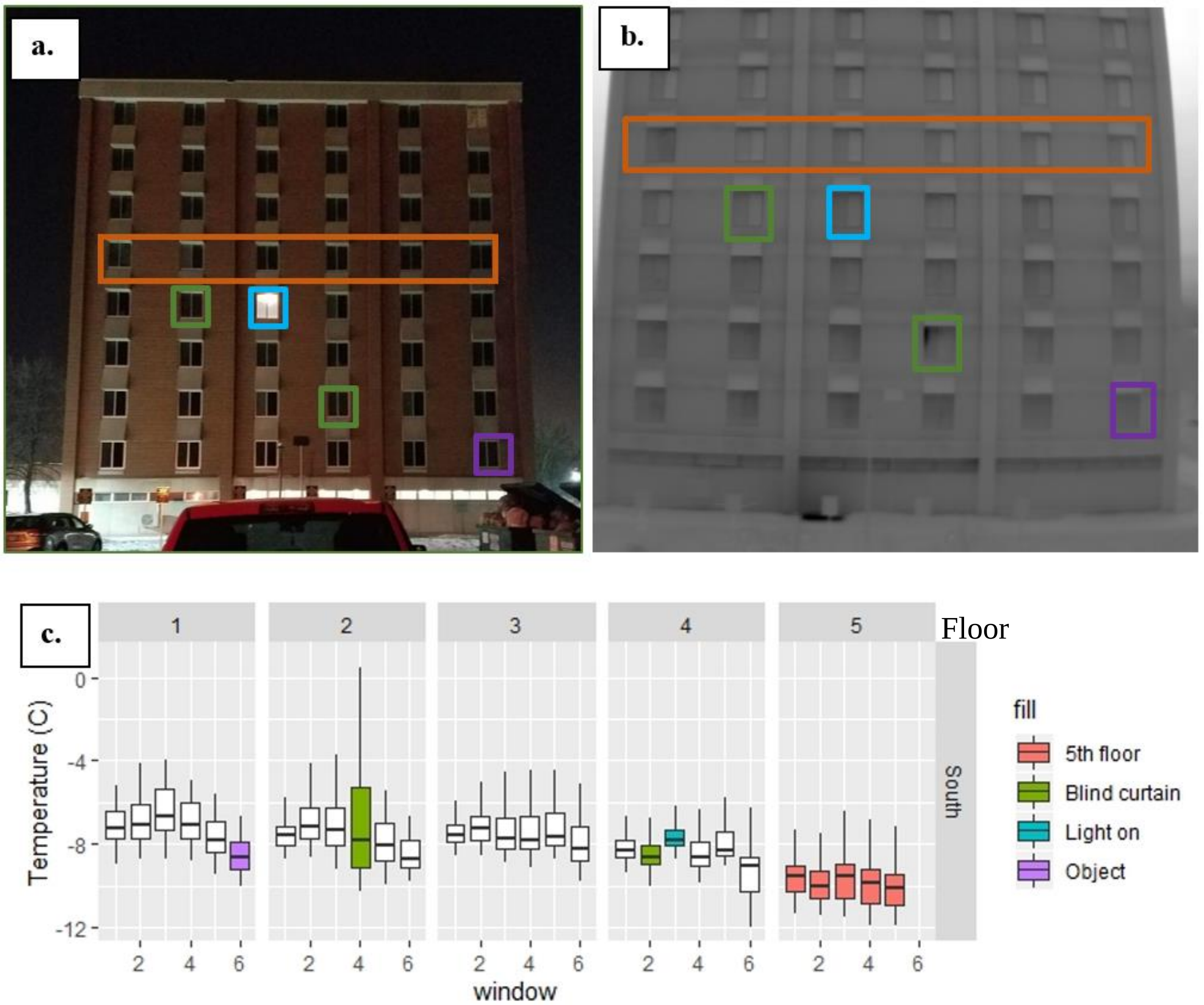

Figure 5.2. a) RGB image, b) thermal image, and c) boxplot of each window temperature range for each measured row for the South side of the building on December 21 (windows numbered from left to right).

Figure 5.3 shows the North side of the building for December 22 including RGB image, thermal image, and boxplot for each window of each row. Since the tree blocked the right side of the building on the North side, only four windows were selected. On the other hand, the air temperature was warmer than the other two studied dates, and the range of measured temperature was higher than that for the other two days. Boxplots show the effect of blind curtain and light bulb inside the room in which increased the standard deviation or changed trend of measured data for each specific row (floor) of windows. In figure 5.3.a, the reflection of landscape light blocked the view of the second window of the second row (floor). The effect of this object was removed by changing the angle of the image capturing and neglecting the effect of light on the windows' reflection. For future works, it would be recommended to avoid any surrounding reflection.

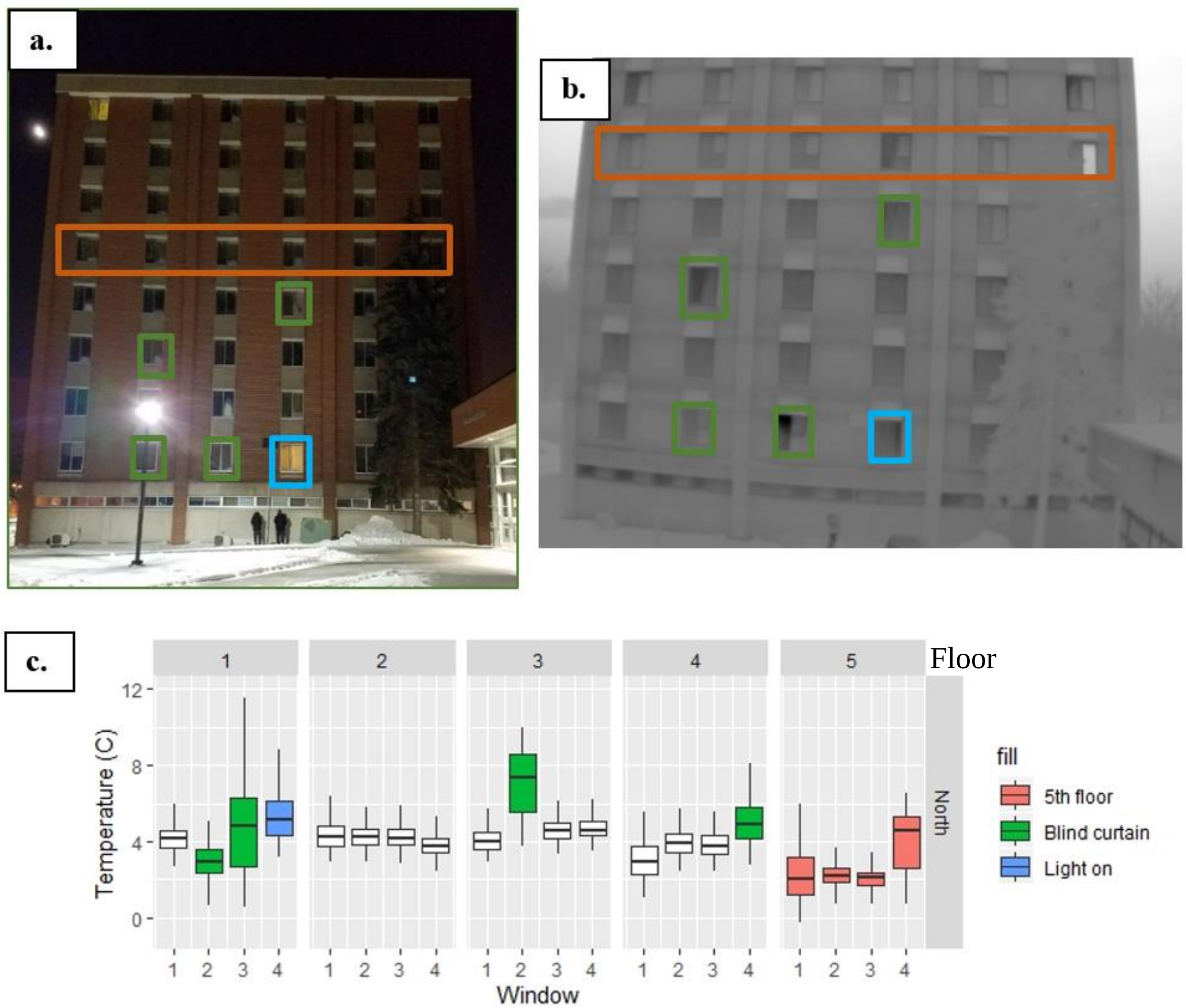

Figure 5.3. a) RGB image, b) thermal image, and c) boxplot of each window temperature range for each measured row for the North side of the building on December 22 (windows numbered from left to right).

5.2. Day-by-day comparison

Day by day analysis was performed to understand each day's variation and effect of building orientation and height on measured temperature. The windows with blind curtain, light on, and any blocking object were excluded from the final dataset. Figure 5.4 shows boxplots for each side of the building. This figure shows the average temperature of all windows on each floor of each side of the building on December 21. Despite the insignificant increments and decrements in the average temperature of windows between subsequent floors, there is a significant temperature decrement comparing the first and fourth row of windows. Even though the average air temperature increased from -8.7 to -8.5 °C above 9 m height, the wind speed increased 0.5 m/s at 10 m of the ground according to the weather information (Table 4.3). Therefore, the reason behind the decreasing average temperature of windows can be due to increment in wind speed above 10 m of the ground. The boxplot for all windows measured values is shown on Appendix B1.

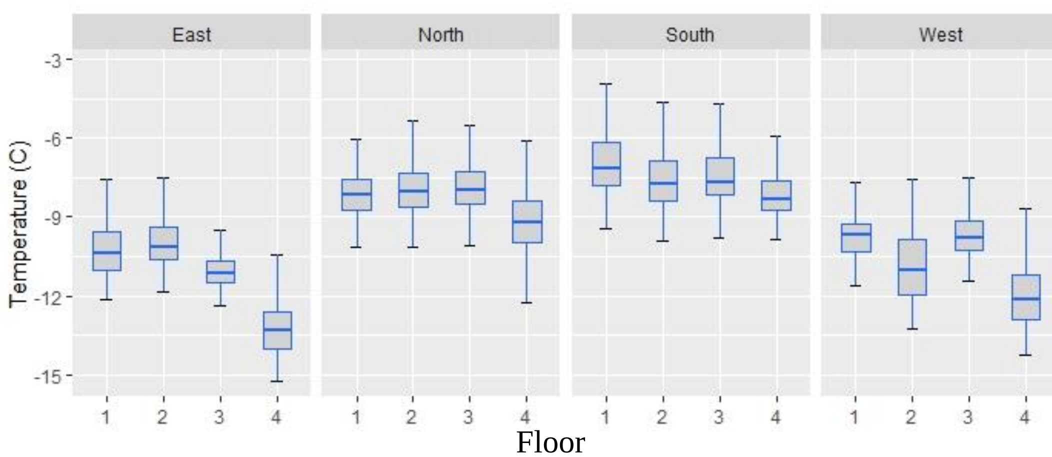

Figure 5.4. The average temperature of all windows for each row of windows on different floors for four sides of the building on December 21.

The wind direction (158 degrees) was from the Northwest on December 21 and the South side of the building was the only side that was not faced directly or partially to the wind. The wind chill was recorded as -14.5 ^{o}C, which caused to have a lower range of temperatures for all sides except the South. Moving from the first floor to the upper floors, the temperature decreased. This trend was either smooth for some sides such as the South, which was protected from the wind direction, or sudden such as other sides that were affected by the wind. Table 5.1 shows the result of the ANOVA test for the measured temperature by considering the floor, side of the building, and relationship of floor and side that affect measured temperature. As shown in the table, the floor and side of the building had a significant effect on the windows' temperature. For both factors, the P-value was less than 0.05 that indicates a significant impact on the measured temperature. Results show a significant impact of each independent variable as well as the interaction between independent variables. The result of residual distribution passed the normality test and is shown on Appendix A1.

Table 5.1. Result of ANOVA model for windows temperature for December 21.

Factors	Df	Sum Sq	Mean Sq	F value	P-value	Significant
Floor	3	28725	9575	7655	<2e-16	Yes
Side	3	91941	30647	24501	<2e-16	Yes
Floor: Side	9	7630	848	678	<2e-16	Yes
Residuals	37000	46281	1			

Due to the significant effect of the floor and side of the building as independent factors on the measured temperature, the result of the post-hoc test for each independent factor is discussed. The result of the interaction effect is reported on Appendix C, Table C1. Table 5.2 shows the statistical description for within-group analysis and the result of the post-hoc test of the measured temperature for each side of the building on December 21. The obtained average values for each side shows that the South side had the highest temperature compared to the other three sides of the building. The standard deviation of the measured temperature for each side is in the same range, which indicates that no outlier remained on the final dataset. The result of the post-hoc test indicates that despite the standard deviation of the average temperature for all four sides of the building was in the same range, there was a significant difference between all four sides of the building in terms of average measured temperature of the windows on December 21. In addition to that, there was a significant difference between the fourth floor average temperature compared to the other floors.

Table 5.2. Statistical summary and results of post-hoc test for the average of measured temperature (ºC) of each side and floor of the building on December 21.

	Avg. (ºC)	SD (ºC)	Min (ºC)	Max (ºC)
Side				
East	-11.1^{d}	1.7	-15.2	-6.4
North	-8.3^{b}	1.3	-12.4	-4.5
South	-7.5^{a}	1.2	-9.9	-3.3
West	-10.9^{c}	1.6	-14.3	-6.6
Floor				
1	-8.6^{A}	1.8	-12	-3.9
2	-8.6^{A}	1.7	-13	-3.5
3	-8.7^{A}	1.8	-12	-3.8
4	-10.6^{B}	2.4	-15	-3.3

Values with the same letters are not significantly different (Tukey's HSD test, $p < 0.05$).

Figure 5.5 shows the average temperature of all windows on each floor of each side of the building on December 22. The explanation of the average thermal performance of the windows is similar to December 21. Besides, the patterns of the thermal changes between floors of each side are like the pattern of the same side as on December 21 at different temperatures. The temperature difference was because of the different average air temperatures on December 21 and December 22. However, the pattern between the building sides on December 21 was quite different from December 22. This arose from air temperature as well as wind speed difference between the two days. The boxplot of all windows measured values are shown in Appendix B2.

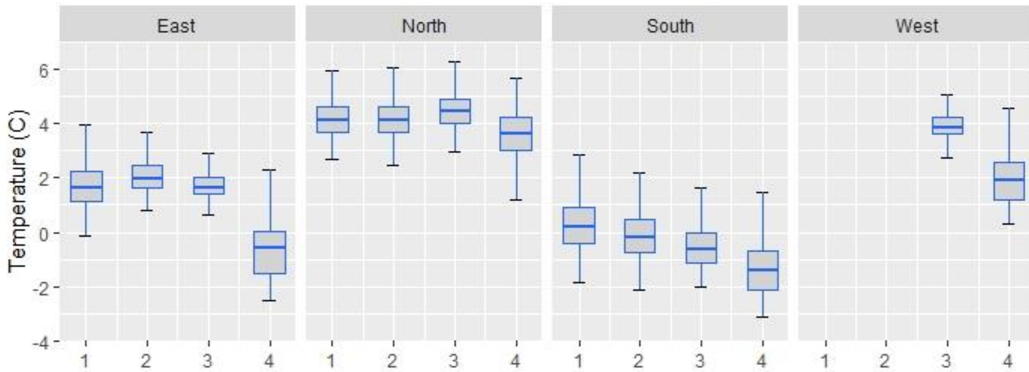

Figure 5.5. The average temperature of all windows for each row of windows on different floors for four sides of the building on December 22.

The second day of study, December 22, had similar wind direction as December 21. However, the wind speed was 1.3 m/s higher than the first day and the average air temperature was 5.6 ^{o}C warmer than the first day. Therefore, the expected temperature for the windows should be higher than the first day. Both the North and West sides of the building were affected by wind direction. The wind chill was recorded as -8.7 ^{o}C, which caused to have a lower standard deviation of temperature for all sides of the building in comparison with day 1. The measured standard deviation between floors on December 22 was similar to the measured standard deviation between floors on December 21. Moving from the first floor to the upper floors, the temperature decreased. For December 22, a linear relationship was observed between each floor temperature of the South side of the building. This may be the result of milder air temperature on December 22 compared to that on December 21. Table 5.3 shows the result of the ANOVA test for the measured temperature by considering floor, side, and combination of floor and side as different factors that affect response value, which is temperature. The results of the ANOVA test shows that there were significant differences between the floors and sides of the building (P-value <0.05). Table 5.4 shows the statistical summary within a group of measured temperature for each side and floors of the building on December 22. Results of the post-hoc test using Tukey's HSD method are shown with lower and uppercase letters in which values with the same letter are not significantly different. Residuals of the ANOVA test showed normal distribution as shown on Appendix A2. The result of the interaction impact of factors on measured temperature is shown on Appendix C, Table C2.

Table 5.3. Result of ANOVA model for windows temperature for December 22.

Factors	Df	Sum Sq	Mean Sq	F value	P-value	Significant
Floor	3	9080	3027	3948	<2e-16	Yes
Side	3	106714	35571	46398	<2e-16	Yes
Floor: Side	9	3982	569	742	<2e-16	Yes
Residuals	31054	23808	1			

Table 5.4. Statistical summary and results of post-hoc test for the average of measured temperature (°C) of each side and floor of the building on December 22.

Factor	Avg. (°C)	SD (°C)	Min (°C)	Max (°C)
Side				
North	4.11^{a}	0.84	1.0	6.9
West	2.68^{b}	1.25	0.3	5.9
East	1.24^{c}	1.39	-2.5	4.5
South	-0.37^{d}	1.12	-3.1	3.0
Floor				
1	1.42^{C}	1.5	-1.9	5.9
2	2.27^{A}	2.0	-2.1	6.3
3	2.05^{B}	2.3	-2.0	6.9
4	0.96^{D}	2.3	-3.1	5.7

Values with the same letter are not significantly different (Tukey's HSD test, $p < 0.05$).

The pattern between the building sides on the third study day, December 23, was different from both the first and second days (December 21 and 22), which was likely caused by the different wind speed and direction. In contrast with the first and second study dates, the wind had Southwest direction (14.5 degrees), which affected mostly the South side of the building. The measured average air temperature was 2.5 °C lower than the second day (December 22) and

3.1 °C higher than the first day (December 23). The patterns of thermal changes between floors of each side were similar to other study dates except for the South side, which was directly affected by the wind as well as by wind dynamic and movement on different sides of the building, especially around any openings. Figure 5.6 shows the trend of variation for each floor and side of the building for December 23. The boxplot of all windows measured values are shown in Appendix B3.

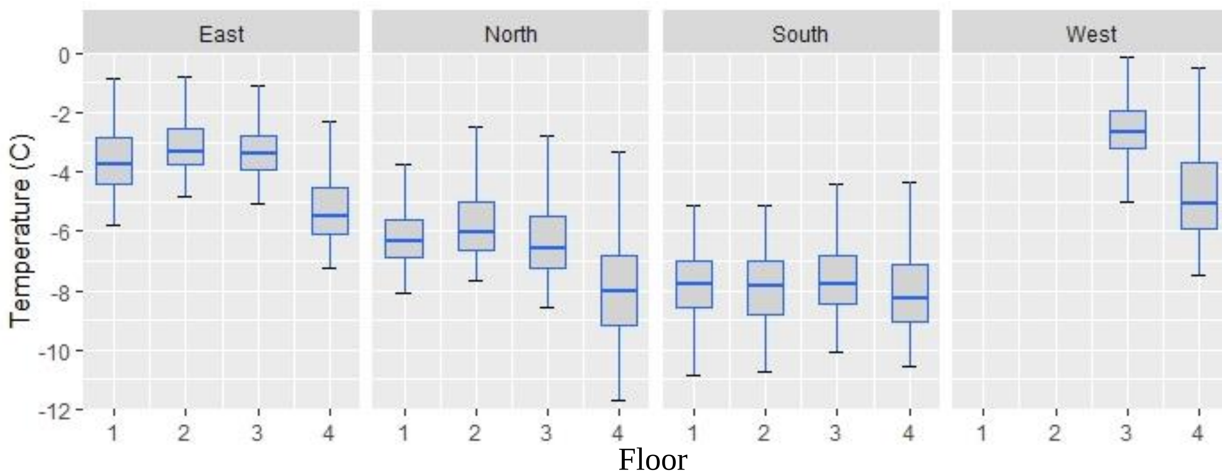

Figure 5.6. The average temperature of all windows for each row of windows on different floors for four sides of the building on December 23.

The results of the ANOVA test for December 23 are shown in Table 5.5. Since the first two floors of the West side were excluded from the final analysis, the degree of freedom for floor and side combination reduced from nine to seven. The results of the ANOVA test were similar to before and showed significant differences between the floors and sides of the building. The results of post-hoc tests in Table 5.6 showed significant differences among floors as well as sides of the building. The statistical summary of the measured temperature for each side and floors are shown in Table 5.6. The result of the interaction post-hoc test is shown on Appendix C, Table C3. Appendix A3 shows the normal distribution for the residuals of the ANOVA test. Appendix A4 shows the normality of distribution for residuals of the ANOVA test.

Table 5.5. Result of ANOVA model for windows temperature for December 23.

Response/Value	Df	Sum Sq	Mean Sq	F	P-value	Significant
Floor	3	7417	2472	1400	<2e-16	Yes
Side	3	104547	34849	19734	<2e-16	Yes
Floor: Side	7	4299	614	348	<2e-16	Yes
Residuals	32364	57152	2			

Table 5.6. Statistical summary and results of post-hoc test for the average of measured temperature (^oC) of each side and floor of the building on December 23.

Factor	Avg. (^oC)	SD (^oC)	Min (^oC)	Max (^oC)
Side				
East	-3.8^b	1.4	-7.3	0.23
North	-6.4^c	1.8	-11.7	-0.5
South	-7.8^d	1.2	-11.4	-4.34
West	-3.4^a	1.9	-7.5	1.93
Floor				
1	-6.0^C	2.1	-11	-0.85
2	-5.7^B	2.2	-11	0.15
3	-5.5^A	2.5	-10	1.93
4	-6.7^D	2.2	-12	0.98

Values with the same letter are not significantly different (Tukey's HSD test, $p < 0.05$).

5.3. Overall analysis

All three study dates' datasets were combined to analyze overall differences and trends among sides and floors of the building, as well as understanding the effect of day on measured values. Figure 5.7 shows the averages of each day temperature range for each side of the building. Figure 5.7 illustrates that all sides followed a similar trend regarding weather variability. Table 5.7 shows the statistical summary of measured thermal values for each side of the building by considering three studied dates and all floors of the building. According to the Tukey's HSD test to analyze within-group differences, there were no significant differences between West and South sides of the building in term of windows temperature; however, North and East side of the building had significant differences on windows temperature, as well as West and South sides of the building.

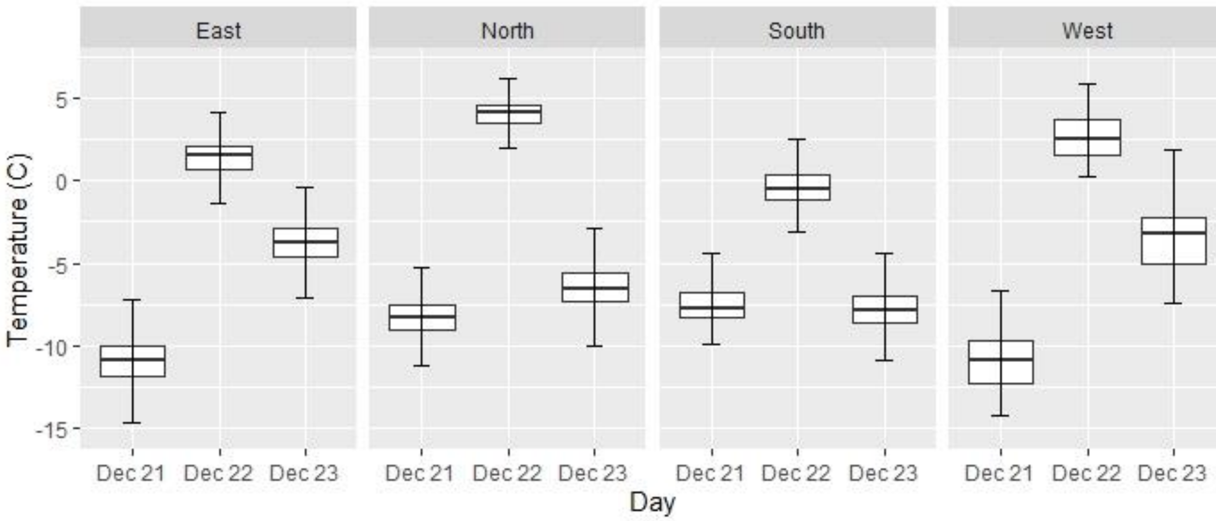

Figure 5.7. Overall thermal performance of each studied dates for building directions.

Table 5.7. Statistical summary of thermal performance (°C) for each side of the building.

Side	Avg. (°C)	SD (°C)	n	Min. (°C)	Max. (°C)
East	-4.5[a]	5.4	12	-13.1	2.1
North	-3.5[b]	5.7	12	-9.2	4.5
South	-5.2[c]	3.6	12	-8	0.3
West	-5.4[c]	6.1	8	-11.9	4

Average thermal values with the same letter have no significant differences (Tukey's HSD test, $p < 0.05$).

By using similar data used for Figure 5.7, Figure 5.8 depicts a different aspect of the weather variability in terms of the effect on measured temperature. As shown in the figure, all three days showed different variations and trends for different sides of the building. The air temperature and wind chill were different for the first two days of study, however, the wind direction stayed almost similar. The difference in measured temperature between the first two days in terms of a range of variation for each side was due to the air temperature differences. On the other hand, the trend was expected to be similar due to the similar wind direction. However, a different trend was observed for the South side, which showed a significantly lower range of temperature compared to the other sides of the building for the second day of data collection. This decrease in measured temperature may be affected by a change in wind speed and direction, as well as a change in air movement around the building. Comparing the third day of study (December 23) with the first two days (December 21 and 22), the difference in the trend of temperature for each side was obvious. Due to the wind direction on December 23, which was toward the South side of the building, the lower range of measured temperature was observed.

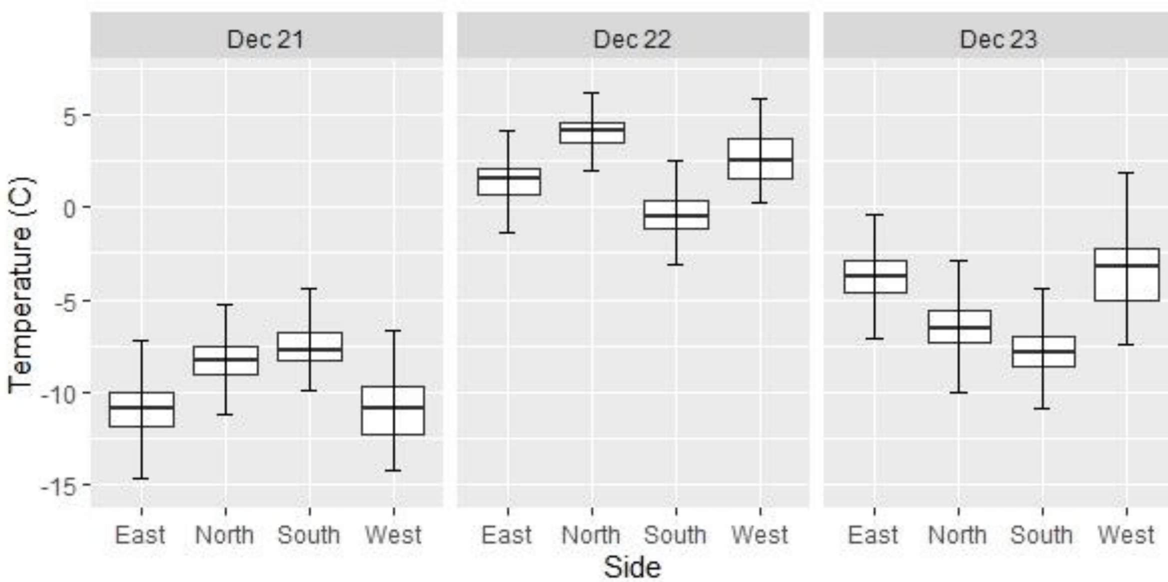

Figure 5.8. Average temperature variation of each side of the building on three different study dates.

Comparing the difference between floors for all three-study dates showed that the trends between lower floors to the upper floors are similar. Sharp decrement was observed from the third floor to the fourth floor. However, the average range of temperatures between the first floor and the second floor is similar, the temperature of the third floor was almost lower than the first two floors, and the temperature of the fourth floor was lower than all floors. Figure 5.9 shows the range of average thermal variation for each floor (row) of the building for three studied dates.

Therefore, despite the insignificant increments and decrements in the average temperature of windows between subsequent floors, there was a significant temperature decrement comparing the first and fourth floor (Table 5.2, 5.4, and 5.6). Table 5.8 shows the Tukey's HSD test results based on four floors average dataset. Using the ANOVA test, floors with a P-value greater than 0.05 had no significant difference in thermal performance.

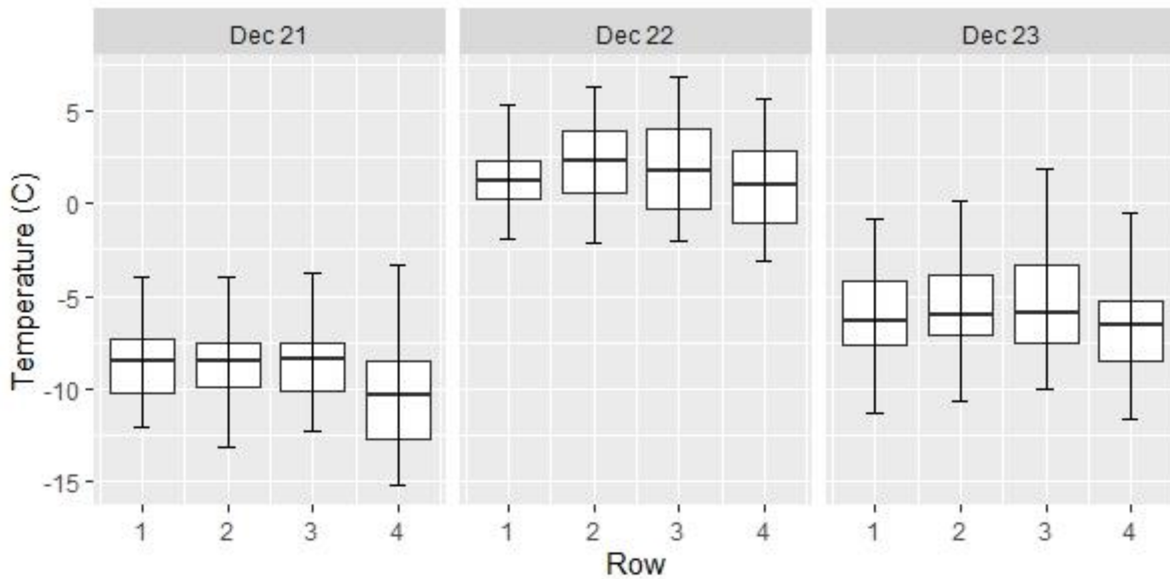

Figure 5.9. Average thermal performance of each row of the building for three different study dates.

Table 5.8. Average temperature differences (°C) between floors for three studied dates (December 21, 22, and 23).

Floors	Difference (°C)	Lower (°C)	Upper (°C)	P-value
1-2	0.005	-0.61	0.62	1
1-3	0.89	0.31	1.48	0*
1-4	-0.67	-1.26	-0.09	0.02*
2-3	0.88	0.3	1.48	0*
2-4	-0.67	-1.26	-0.09	0.02*
3-4	-1.56	-2.13	-1.01	0*

*P-values lower than 0.05 shows significant differences (Tukey's HSD test, $p < 0.05$).

Despite similar inside room temperature (20 °C) on all floors, measured windows temperature showed a decreasing trend by going upper floors. This reduction happened for most of the windows on different sides of the building as well as three studied dates. The temperature difference of the windows on subsequent floors might appear insignificant. However, comparing the window's thermal performance of the first and fourth floor showed a significant reduction. Results of Tukey's HSD test for studied dates and sides of the building are provided in appendix C, Table C4.

Figure 5.10 shows the regression line, correlation coefficient, and p-value using the average thermal value of each floor and each side of the building for the three studied dates. As described before, the East side of the building had the same pattern on average temperature from first to the fourth floor for every day since it was not affected by the wind. On average, there was a slightly lower temperature recorded for the first floor compared to the second floor. This lower temperature maybe is due to the snow coverage around the building. The existence of the snow surrounding the building can reduce the average temperature at a lower level close to the snow that may affect the measured temperature. The results of the study indicated that, in order to make accurate measurements and predictions about building thermal energy performance, the interaction between the building and the surrounding should be taken into account (Pisello et al. 2014).

In addition, perpendicularity of the thermal camera to the second row of the windows, which can cause a high reflection from the windows can be another reason for the higher recorded temperature for the second floor compared to the first floor. The North side of the building had a similar trend as the East side except for the second day of study where the temperature of the third floor was suddenly raised. This higher temperature partially observed for the third floor on the North side on the first study date. At the moment, there was no clear explanation of this phenomenon except the reflectance of the landscape light on the window of the third floor. Although the effect of any objects on reflectance was considered during the imaging process, some may exist that can affect the overall average. The South side of the building, especially on December 22, had different trends compared to the other sides of the building and this difference observed at previous figures and tables and showed significant differences on December 22 between the measured temperature among the floors. The West side was excluded from the final analysis due to the inconsistency of the measured values, existence of the tree, and limitation on imaging from a proper distance.

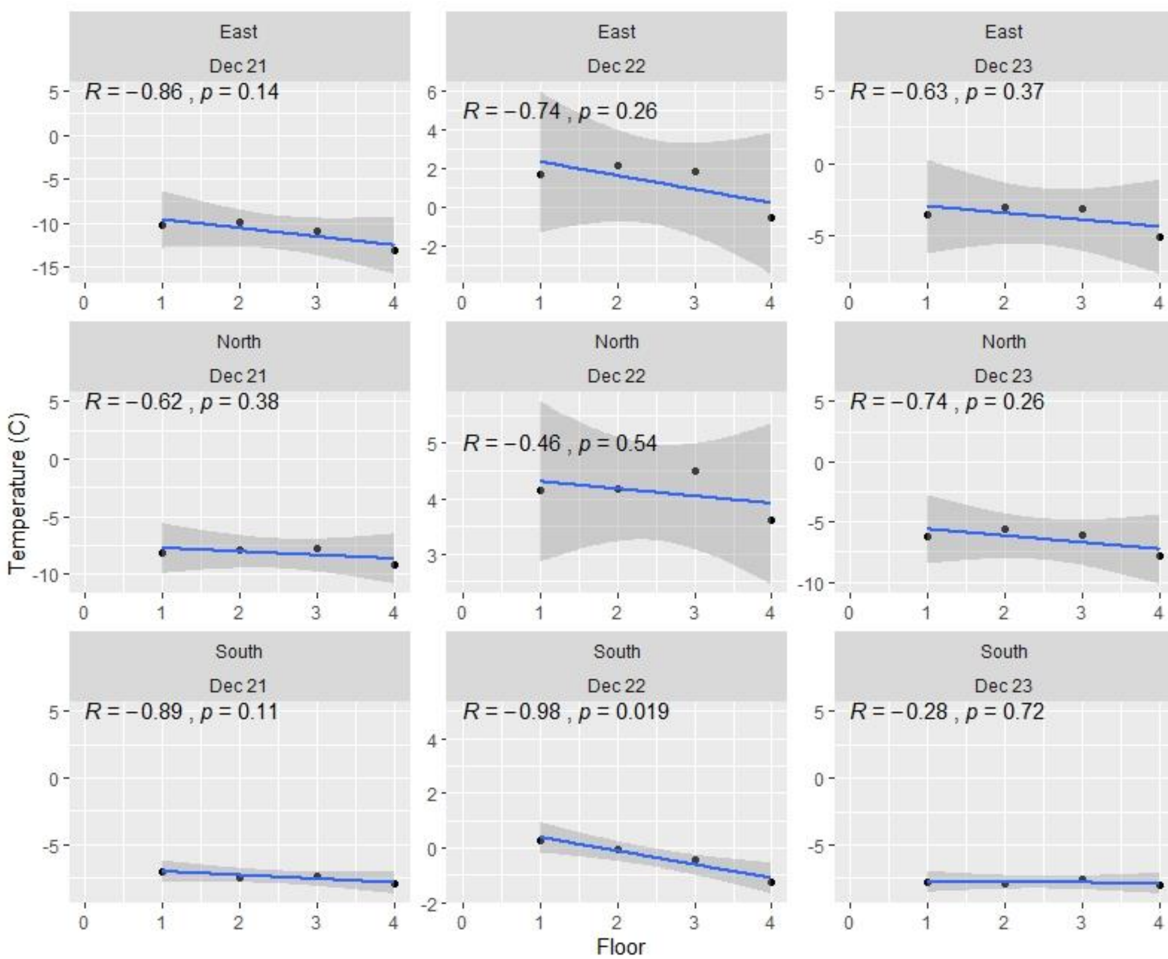

Figure 5.10. The regression line for the average of measured thermal values of each floor of three different sides of the building on studied dates.

The availability of performance data for existing buildings is one of the big challenges in building energy assessment studies (Wang, Yan, and Xiao 2012). Thus, applying a measurement approach by using a thermal camera can be considered a useful solution for this challenge. The results of this study revealed how a thermal camera can be a precise and quick tool for measurement to study the thermal performance of windows. Other researchers observed reliable performance of a thermal camera for studying other components of building's envelop (Ariwoola, Uddin, and Johnson 2016; Krawczyk et al. 2015); however, thermal camera is a very sensitive tool and there are some limitations and considerations that should be applied precisely to reduce possible errors (Lehmann et al. 2013). Results of the study by Mohamad Omar & Syed Fadzil (2014) showed great performance of a thermal camera for field study and indicated that the readings taken from the IR thermal camera and the IR thermometer were consistent with one another.

Results of ANOVA analysis and the post-hoc test revealed that weather condition including air temperature, wind speed and direction, and windows' location including orientation, and height have a significant effect on window energy performance. When designing a building, it is important to consider how conditions around the building will alter local winds and thus, temperature differentials (Fleming, 2015). The wind can interact with buildings and speed up in local areas, especially when the parallel buildings create a channel, accelerate wind around building corners and through building openings.

Tall buildings exposed to oncoming wind can direct the higher-speed winds at higher elevations down the building that face to the street level (Fleming, 2015). Heat loss increases significantly on upper floors particularly from the 4^{th} floor and above. In addition, not only building shape and height but also wind direction and speed have a considerable effect on air pressure and wind dynamic, which subsequently affects heat loss from windows. The East side was the only side that showed an almost similar pattern in its thermal performance with different temperature since it was the only side that didn't face the wind in three days. North and South showed the coldest temperature which means more heat loss occasionally since they were facing the wind directly.

Any changes to any of the factors in a building such as temperature, wind speed, and wind direction can cause a very different result in windows' heat loss. However, more studies are required in order to have more detailed results regarding wind dynamic and heat loss prediction. When a building obstructs wind flow, the wind exerts pressure on the building. On the other hand, the shape of the building can affect the amount of wind pressure, and resultant wind force, that acts on its surface. Creating positive or negative pressure along the building surface and corners can cause various trends of heat loss (Fleming 2015). Therefore, even by considering the dominant wind direction and speed, the best configuration can be applied for existing or any new building with the same condition and location.

6. CONCLUSION

This study was focused on window energy performance due to its significant role in building energy consumption. The results of statistical analysis showed the accuracy and validity of the thermal camera as a measurement tool to study window energy performance. However, some limitations and factors must be considered. Significant differences in average windows temperature were observed among floors, except the first and second floors. Further, a significant temperature decrement was found by comparing the windows' temperatures of the first floor and fourth floor. The results indicated that building height has a significant effect on window energy performance and the amount of heat loss by windows increases significantly in upper floors particularly from the fourth floor and above. Comparing sides of the building, the significant difference observed at 0.05 level for all three-studied dates. Wind speed and direction, as well as building height, which has considerable effects on air pressure and wind dynamic, were affected by the amount of heat loss from windows. Among the four sides of the building, the East side showed a similar pattern of window thermal performance because of the neutral wind effect. The coldest temperature was measured for North and South sides occasionally that indicates more heat loss due to the wind direction effect. However, weather variation made any conclusion impossible in terms of publishing any exact values. Hence, more studies are required in order to have more detailed results regarding wind dynamic and heat loss prediction. This study suggests using more efficient windows as well as various types of windows in building according to the height of the building and window, particularly from fourth floors and above. Considering dominant wind direction and wind speed would play a paramount role in the searching best configuration of window design and choice for a building.

6.1. Limitations

This study has passed various limitations. First, due to the flight regulation and safety issue, it was not possible to use neither a drone nor a lifter. Using a 9 m pole was not enough to capture images of all the floors properly, so for future work, it is recommended to use a drone, lifter, or any other equipment that makes it possible to fix the camera in a higher level to capture all floors. Second, however, early morning was chosen to avoid the daylight reflection, the reflection of the lights around the building was unavoidable and caused many of windows has been ignored in data analysis. For future studies, considering this factor and avoiding any light around the building would be very helpful. Third, it is encouraged to decrease the number of invalid windows for measurement and analysis by reducing the number of windows that has blind curtains, light bulb or any kinds of reflections, or blocking objectives in order to have enough replication and avoid the effect of outliers on collected data.

6.2. Future work

The possible future work can be developing this study by imaging within various distances to observe the effect of distance on data accuracy. Another approach can be comparing the data and results of different buildings with the same features such as buildings' location and weather condition to examine the variation of the results with this method. For instance, there are three other buildings exactly like Thompson Hall (shown in Figure 3.1), which are located very close to it and can be studied and compared to each other to understand the impact of building location and performance in terms of energy loss. In addition, the results of this method can be compared with the results of the simulation to figure out the closeness of two methodologies for future studies. Beyond that, this methodology can be adapted for warm weather, in which the windows' energy performance can be studied from inside the building to observe the exchange of outside's warm load and inside's cool load on different floors and sides of the building.

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APPENDIX A. RESIDUALS

The following figures (figure A1-A4) illustrates the normality of residuals for ANOVA tables.

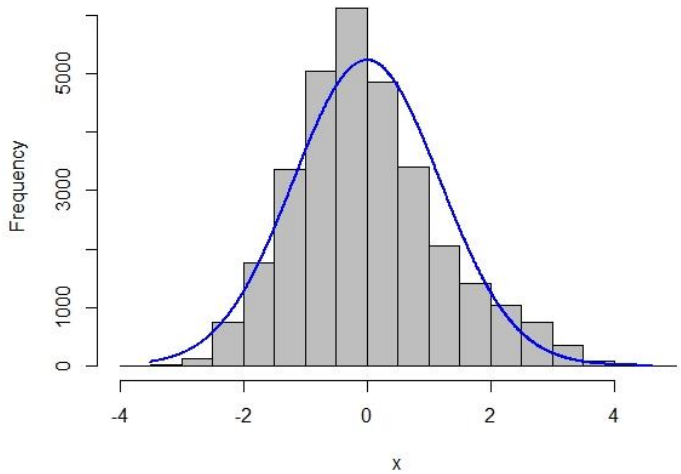

Figure A1. Residual distribution for measured thermal data on December 21.

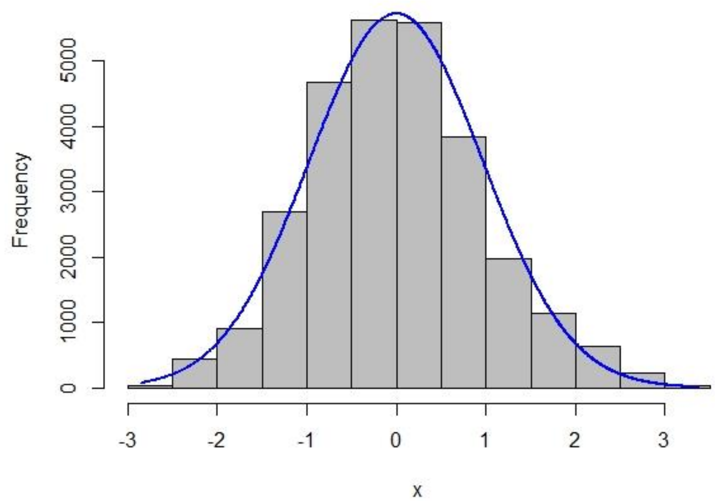

Figure A2. Residual distribution for measured thermal data on December 22.

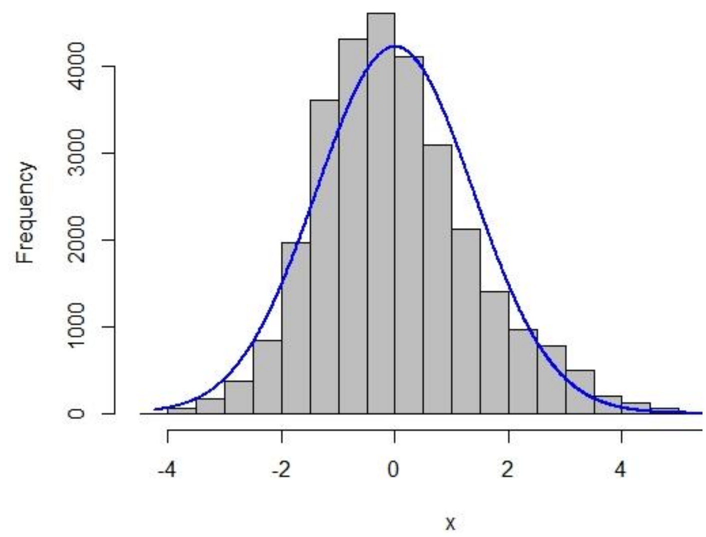

Figure A3. Residual distribution for measured thermal data on December 23.

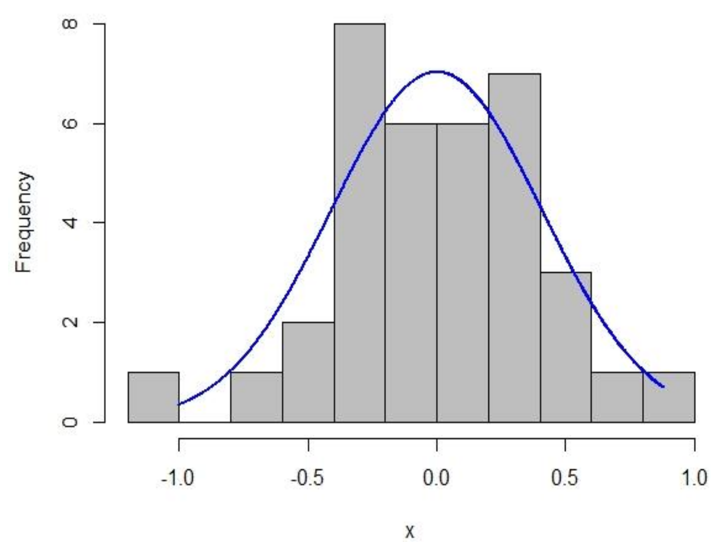

Figure A4. Residual distribution for measured thermal data for all three-studied dates.

APPENDIX B. BOXPLOTS

The following are the boxplots for the windows that have been used for the final analysis. Windows that had a blind curtain, light on, or blocked by objects are excluded.

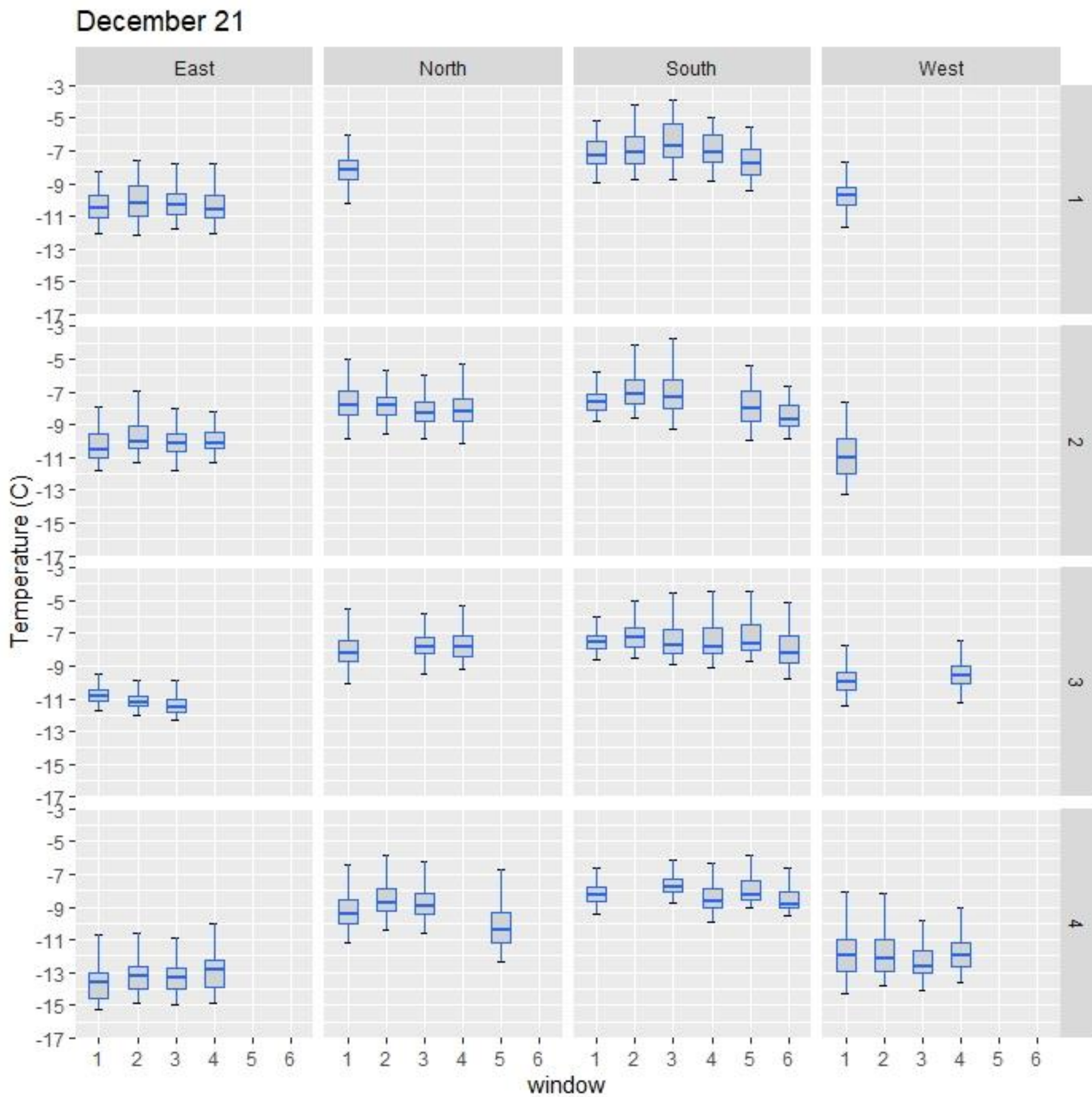

Figure B1. Thermal performance of all valid windows (comparing sides on each floor) for December 21.

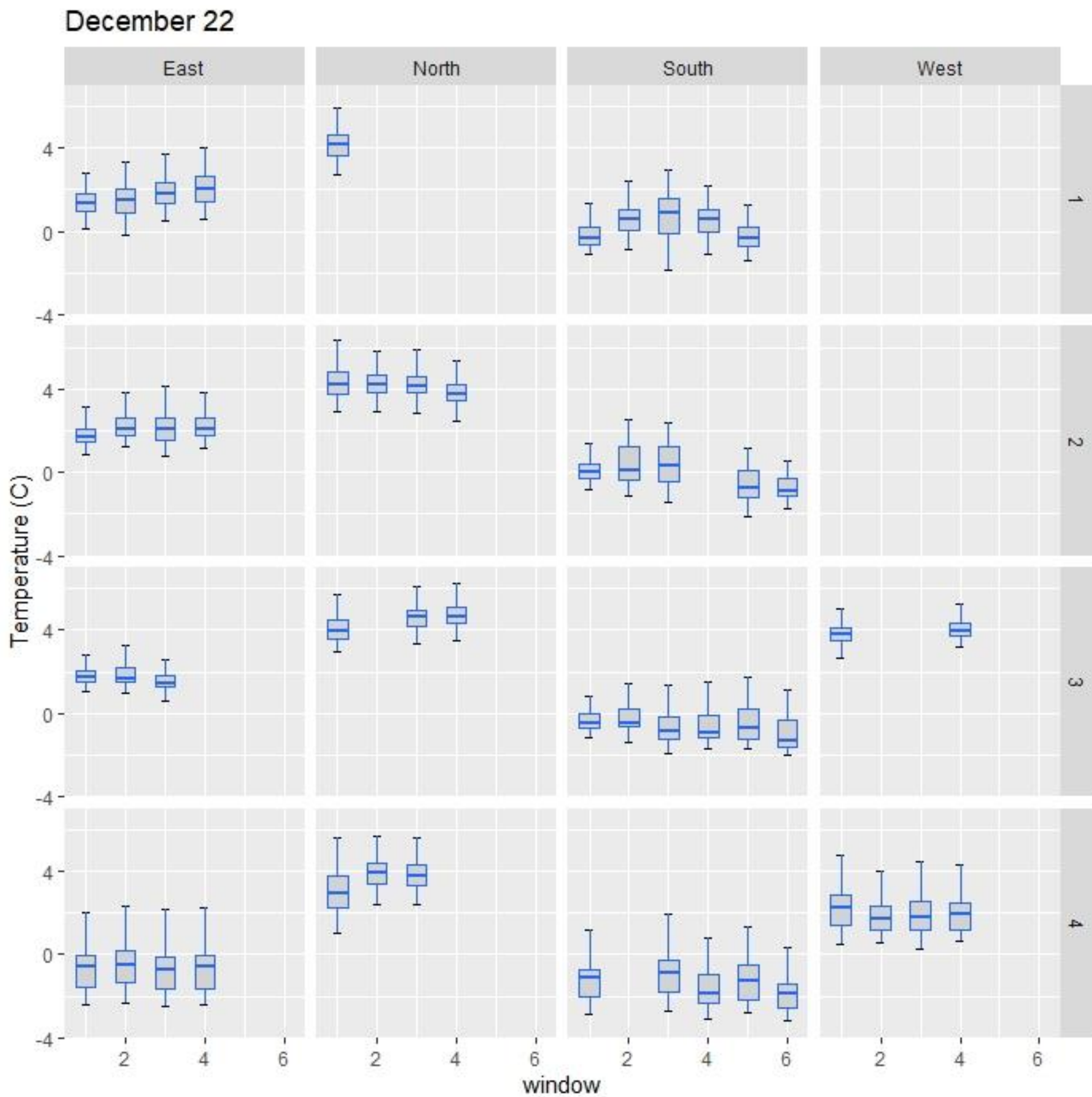

Figure B2. Thermal performance of all valid windows (comparing sides on each floor) for December 22.

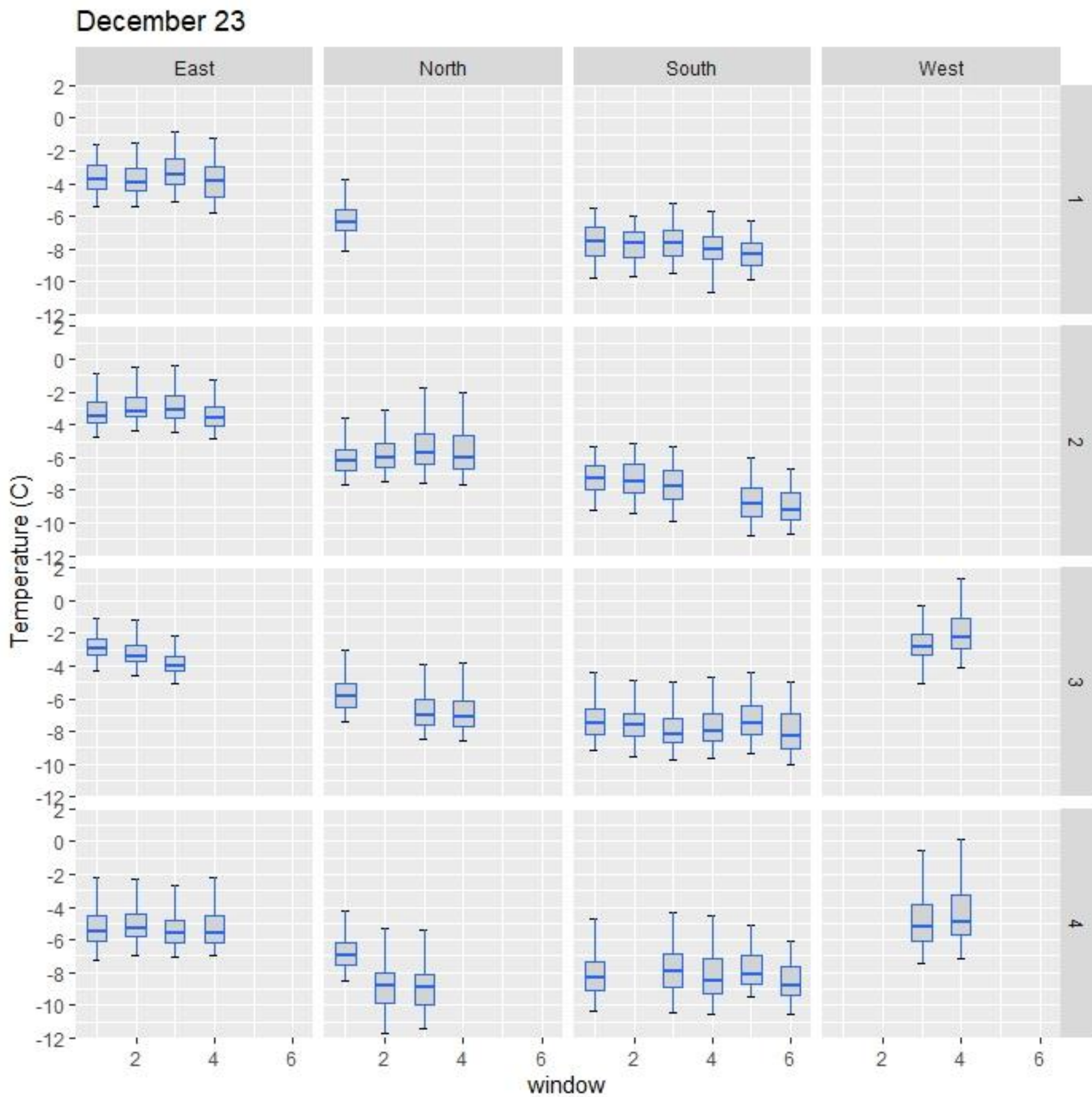

Figure B3. Thermal performance of all valid windows (comparing sides on each floor) for December 23.

APPENDIX C. RESULTS OF TUKEY'S HSD TEST

Table C1. Results of Tukey's HSD test for the interaction between the floor and side of the building on December 21.

Floor: Side	Avg. temperature (°C)	groups
1:South	-7	a
3:South	-7.4	b
2:South	-7.5	c
3:North	-7.8	d
2:North	-7.9	e
4:South	-8	f
1:North	-8.1	g
4:North	-9.2	h
3:West	-9.6	i
1:West	-9.8	j
2:East	-9.9	k
1:East	-10.2	l
2:West	-10.8	m
3:East	-10.9	m
4:West	-11.9	n
4:East	-13.1	o

Data with the same group name had no significant difference with a 95% confidence interval.

Table C2. Results of Tukey's HSD test for the interaction between the floor and side of the building on December 22.

Floor: Side	Avg. temperature (°C)	groups
3:North	4.502	a
2:North	4.167	b
1:North	4.158	b
3:West	3.95	c
4:North	3.608	d
2:East	2.129	e
4:West	2.04	e
3:East	1.82	f
1:East	1.712	g
1:South	0.299	h
2:South	-0.056	i
3:South	-0.458	j
4:East	-0.558	k
4:South	-1.231	l

Data with the same group name had no significant difference with a 95% confidence interval.

Table C3. Results of Tukey's HSD test for the interaction between the floor and side of the building on December 23.

Floor: Side	Avg. temperature (°C)	groups
3:West	-2.3	a
2:East	-3	b
3:East	-3.2	b
1:East	-3.6	c
4:West	-4.6	d
4:East	-5.1	e
2:North	-5.7	f
3:North	-6.1	g
1:North	-6.2	g
3:South	-7.6	h
1:South	-7.8	i
4:North	-7.9	i
2:South	-7.9	i
4:South	-8	j

Data with the same group name had no significant difference with a 95% confidence interval.

Table C4. Results of Tukey's HSD test using for windows thermal performance (°C) for the three-studied dates by considering four sides of the building.

Date: Side	Avg.	group	SD	Min	Max	Q25	Q50	Q75
Dec 22:North	4.1	a	0.4	3.6	4.5	4.0	4.2	4.3
Dec 22:West	3.0	a	1.4	2.0	4.0	2.5	3.0	3.5
Dec 22:East	1.3	b	1.2	-0.6	2.1	1.1	1.8	1.9
Dec 22:South	-0.4	c	0.7	-1.2	0.3	-0.7	-0.3	0.0
Dec 23:West	-3.4	d	1.6	-4.6	-2.3	-4.0	-3.4	-2.9
Dec 23:East	-3.7	d	1.0	-5.1	-3.0	-4.0	-3.4	-3.1
Dec 23:North	-6.5	e	1.0	-7.9	-5.7	-6.6	-6.2	-6.0
Dec 21:South	-7.5	ef	0.4	-8.0	-7.0	-7.6	-7.5	-7.3
Dec 23:South	-7.8	f	0.2	-8.0	-7.6	-7.9	-7.8	-7.7
Dec 21:North	-8.2	f	0.6	-9.2	-7.8	-8.4	-8.0	-7.8
Dec 21:West	-10.5	g	1.1	-11.9	-9.6	-11.1	-10.3	-9.7
Dec 21:East	-11.1	g	1.5	-13.1	-9.9	-11.5	-10.6	-10.2

Q25, Q50, and Q75 represent the first, second, and third quartile of the data.
Data with the same group name had no significant difference with a 95% confidence interval.