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"Using Infrared Thermography to assess the influence of thermal bridges on Energy performance of a Residential Building in a Temperate region"

by

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Declaration

I hereby declare that the thesis entitled **"Using Infrared Thermography to assess the influence of thermal bridges on Energy performance of a Residential Building in a Temperate region"** submitted to the Department of Architecture in partial fulfilment of the requirement for the degree of Master of Science in Engineering in Energy Efficient Building, is a record of an original work done under the guidance of Associate Prof. Dr. Sanjaya Uprety, Institure of Engineering, Pulchowk Campus. This thesis contains work completed by me except for the consulted material which has been duly referenced and acknowledged.

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Abstract

Buildings are significant contributors to global energy consumption and greenhouse gas emissions, with thermal bridges playing a critical role in undermining the thermal performance of building envelopes. Thermal bridges which are areas of low thermal resistance in the building envelope, lead to increased heat transfer, higher energy consumption, and potential issues such as condensation and mold growth. This study focuses on identifying and analyzing thermal bridges in residential buildings in Kathmandu, Nepal, using infrared thermography along with numerical simulation (THERM) and finally using a building energy modelling software (OpenStudio) to determine the impact of thermal bridges on energy performance of a building. The research examines key areas such as balcony wall junctions, roof wall junctions and window frame junctions to asses and analyze thermal bridges. Through thermal imaging and 2D heat transfer analysis using THERM software, the study quantifies the linear thermal transmittance (ψ value) of these thermal bridges. Thermal images of six RCC framed structures were analyzed to identify key heat loss areas across the building envelope. The findings reveal that roof wall junctions are particularly prone to thermal bridging, with a calculated linear thermal transmittance of 0.5275 W/m-K, which is high compared to passivhaus standard (<0.01 W/m-K) and other thermal bridging guides (<0.3 W/m-K). By applying expanded polystyrene (EPS) along this roof wall junction the ψ value reduced by 42% to 0.3051 W/m-K, demonstrating the potential for mitigating heat losses. Simulation in OpenStudio showed a 4.12% reduction in total site energy as well as the energy use intensity (EUI) after the application of the EPS insulation material, highlighting the impact of thermal bridges on overall building efficiency. This study highlights the importance of addressing thermal bridges in building design to improve energy efficiency, reduce heat loss, and enhance indoor comfort in the context of Nepal's rapidly urbanizing environment.

Keywords: Thermal bridge, overall heat transfer coefficient, linear thermal transmittance, infrared thermography

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Abbreviations

ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BCL	Building Component Library
BEEN	Building Energy Efficiency Nepal
BEM	Building Energy Modelling
DHM	Department of Hydrology and Meteorology
EPI	Energy Performance Index
EPS	Expanded Polystyrene
EPW	Energy Plus Weather
EUI	Energy Use Intensity
IRT	Infrared Thermography
LBNL	Lawrence Berkeley National Laboratory

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CHAPTER 1 INTRODUCTION

1.1 Background

Buildings contribute greatly to the global energy use and greenhouse gas emissions, emphasizing the urgent need for energy saving measures ((NRCBT), 2024). Worldwide, buildings are responsible for 30% of the final energy consumption and 26% of the energy related CO_2 emissions. By 2030, the global building stock is projected to grow by 15% (IEA, 2023).

Energy efficient buildings helps to curb not only the energy consumption but also fosters comfortable living spaces while also reducing carbon emissions and mitigating climate change ((NRCBT), 2024). The cooling and heating costs of systems can be significantly reduced through energy efficient building improvements. Energy efficient buildings are the first step towards achieving sustainability in buildings, to control the growing energy costs, decrease the environmental footprints as well as increasing the value of buildings (Bajracharya et al., 2014).

In the context of Nepal, rapid urbanization and increased economic activities have led to a rise in construction, increasing energy demand, particularly for space heating, cooling, lighting and electrical appliances ((NRCBT), 2024). Nepal ranks among the top ten fastest urbanizing developing nations. However, many recently constructed buildings overlook local climate conditions and energy efficiency, leading to uncomfortable indoor environments and increased energy use to offset this discomfort. These issues could be addressed through better building envelope design, such as improved insulation of walls and roofs. Notably, residential energy consumption in Nepal is rising at an annual rate of 2.23%, which exceed the country's population growth rate ((BEEN), 2024). The residential sector accounted for 60.59% of the national energy consumption in Nepal based on data from 2022. In a span of a decade 1.24 million houses were added to the building stock in Nepal totalling up to 6.67 million houses in 2021. The buildings that have been designed and constructed during this time have not taken the local bio climate into consideration leading to compromised thermal comfort as well as an increase in energy consumption to compensate for the discomfort created throughout the lifespan of the building operation. As the move from traditional to modern construction practices has increased, especially in the temperate and warm temperate regions, the demand for space cooling has increased (Building Energy Efficiency in Nepal, 2024).

In Nepal, the predominant construction technique in cold climate is load bearing (77%) followed by rubble masonry. In temperate and warm temperate climate RCC framed constructions dominate (90.8% and 86.6% respectively) followed by load bearing construction. In cool temperate climate RCC frame construction and load bearing construction (58.7% and 38% respectively) share the construction typology. Buildings in cold regions in Nepal have thicker walls which reduces at lower altitudes. Solid burnt bricks are the key wall construction materials in climatic regions other than cold region where stone masonry are dominant. 80% of the buildings have flat roof in cold, temperate and warm temperate regions followed by inclined roofs. RCC roofs with cement plaster is the dominant material in temperate and warm temperate climates (Building Energy Efficiency in Nepal, 2024). Under utilization of natural ventilation in the summer time can increase the cooling loads in the temperate climatic region. Heat loss in winter occurs mostly through the roof, conduction through glass and conduction through the wall. Heat gain in summer occurs mostly through conduction from the roof and transmission from glazed windows ((BEEN), 2024).

Heat transfers easily from building envelope areas which has low thermal resistance such as windows, doors and thermal bridges. Locations in the building envelope where there is low thermal resistance, usually due to penetration through the insulation layers of the building envelope are referred to as thermal bridges (Alhawari & Mukhopadhyaya, June 2018). Thermal bridges allow greater heat flow, which raises the overall heat transfer coefficient (U-value) of the building elements. This increased heat transfer can lead to indoor condensation, mold growth, heat loss, reduced indoor air quality and potential structural issues within the whole building (Kaymaz, 2019). As a building’s thermal insulation improves, the relative impact of thermal bridges on its energy demand becomes more significant. In residential buildings, thermal bridges can substantially raise heating and cooling loads, with some studies suggesting they may account for up to 20% of the total energy use, depending on the climate. Among the common thermal bridge locations, balcony slabs are particularly detrimental to a building's energy efficiency (Carramiñana et al., 2024). External building elements typically have fairly uniform surface temperature. However, thermal bridges disrupt this uniformity by lowering the surface temperature on the interior side and raising them on the exterior side (O'Grady et al., 2016). The heat loss through thermal bridges is influenced by their thermal transmittance, whether linear or point based. These transmittance values can be sourced from standard tables for common building details or they can be determined using theoretical calculations (Smusz & Korzeniowski, 2018).

Thermographic inspection allows instant location of thermal bridges (cold bridges) as well as specification of the range and surface temperature evaluation. Thermal inspection not only determines the presence of thermal bridges but also assesses their potential impact on the overall heat loss, as well as the likelihood of mold growth or surface condensation (Wróbel & Kisilewicz, 2008). Infrared (IR) thermography technique is very valuable to conduct on site examination, this method allows a qualitative inspection to examine the surface temperatures of the envelope surfaces. Through this investigation assessment of deficiencies such as air leakages, infiltration, poor insulation and mold are easily recognized (Asdrubali et al., 2012). Infrared thermography is a very effective diagnostic tool for identifying non-uniform elements, such as the impact of windows and doors, as well as the presence of structural components within wall and ceiling insulations (Bianchi et al., 2014). Infrared thermography is a very useful tool for quickly assessing buildings, as it can identify structural issues and convert infrared radiation from an object into a thermal image that reflects its temperature (Choi et al., 2022). Infrared thermography is considered one of the most dependable qualitative methods used in building assessment today. However, the effectiveness of this technique can be affected by factors like environmental conditions as well as the user's level of expertise (Bianchi et al., 2014).

Given the lack of relevant studies of thermal bridging in the context of Nepal, there is a need for the study of this phenomena to understand their influence as well as their impact on the energy requirements of a building. This work hopes to analyze the influence of thermal bridges in a residential building in Kathmandu using thermographic images.

1.2 Need of the Research

Thermal bridges in residential buildings can significantly raise the heating and cooling demands, with studies showing increases of up to 20%. However, these results can vary depending on the climate and the methods used for calculation (Carramiñana et al., 2024). Temperature patterns recorded on building surfaces, both internally and externally, are directly impacted by thermal bridges resulting from poor construction or material degradation. These uneven temperature distributions can significantly compromise the longevity of building materials, reduce energy efficiency and lower occupant comfort (Kaymaz, 2019). Thermal bridging through building elements like walls and ceiling studs can create localized cold spots, which may result in discoloration or staining on walls, a phenomenon known as "ghosting". Simply adding extra layers of insulation to the building envelope without addressing the effects of thermal bridges may not significantly reduce heat loss, in some cases, it could even intensify the impact of thermal bridging (Alhawari & Mukhopadhyaya, June 2018). Capturing thermographic images provides approximate data on the temperature of external building envelope surfaces, enabling the identification of areas with higher energy loss from the building's interior to its exterior surface (Carramiñana et al., 2024).

1.3 Importance of the Research

Given the absence of relevant studies of thermal bridging in the context of Nepal, studies are necessary to study their effects on the energy performance of buildings. This work hopes to analyze the influence of thermal bridges in a residential building in Kathmandu using thermographic images. With this research the aim is to understand more clearly the importance of thermal bridging in regards to the thermal performance of a residential building. Better understanding of thermal bridging patterns in the different components of a building through which heat is lost due to the effect of thermal bridging. Understanding better how thermal bridging impacts increased heat losses in the building as well as the decreased temperature of the internal surface leads to local vapor condensation, mold growth as well as air contamination. By assessing thermal bridges using infrared thermography this research could provide important insights into how to optimize energy performance in a residential building.

Thermal bridges lead to additional heat losses through the building envelope, hence understanding the concept of this phenomena is necessary to mitigate the risks of these thermal anomalies as this may lead to higher energy consumption and lower indoor thermal comfort. Due to lack of research and data on thermal bridges in the context of Nepal, this study hopes to give a better understanding in recognizing the importance of the consideration of thermal bridges in building practices.

1.4 Problem Statement

Through various research studies it is clear that thermal bridges have a critical role in influencing the energy performance of different types of buildings including residential but there is a significant lack of empirical data and understanding regarding their impact in the context of Nepal. Also, the manual released by building energy efficiency in Nepal (BEEN) gives only a brief introduction about thermal bridges without going into much detail.

The thermal bridging effects in buildings lead to several negative consequences: increase in energy consumption for heating and cooling loads, uncomfortable zones due to colder indoor surfaces and condensation on cold surfaces that lead to dampness and mold growth. In some buildings the effects of thermal bridges can lead to an increase in thermal loads if the effects are not checked for, studies have shown a 35% variation from initial calculations. The quantity of heat transfer from insulated elements of a building can be surpassed by the quantity of transfer of heat from thermal bridge locations (Alhawari & Mukhopadhyaya, June 2018). The presence, size and position of thermal bridges can lead to an increase in the oveall heat transfer coefficient of the building envelope, while simultaneously reducing energy efficiency, compromising occupant comfort and deteriorating indoor air quality (Kaymaz, 2019).

The lack of relevant studies of thermal bridging in the context of Nepal, researches are required to inspect their effect on the energy requirements that a building needs. This work hopes to analyze the influence of thermal bridges in a residential building in Kathmandu using thermographic images.

1.5 Research Objectives

The main objective of this research is to identify and analyze thermal bridges in key areas such as balcony wall junction, roof and wall connection and finally window frame junctions.

The specific objectives of this research are

- Estimate heat loss or gain through thermal bridges focusing on balcony slab and external wall/roof junction
- Estimate the impact of thermal bridges on energy performance of a building

1.6 Expected output

Through this research a better understanding about thermal bridges from various building elements specifically from balcony and roof/wall junction may be identified with the help of thermal images. An estimation of loss of heat or gain through these thermal bridges and a basic assessment of their contribution to the overall building's energy efficiency is also an aim of this study. As thermal bridges have an effect on the indoor surface temperature, a better understanding on the risk of condensation, mould growth and discomfort for occupants is also an outcome which is anticipated. Through the application of infrared thermography, the main aim is to have a better understanding of thermal bridges in the building envelope components and compare the thermal imaging results with output from the simulation results.

1.7 Limitation of the study

Due to the time limitation, the study was focused only on a certain number of buildings and only a certain typology of buildings in the study area. The logging of data for temperature and humidity was carried out for only one building due to unavailability of more data loggers. Similarly, due to the properties of thermographic camera used in the study, which has low resolution, more cleared images could not be gathered, but still noticeable difference could be seen from thermal bridging locations compared to the surrounding areas. Use of higher resolution cameras could give better and cleared results. The thermal properties of the building materials were acquired from secondary sources due to the absence of actual material data in our context.

1.8 Validity of research

The literature review is carried out in order to indicate validity of the above-mentioned research objectives. There have been many researches carried out on the specific topic of thermal bridges all around the world specifically in Europe and North America, but not in the context of our country Nepal. The use of infrared thermography in assessment of thermal bridges have been carried out extensively both qualitatively and quantitatively, in the above-mentioned regions of the world with their building practices and climate, but similar research in the context of our building practices, materials and climate have not been carried out. This research hopes to give a better understanding of thermal bridges and its importance in consideration during building practices for better energy and thermal performance of buildings.

1.9 Framework of the Research

The frame of the research has been shown in Figure 1. The research commences with the identification of the issue and topic selection. Extensive literature is carried out for defining clear objective of the study followed identification of various parameters of the study. Some of the important parameters identified from literature were linear thermal transmittance, thermal conductivity, thermal transmittance and infrared thermography. After the identification of various parameters, a detailed methodology was created to carry out the research work. For this research work primary and secondary data need to collected from thermographic inspection to temperature data logging as well as acquiring secondary weather data and material properties. Simulation is an important process in this study and two simulation software are used in this study, one for two-dimensional heat transfer analysis and the other for energy performance analysis. After the simulation process, the output from thermal images, simulation results are analyzed.

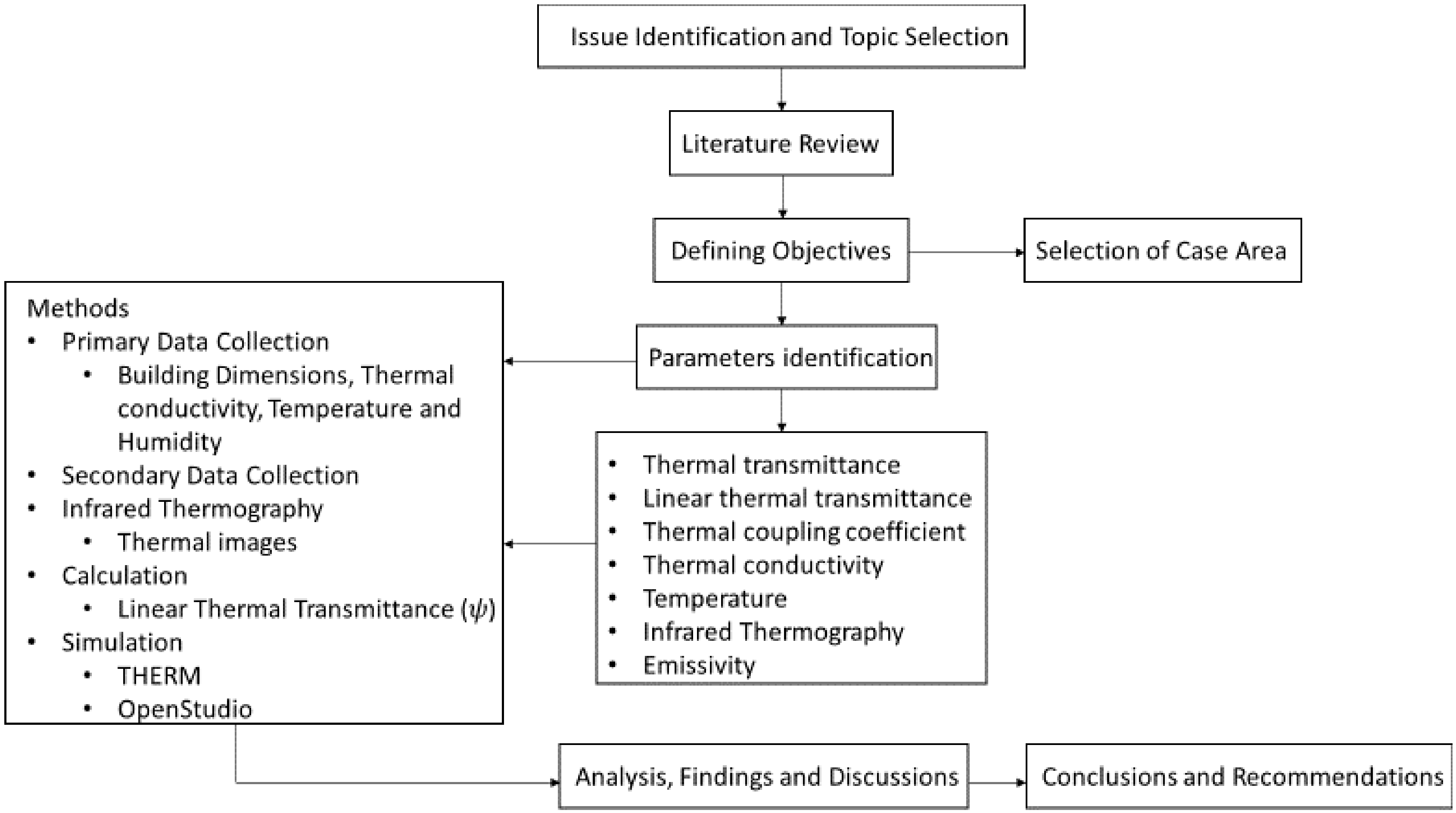

Figure 1: Research Framework of the Study

CHAPTER 2 LITERATURE REVIEW

2.1 Heat Transfer Mechanism

The transfer of energy due of temperature difference is referred to as heat transfer. The flow of heat is always from higher temperature to lower temperature naturally, as materials try to balance out the difference in temperature (Lienhard IV & Leinhard V, 2019). Generally, flow of heat occurs in three different mechanism from one location to another:

Conduction

Conduction refers to the process where heat moves from a warmer area to a cooler one within a material due to direct contact at the molecular level. It involves the transfer of thermal energy between adjacent particles without any movement or mixing of the material itself (Levenspiel, 2014). In building, conduction occurs when the heat moves through building components such as floors, walls, roofs and other structural materials. The rate of heat transfer through the building components depends on the thermal properties of these materials and the difference in temperature between the outer and inner environment ((BEEN), 2024).

Convection

Convection refers to the transfer of heat through the movement of fluid masses. There are two main types of convection: natural convection, which occurs due to temperature induced density differences in the fluid leading to circulation, and forced convection, where an external device like a fan or pump drives the fluid movement to facilitate heat transfer (Levenspiel, 2014). In buildings, convection heat transfer happens in two ways, one of which involves the transfer of heat from a wall's surface to the nearby air. The air molecules near the higher temperature air is heated up which results in the decrease in density of air, leading to less weight compared to the air away from this area and then the heated air starts moving upwards. Colder air then replaces this upward moving air, this process is continuous and is a natural convection process. Secondly, air exchange occurs through openings in buildings such as cracks and fenestration. The extent of heat transfer through air exchange is influenced by various factors such as the size of the openings, wind speed outside as well as the temperature difference between the interior and exterior environment ((BEEN), 2024).

Radiation

Radiation is essentially the heat transferred between surfaces through electromagnetic waves. Hotter body originate radiation like light, infrared, ultraviolet and radio waves which are then absorbed by a cooler body (Levenspiel, 2014). The greater is the temperature, greater the radiation effect will be and shorter the wavelength of the radiation emitted by an object. The thermal radiation of building materials has wavelengths higher than 3000nm. Radiative heat transfer through buildings takes place through short wave and long wave radiation. Short wave radiation is released by the sun which passes through the transparent building components such windows and doors. Long wave radiation is emitted by all building components as well as the surface of the human body ((BEEN), 2024).

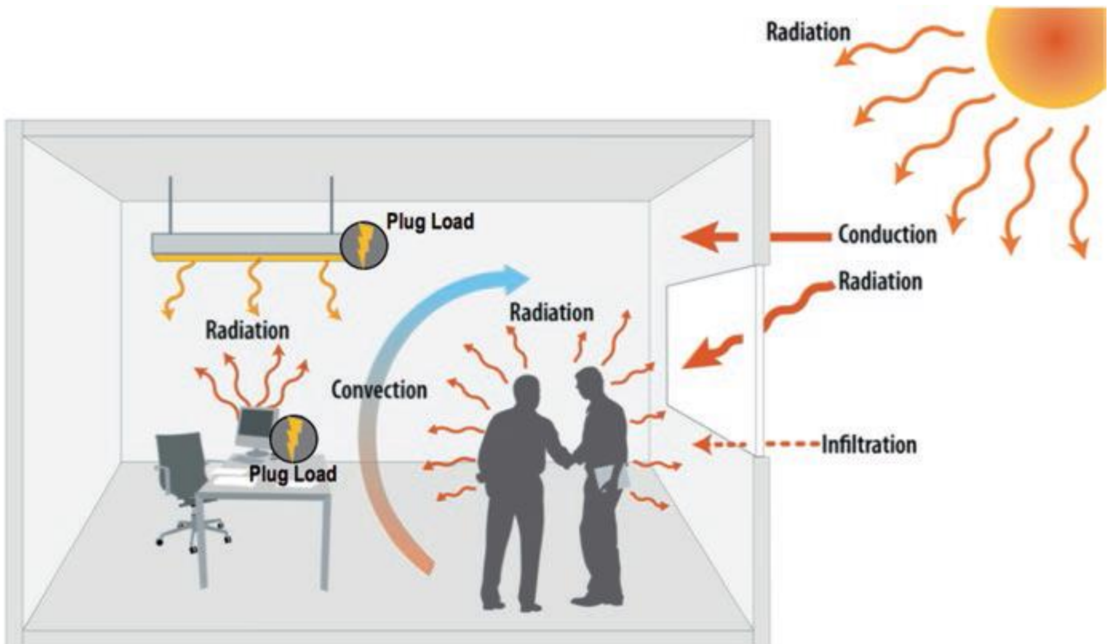

Figure 2: Heat transfer mechanism within a space (Brackney et al., 2018).

Sensible heat and latent heat are two forms of heat transfer exchange principles in a building. The transfer of heat which causes a change in the temperature of a substance without changing its form is the sensible heat whereas when a substance changes its from without changing its temperature it is latent heat. There are various heat sources for a building which can be internal as well as external. For internal heat gains, these can be through occupancy heat gains, lighting heat gains and equipment heat gains. The heat transferred through the building envelope from natural sources like the sun, earth and external environment describe the external heat gains ((BEEN), 2024).

Figure 3: Internal heat gains through occupants, equipment and lighting ((BEEN), 2024).

2.2 Thermal bridge

Thermal bridge is a type of conductive heat transfer through materials. The speed of heat transfer is influenced by both the material's thermal conductivity and the temperature difference across the thermal bridge. When a temperature gradient exists, heat tends to move along the path offering the least resistance, typically through materials with higher thermal conductivity. Thermal bridging refers to a situation in a building where certain elements with higher thermal conductivity create a direct path for heat flow between the interior and exterior, bypassing the better insulated parts of the building envelope (Kumar, 2023). There are two main negative effects caused due to the presence of thermal bridges firstly, the increase of energy losses through the building envelope and secondly, the internal surface temperature reduction which may cause condensation and mold growth (Nardi et al., 2015). Thermal bridges can be classified into:

Geometrical thermal bridge

The change in the geometry or shape of the building structure develops a thermal anomaly referred to as geometrical thermal bridge (Nagy, 2014). Thermal bridging occurs in parts of a building envelope where there is a mismatch between the internal heat absorbing surfaces and the external heat releasing surfaces, typically found at locations like building corners and edges. Thermal bridge at corner occurs at the junction between wall to roof or floor as well as between wall to wall (Alhawari & Mukhopadhyaya, June 2018).

Structural thermal bridge

This type of thermal bridge occurs when the insulation layer of the building's exterior envelope is interrupted or penetrated by another material or component. These are basic type of thermal bridges and cause significant negative impacts. A discontinuity is caused in the insulation layers of the envelope due to this. Edges of buildings, projection of balconies are structural thermal bridges (Alhawari & Mukhopadhyaya, June 2018).

Material thermal bridge

This type of thermal bridge can form when the material composition of a building element changes, even if its shape or geometry remains unchanged (Nagy, 2014).

Repeating thermal bridge

These thermal bridges occur in a consistent, repeating pattern across a section of the building envelope, often due to regular structural components like studs (Nagy, 2014).

Non-repeating thermal bridge

This type of thermal bridge occurs appears in a recurring manner and typically occurs at points where the continuity of the building's thermal insulation is disrupted (Nagy, 2014).

Linear thermal bridge

The type of thermal bridge that occurs from breaks in the continuity of the thermal envelope that extend along a specific length (Nagy, 2014). Linear thermal bridges are thermal irregularities that occur in a straight line across a building surface. For example, floor slabs, building corners, parapets or transitions between components whose characteristics lengths can be reduced to a line. The linear thermal bridges are defined by the linear thermal transmittance for the additional heat flow through this thermal anomaly (Norris et al., 2012). Common locations for linear thermal bridges include the connections between external walls and roofs or floors, at building corners, where internal walls meet external walls or roofs, at intersections between intermediate floors and exterior walls, and around structural columns, windows and doors (BS EN ISO 14683:2007, 2007).

Point thermal bridge

The type of thermal bridge that occur in one spot (Nagy, 2014). These thermal bridges are isolated occurrences that appear at specific points within the building envelope. They are singular thermal anomalies, typically caused by elements like beams or pipe penetrations that pass through the envelope. The point thermal bridges are defined by the point thermal transmittance for the additional heat flow through this thermal anomaly (Norris et al., 2012).

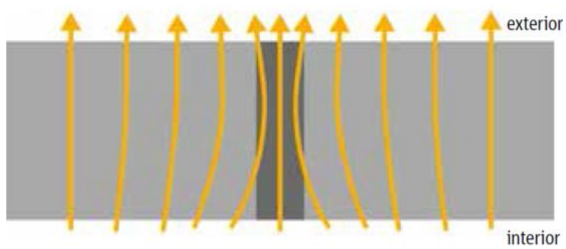

Figure 4: Material Thermal Bridge (Isokorb, 2018)

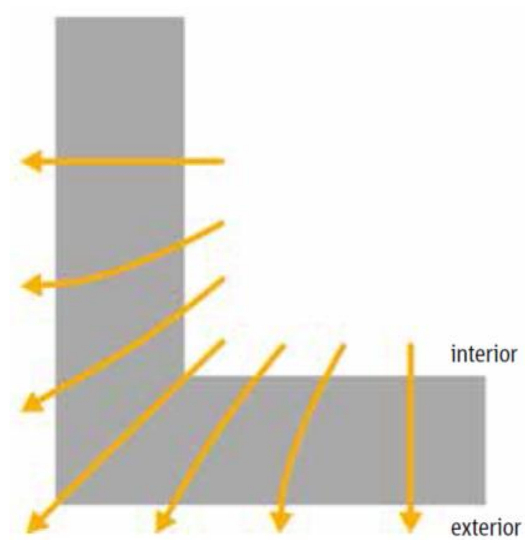

Figure 5: Geometric Thermal Bridge (Isokorb, 2018)

2.3 Thermal Transmittance

Thermal transmittance which is also referred to as the U-value, represents the rate at which heat passes through a material per unit area for a given temperature difference across its surfaces under steady state conditions. It is a key metric used to describe the insulating performance of building materials. Thermal transmittance is the rate of transfer of heat through matter. Essentially, thermal transmittance measures how much heat flows through a component, with lower U-values indicating better insulation and greater potential for energy savings in buildings by minimizing the influence of external climate conditions. The unit of thermal transmittance is W/m^2k (Santana et al., 2020). In heat transfer calculations, three primary types of transmittance are considered: clear field, linear and point transmittance. The clear field pertains to the standard, uninterrupted part of a building elements, while linear and point transmittances refer to thermal irregularities or bridges (Norris et al., 2012).

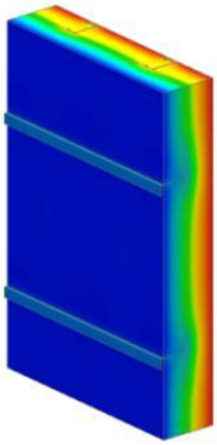

Figure 6: Clear field example (Norris et al., 2012)

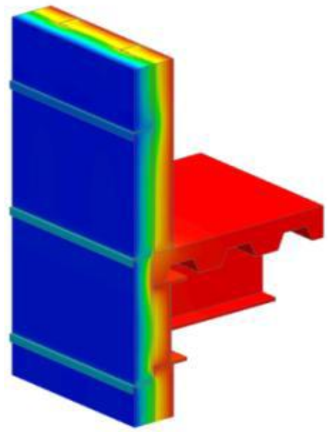

Figure 7: Linear anomaly example (Norris et al., 2012)

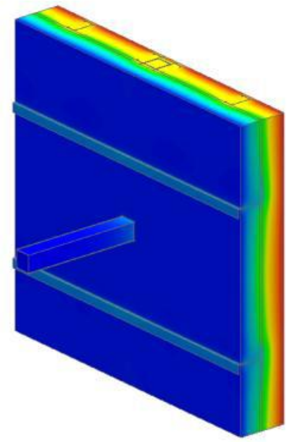

Figure 8: Point anomaly example (Norris et al., 2012)

Linear Thermal Transmittance (ψ)

The heat flow coefficient indicates the additional heat transfer caused by linear thermal bridges, which are not accounted for in the standard clear field U-value. These types of thermal bridges usually appear at junctions or connection details within the building envelope (Hershfield, 2021). Linear thermal transmittance is the heat flow rate per unit length for a given temperature difference between the indoor and outdoor environment where thermal bridge exists. Linear thermal transmittance can be determined through numerical calculations, thermal bridge catalogues, manual calculations or through default values (BS EN ISO 14683:2007, 2007).

Point Thermal Transmittance (χ)

The heat flow coefficient represents the additional heat transfer due to point thermal bridges, this type of thermal anomalies is also excluded from the clear field U-value. These occur at specific, countable locations and can be individually considered in U-value calculations (Hershfield, 2021).

The transmission heat transfer coefficient takes into account not only the heat loss through the primary building envelope components but also the additional heat flow due to thermal bridges, as outlined in (BS EN ISO 14683:2007, 2007):

$$H_D = \sum_i A_i U_i + \sum_k l_k \psi_k + \sum_j \chi_j$$

Where,

A_i refers to the surface area of i-th building envelop component (in m^2)

U_i denotes thermal transmittance of i-th building envelope component (in $W/(m^2.K)$)

l_k is the length of the k-th linear thermal bridge (in m)

ψ_k represents the linear thermal transmittance of k-th linear thermal bridge (in W/(m.K))

χ_j denotes the point thermal transmittance of j-th point thermal bridge (in W/K)

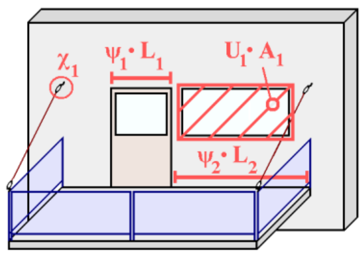

Figure 9: Example on where to use different thermal transmittance (Source: (Nyberg, 2011; Nyberg, 2011))

Several approaches exist to determine the linear thermal transmittance values. These include: numerical calculations (typical accuracy within $\pm$ 5%), thermal bridge catalogues (approximate accuracy $\pm$ 20%), manual calculations (similar accuracy of $\pm$ 20%) and default values, which may vary widely (accuracy 0% to 50%) (BS EN ISO 14683:2007, 2007).

Furthermore, BS EN ISO 10211:2007 (2007) provides a method for calculating the linear thermal transmittance (ψ) of a thermal bridge that separates two distinct environments, using the formula:

$$\psi = L_{2D} - \sum_{j=1}^{Nj} Ujlj$$

Where,

L_{2D} refers to the thermal coupling coefficient derived from a two-dimensional heat transfer analysis separating the two environments being considered

U_j denotes one-dimensional thermal transmittance component j, separating the two environments being considered

l_j represents the length in which the value U_j applies

2.4 Thermal conductivity

Thermal conductivity defines a material's ability to conduct heat. It essentially describes how easily heat can transfer through a material. Materials which have higher thermal conductivity, transfer more heat whereas those with lower thermal conductivity values serve as better insulators by reducing the transfer of heat through that material. Thermal conductivity values of many of the common building materials such as reinforced cement concrete, brick wall etc. typically range between 0.6 and 1.0 W/m-K whereas insulation materials typically have values less than 0.1 W/m-K. Similarly, higher thermal conductivity materials also have higher density and specific heat capacity values. Thermal conductivity is a natural property and is only dependent on the material ((BEEN), 2024). Thermal conductivity measures the ease in which heat flows through a certain material. Lower thermal conductivity values mean the less heat flows through a material and greater insulation properties. Thermal conductivity depends on certain characteristics of a material such as density and specific heat capacity. Materials having thermal conductivity values lower than 0.08 W/m-K are considered as insulation materials. Lower the thermal conductivity of a material higher the resistance against heat gains and higher the conductivity lower the resistance (UN Habitat, 2015).

2.5 Impacts of Thermal bridge

Thermal bridging can lead to higher energy consumption for heating or cooling a conditioned space, as it causes heat loss in winter and heat gain in summer. When there's a significant temperature difference between indoors and outdoors, and the indoor air is warm and humid, condensation can from within the building envelope at thermal bridge points due to the cooler interior surface temperature in those areas (Kumar, 2023). Thermal bridges affect a building's energy efficiency by increasing heat flow through the building envelope, leading to extra transmission losses during both summer and winter. Their overall influence on heating energy demand can be significant, potentially reaching up to 30% (Erhorn-Kluttig & Erhorn, 2009). Overlooking of major thermal bridging areas or locations such as a balcony can lead to undervaluing of 20% to 70% of the total heat flow. A reduction in the total thermal resistance of the plain wall due to thermal bridge may occur by almost 40% (Alhawari & Mukhopadhyaya, June 2018). The impact and influence of thermal bridges increases the overall heat transmission losses of a building as the building envelope insulation becomes better (Ilomets et al., 2014). A localized drop in thermal resistance over a thermal bridge leads to lower inner surface temperatures during the heating season. This temperature drop can result in condensation and mold formation, potentially deteriorating the quality of building materials and lowering the indoor air quality (Evola et al., 2011).

Ge, McClung, & Zhang (2013) in their study used a 2D heat transfer simulation (THERM) along with whole building energy simulation (eQuest) to access the impact of introducing a balcony thermal break (insulated balcony separator-EPS module) on the overall heat transmittance along with consumption of energy for heating and cooling, for a twenty six storey multi unit residential building in Canada. The installation of the thermal breaks reduced the U value by 72 to 85%, whereas the heating and cooling load could be reduced by 6 to 16% and 1 to 3% respectively. The findings demonstrate that elimination of thermal bridges through thermal breaks is effective to enhance the performance of a building envelope, thermally.

Altman & Kim, (2014) in their study used computer simulations (DesignBuilder) to quantify the impact on heating energy consumption through the replacement of conventional steel lintels with glass reinforced plastic lintels for a typical four bedroom terraced house in UK. The introduction of the glass reinforced plastic lintels in doors and windows presented an improvement in the energy performance levels especially, in heating energy consumption, CO_2 emisssions as well as general cost of energy. Compared to the conventional use of steel in lintels a 10% reduction in the energy demand was achieved.

Ge & Baba, (2015) in their study employed WUFI Plus which is a comprehensive simulation tool for heat, air and mositure (HAM) analysis, to explore the dynamic effect of thermal bridges on the energy performance of a two storey residential building in Canada across two different climatic regions. They evaluated three approaches to represent htermal bridges: the equivalent U-value method, the equivalent wall method and direct 2D/3D modelling. When comparing the results to those obtained through detailed 3D simulations for calculating annal heating and cooling loads, the study found that in cold climates, the equivalent U-value and equivalent wall methods underestimated energy loads by approximately 8 to 13% and 4 to

9% respectively. In hot climates, the underestimations were around 17% for the equivalent U-value method and 14% for the equivalent wall method.

Pelss, Blumberga, & Kamenders, (2010) in their study used detailed calculation method using computer software (THERM) as well as a simplified calculation method to investigate the thermal bridging impact on the transmission heat losses of a low energy house in Latvia. Through the study it was found that 7.7% of additional heat transmission losses was attributed to thermal bridges from the building envelope. The finding of the study suggested that the quality of construction solutions, especially at the junctions between window frames and the outer wall need to be considered carefully.

2.6 Calculation of Thermal bridges

Various European countries have outlined specific approaches for calculating thermal bridges within their building codes. In France, thermal bridge values are determined using designated energy calculation software, where the use of official software is mandatory for assessing energy performance. In countries like Austria, Cyprus, Greece and Spain, energy simulation tools utilize predefined, tabulated thermal bridge values that are automatically applied without the need for user input. Belgium adopts a simpler method based on predefined verification rules- if these rules are met, there is no need to calculate the linear thermal transmittance values. In Estonia, standardized values listed in national legislation are permitted for use in thermal bridge calculations. Meanwhile, Romania and Sweden incorporate thermal bridge effects within average U-values, where the calculated mean U-values for envelope elements already account for both linear and point thermal bridges (Kuusk et al., 2017).

There are also other calculation methods for the determination of thermal bridges. Some of which are the default value method which estimates the direct heat transfer coefficient through the building envelope using simple calculation processes. In this method default values of linear and point thermal transmittance coefficient are used, hence this method has the least accuracy among all the calculation methods. Surface temperature and condensation estimation is not applicable using this method. ISO 14683 specifies simplified thermal bridge catalogue for the determination of thermal bridges, this method only recognizes effect of the linear thermal bridges, ignoring the effect of point thermal bridges. This gives the default values of thermal bridges at different locations in the building envelope components. Another method for calculating thermal bridges are through numerical calculation method which is one of the most accurate methods for calculating linear thermal transmittance. ISO 10211 gives details on the numerical calculation method. One dimensional, two dimensional and three-dimensional heat transfer are considered to estimate the total heat transfer through building envelope. There are thermal bridging catalogs which provides values for linear thermal transmittance for a variety of construction details, these are values which were calculated by individual groups and experts through various analysis and simulations. BC housing have released a thermal bridging catalog to determine thermal bridging values at various locations (Jahangiri, 2021).

2.7 Infrared Thermography

Thermal infrared imaging is an effective, non-invasive method for conducting qualitative assessments of a building's envelope performance. Infrared thermography analysis is considered one of the most dependable techniques to investigate thermal bridges by finding weak spots in the building envelope. Infrared thermography works by detecting the infrared radiation emitted by a surface, converting that radiation into temperature data and generating an image that illustrates the temperature distribution (Bianchi et al., 2014). The temperature variations shown in thermographic images help reveal thermal irregularities, these irregularities can be linked to issues such as cracks, moisture intrusion, infiltration or heat loss. A more in-depth evaluation of these images can determine the severity of the anomalies, allowing for timely intervention and targeted improvements to enhance a building's energy efficiency (Santiso et al., 2024). The global use of infrared thermography has grown significantly, especially in research focused on surface heat transfer analysis. It is recognized as a dependable technique for measuring surface temperature distribution. For optimal results when inspecting external building components, it is recommended to carry out thermographic scans at night or under overcast conditions, as this minimizes interference from solar radiation and other environmental influences such as wind. Accurate temperature field analysis requires knowledge of factors such as the material's emissivity, the reflective temperature and the atmospheric transmittance. In building envelope diagnostics, infrared thermography is valuable for detecting various issues, including heat loss, compromised or missing insulation in walls and roofs, thermal bridges, air leakage and moisture intrusion (Fokaides & Kalogirou, 2011). In civil construction works, infrared thermography has been used as a non-destructive monitoring tool of buildings, both in a qualitative aspect as well as in a quantitative aspect. The qualitative analysis provides instantaneous reports as its focus is the profile and not the values. In quantitative analysis there is a possibility to define the seriousness of the condition for the studied object, this helps in the accurate determination of the temperature at a particular point in a certain region (Silva et al., 2019). Potential reduction of additional energy usage for space heating and cooling could be significantly achieved with the analysis of thermal bridges. The thermal camera's detectors detect infrared radiation which are then executed by the camera's image processor. This is then transformed by the camera into a pixilated image which is known as a thermogram. Each color of the pixel in the image displays an associated temperature level (Kaymaz, 2019). Accurate input details of various parameters such as emissivity of the examined material, indoor air temperature, relative humidity and shooting distance, needs to be supplied to proper evaluation (Nardi et al., 2015).

2.8 Infrared Thermography in assessment of Thermal bridges

Researchers who have evaluated the heat loss caused by thermal bridging have used different approaches. Also summarized in Table 1.

Asdrubali, Baldinelli, & Bianchi (2012) in their study carried out a quantitative analysis, using infrared thermography through thermographic surveys along with heat flow meters and then carry out analytical processing. The researchers represented heat loss due to thermal bridging using a ration known as the incidence factor, which quantifies the increase in heat transfer when a thermal bridge is present. This factor was validated through analysis of thermal bridge formed between window glazing and the window frame. FLUENT software was used for the Computational Fluid Dynamic analysis for finite volume analysis. The thermal output gathered from the three methods were very similar giving similar values of the incidence factor of the thermal bridge. Through simulations it was found that thermal bridges caused an overall heat loss of 13.4% which reduced to 8.8% with a correction of the thermal bridge through insulation in winter time.

Bianchi, et al. (2014) conducted a study involving a quantitative assessment using infrared thermography during on site measurement to investigate energy loss in a building. The analysis focused on evaluating heat loss through the external walls, ceiling and floor. This study was a futher continuation of the study in 2012. This study concerend the application and an experimental validation in a full scale continuously monitored building. The thermography results were compared to the quantitative measured data.

O'Grady, Lechowska, & Harte (2016) in their study presented a method for directly quantifying heat flow from thermal bridges using only infrared thermography, without relying on heat flow meters (HFM) or other calculation methods. This study only uses infrared thermography to quantify the additional heat loss due to thermal bridging. Their approach involved calculating the heat flow rate for each pixel along a thermal image line, allowing for a complete assessment of heat loss caused by thermal bridges. Through this study it was found that linear thermal transmittance could be calculated which mirror the real thermal performance of the thermal bridge.

Carramiñana, et al. (2024) in their study conducted an in-depth investigation of thermal bridges with a specific focus on slab and balcony connections in two buildings, located in Spain. Both through a qualitative and quantitative aspect to evaluate the impact of thermal bridges on energy efficiency. Thermographic imaging was employed for qualitative analysis, while heat flow meter was used to measure thermal transmittance. Additionally, overall annual energy demand was estimated using building energy simulation software (Líder-Calener Unified Tool, an official Spanish software). Through the study it was found that about 40% of the total annual energy needs of a resisdential building were caused because of thermal bridges, with balcony facades and slab edge junctions identified as the most critical areas.

Ramenah (2024) in his study highlighted the assessment of balcony to wall thermal bridge using infrared thermography. The intent of the research was to show the thermal imaging method as a process to provide quality assurance for buildings by determining the position and scale of thermal bridges.

Smusz & Korzeniowski (2018) in their study applied infrared thermography during the winter season, under actual conditions of the building to study the effect of thermal bridges on heat losses through the building envelope. COMSOL Multiphysics commercial software was used to verify and validate the results of the two- dimensional numerical calculations. Through this study it was found that a fast and simple heat loss evaluation can be carried out in situ with the use of infrared thermography measurements.

Choi, et al. (2022) in their study analysed the faults in the insulation at the window wall joint through the use of infrared thermography. These faults which are caused by thermal bridges were examined in a dynamic environment. For the verification of the study, a chamber that allows the temperature to be controlled was constructed and accurate thermal inspection with a thermal camera was carried out into cases with and without insulation at window wall joints. Simulation were performed with the use of different properties as variable to match the simulation results with the thermal image results. The result of the surface temperature from simulation and pattern close to the thermal image results which were obtained when the insulation performance was reduced was confirmed.

Kaymaz (2019) in her study used infrared thermography as a visualization technique for thermal bridges and recognize patterns for thermal anomalies of exposed surfaces. An apartment block was considered for the study focusing on the external envelope components. External wall system componets with infill masonry walls and transparent sub components were examined from inside and outside of the building. Through this research she concluded that infrared thermography can be practically used on site for thermal bridge diagnostics.

Moga, et al. (2023) in their study developed a software THERMOG which used infrared thermography for the evaluation of building envelope thermal performance under actual real world operating conditions. The study’s aim was to examine and confirm the accuracy of their software designed to assess the thermal resistance of building components directly on site. In their study they used aerial and terrestrail thermograhy methods for evaluation. They presented their initial findings which will be used to adjust any limitations and weaknesses and will be tesetd for various building types in different climatic conditions.

2.9 THERM

THERM is a computer program developed at Lawrence Berkeley National Laboratory (LBNL) for the purpose of heat transfer in buildings. THERM is used to simulate two-dimensional heat transfer in various building elements, including windows, walls, roofs, foundations, doors and other areas where thermal bridging may occur. It enables detailed assessment of energy performance and surface temperature distribution, which can help identify issues related to condensation, moisture buildup and potential structural problems. The software conducts its analysis using the finite element method to model heat transfer through conduction and radiation in two dimensions (Berkeley Lab, 2023).

THERM utilizes the finite element method to perform analysis. It enables the evaluation of two-dimensional steady state heat transfer through various building elements, helping to identify localized changes in thermal transmittance caused by variations in heat flow. This software also shows the temperature distribution of the modelled building components (Nardi et al., 2015). THERM is a software program which uses the finite element method for modelling two-dimensional heat transfer problems in a stead state condition. This software allows the modelling of two-dimensional heat transfer effects of various building components where an issue of thermal bridges is present. The heat transfer analysis capability of this software allows the evaluation of a building components energy efficiency as well as local temperature patterns, which may lead to issues in the building such as condensation, dampness, mold growth and structural integrity. This software has also been used for the creation of thermal bridge catalogues of various building components (Pelss et al., 2010).

2.10 OpenStudio

OpenStudio is a software tool which supports whole building energy modelling which uses the EnergyPlus engine and Radiance for advanced daylight analysis. Open Studio is one of the most powerful building energy model software which is a physics-based simulation software for building energy use describing the physical building, the patterns of energy use and prevailing weather conditions. Buildings using building energy model have shown they use less energy, studies showing up to 20% less compared to those which are designed without it. They also play a major role in developing and updating codes and standards that supports energy efficiency in building projects. In each stage during a building's lifecycle, building energy model guides us to make decisions (Brackney et al., 2018).

OpenStudio is a software used for building energy modeling (BEM), aimed at reducing the effort required to building and maintain application that use BEM. The building component library (BCL) is an "open online database of OpenStudio" related contents which have weather files, construction and equipment specifications. OpenStudio provides an "application programming interface (API)" to assess the EnergyPlus modelling engine, this interface make it easier for users to model buildings. Sketchup Plug-in which is a popular 3D modelling tool, this helps the users to create geometry in quick and simple manner, needed for EnergyPlus. This BCL contains measures which are used for various tasks such as creating custom reports and analysis of specific functions (OpenStudio, 2023).

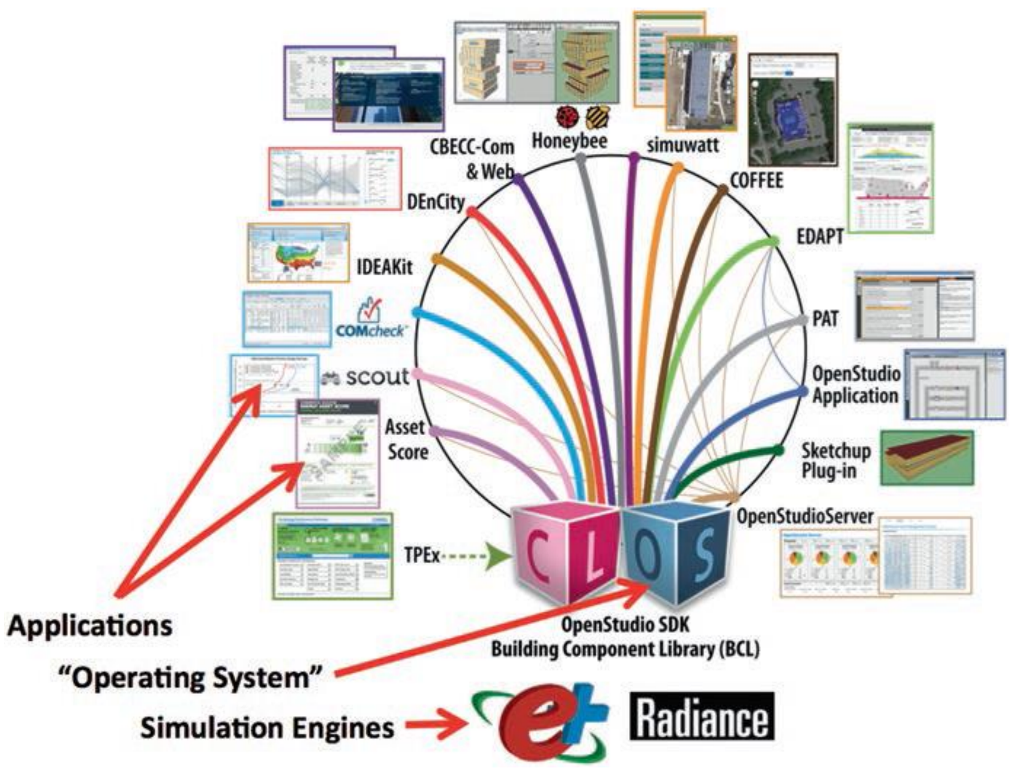

Figure 10: OpenStudio as a BEM operating system (Brackney et al., 2018)

In the OpenStudio application the work process is organized in a certain manner, where each tab serves an important purpose which need to be carried out. The tab on the left side of the application have to be entered for proper simulation of any model. The tabs include the following: Site (to specify weather), schedules (to specify and define schedules applied to building loads, these range from equipment, lights, HVAC as well as people), construction (to specify materials and construction assemblies to be used in the building being modelled), loads (to define loads in each spaces or thermal zones), space types (to create profiles of how each space in the building is occupied), geometry (define the geometry of the building, this can be done in the application itself or can be carried out in Sketchup through the OpenStudio plugin), building (to assign a default construction set and schedule set, which will be applied as default for the whole building components), spaces (to assign profiles to each building spaces), thermal zones (to assign thermal zones to each space or group spaces into thermal zones, assign zone equipment, this is the main component through which the simulation of the whole building is carried out), HVAC (to specify heating, cooling systems for the building), simulation settings (customize settings for simulation such as the time interval), measures (through the building component library new measures can be added, helps to transform OpenStudio model in a number of different ways), run simulations (to perform energy simulation of the modelled building) and reports (to generate reports from the simulation, the OpenStudio application gives reports in the EnergyPlus format, OpenStudio report format can also be generated through adding it in the measures tab) (Brackney et al., 2018).

2.11 Standards relating to Thermal bridges

"Thermal bridges in building construction – Heat flows and surface temperatures – Detailed calculation (BS EN ISO 10211:2007)" is the International Standard implemented in the UK. This standard outlines the requirements for creating both two-dimensional and three-dimensional geometric models of thermal bridges to numerically calculate heat flow used to evaluate overall heat loss from a building or its components and minimum surface temperatures, which help assess the potential for surface condensation. This standard provides methods for calculating flow of heat and surface temperatures in thermal bridge locations (locations in the building where insulation is weakened, leading to higher heat loss).

"Thermal bridges in building construction – Linear thermal transmittance – Simplified methods and default values (BS ISO 14683:2007)" is the International Standard implemented in the UK. This standard also addresses simplified approaches for calculating heat flows through linear thermal bridges found at junctions between building elements. It includes guidelines for thermal bridge catalogues, manual calculation techniques and provides default values for linear thermal transmittance. This standard provides simplified methods for estimating linear thermal transmittance of thermal bridges, which quantifies heat loss per unit length. This standard included default values for common construction components, reducing the need for complex calculations.

There are also national regulations to tackle the problem against thermal bridges mainly in Europe (Evola et al., 2011).

2.12 Energy Performance of buildings

Energy performance of a building is related to the amount of energy actually consumed to meet the different requirements for the functioning of a building which may include lighting, heating, cooling etc. (Agency, 2002). The energy performance of a building plays a crucial role in tracking how much energy it uses and the level of greenhouse gas emissions it contributes to the environment (Netatmo, 2023). Assessing a building's energy performance is essential for evaluating how efficiently energy is being used and serves as a foundation for making decisions to enhance energy efficiency. Energy performance classification is a valuable tool that presents building owners and the public with clear and accessible information about a building's energy efficiency. This helps motivate owners to take steps toward improving their building's energy performance. Several factors influence a building's energy performance, including climate conditions, the building envelope, energy and service systems, operational practices, maintenance, occupant behaviour and usage patterns, as well as indoor environment (Wang et al., 2012). Figure 11 shows the process to carry out simulation to generate various energy performance indicators.

Energy performance of buildings can be conducted in three levels based on the nature of the building services ("the whole building level, the system or service level and finally the component or equipment level"). Whole building performance indicators have been mostly developed for use in building rating and certifications when implementing building energy codes. Some common building level performance indicators are total site energy, energy use intensity (EUI), energy performance index (EPI), building efficiency index (BEI) etc. The system or service level refers to a combination of individual equipment and components that delivers a particular building service. Some common system level performance indicators are lighting power density, daylight effectiveness indicator, load energy ratio etc. The component level refers to the individual equipment which comprise the building system. Some common component level performance indicators are coefficient of performance (COP), energy efficiency ratio, luminous efficacy, energy star label etc. (Li et al., 2020).

Assessing a building's energy performance involves comparing its measured or estimated performance against a defined standard or reference system. These values may represent energy consumption of specific building systems or some characteristics of the buildings, but evaluations based on whole building energy consumption is common. Energy performance indicators such as energy use intensity are defined. Benchmarking is often used in energy performance evaluation through comparison with similar buildings, comparison of actual measured building energy performance against the broader building market. It offers a straightforward approach to provide stakeholders with insight into how a building performs by relating its overall energy performance index to established benchmarks. However, differences can exist between expected and actual performances, often referred to as the performance gap. Extremely detailed building physics simulations which require detailed parameter inputs are used during building energy simulation by skilled professionals and hence the output is expected to be highly accurate for energy performance predictions. But there is the possibility of performance gap in the predicted and observed performance due to various factors such as occupant behaviour, poor operational practices, poor onsite workmanship, simplification of simulation model, weather data and operational schedules. Hence these factors should be considered in order to minimize the performance gaps during evaluation of energy performance of a building (Borgstein et al., 2016).

Energy simulation software are a key factor in evaluating building energy consumption, to verify design performances as well as assess their impact on the environment. These simulations are an important factor to evaluate building energy consumption to maintain and achieve high performance building standards and in the future net zero standards. EnergyPlus and similar energy modelling software have been developed and are in use for the testing and validating the projected performance of buildings that are to be constructed. Inaccurate results and uncertainty could arise if more default options of the simulation software are used during the simulation process. There are also different simulation engines present for energy modelling simulation which also create inconsistency in the building energy performance estimation (Choi J. , 2017).

2.13 Energy Use Intensity (EUI)

Energy use intensity (EUI) is an indicator of a building's energy efficiency. It is applied in various ways, such as establishing energy performance goals before the design begins, comparing a building's design or operational efficiency to similar building types or assessing whether it meets the energy code standards, compliant with the energy code or not (AIA California, 2020). EUI represents the annual energy consumption per unit of floor area. It is determined by dividing the building's total yearly energy usage by its gross floor area (Bulman, 2022).

Energy use intensity (EUI) represents a building's energy consumption relative to its purpose, size and other features. It is determined by dividing the building's total annual energy use by its gross floor area. EUI serves as a key metric for assessing a building's energy efficiency and identifying opportunities for energy savings. It can also be used as a benchmarking tool, where tracking and recording a building's energy usage over time helps establish a performance baseline (Yang & Choi, 2015). EUI measures how much energy a building uses in relation to its size. Essentially, it serves as an indicator of energy efficiency- the lower the EUI, the more energy efficient the building is (Anderson, 2024).

Energy use intensity of residential buildings is shaped significantly by various factors such as features of a house, socio-demographic aspects, technology as well as energy linked to behavioural actions. Income levels of a household also plays a role in the energy use intensity, this value differs across different income groups, lower income households have a higher EUI compared to higher income households, this may be due to lack of capability or willingness to buy or upgrade to more energy efficient equipment and appliances (Chen et al., 2022).

Energy use intensity (EUI) is an indicator of a building's energy efficiency, design as well as operation. This index is used to set a benchmark or target to evaluate the energy performance of a building. A low value of EUI generally indicates a good energy performance of a building and vise versa for high EUI. But, the EUI varies based on the type of building (hospitals, schools, office, residential), all these have different baselines for EUI values and also impact the environment differently. This indicator helps us identify opportunities for energy saving, track performance over time and prioritize efficiency improvements (Flynn, 2021).

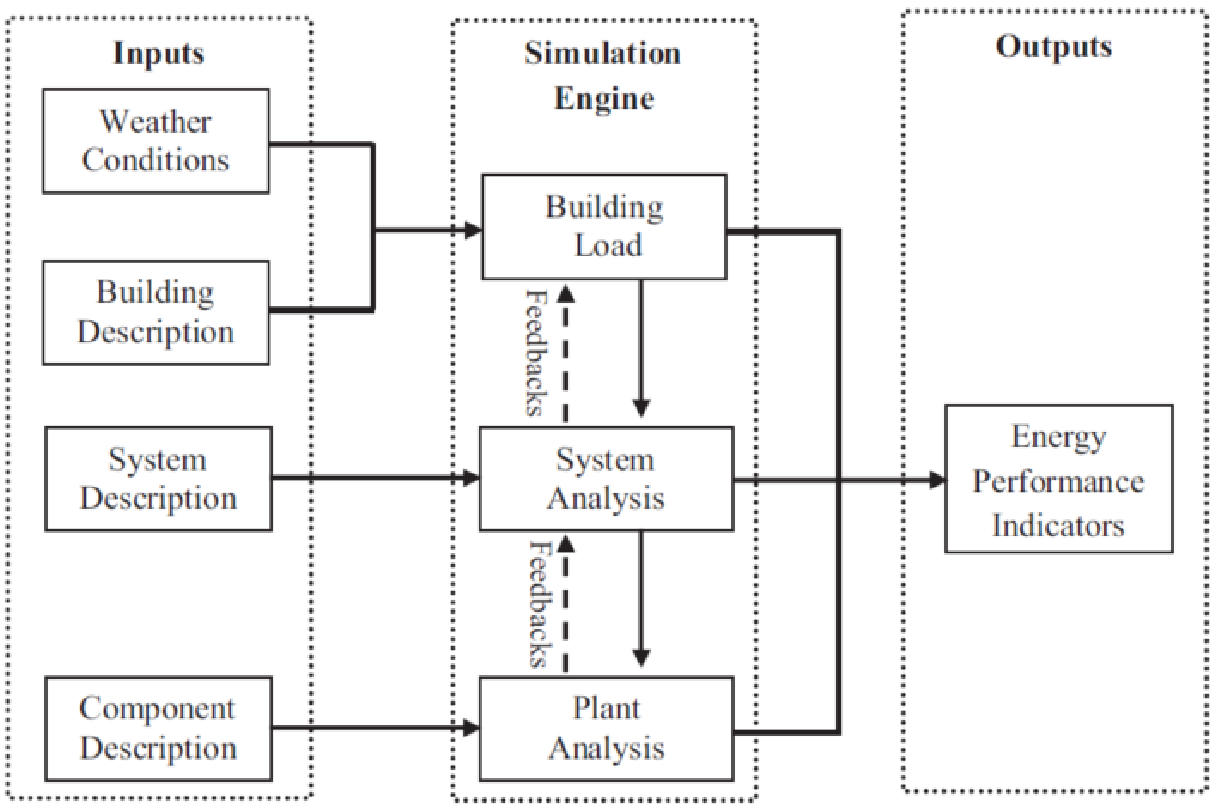

Figure 11: Main steps for a detailed simulation process (Wang et al., 2012)

Table 1: Summary of literature relating to infrared thermography in the assessment of thermal bridges

Literature Source	Title	Location	Criteria used	Key findings
(Asdrubali et al., 2012)	"A quantitative methodology to evaluate thermal bridges in buildings"	Italy	A quantitative analysis, using infrared thermography through thermographic surveys with heat flow meters and then carry out analytical processing. They expressed the loss of heat linked with thermal bridging as a ratio which shows the increase of heat loss, this ratio is the incidence factor. Thermal bridge between window glazing and window frame were evaluated. FLUENT software was used for CFD analysis.	The incidence factor values obtained with the 3 methods produced similar results. Through simulations it was found that thermal bridges caused an overall heat loss of 13.4% which reduced to 8.8% with a correction of the thermal bridge through insulation in winter time
(Bianchi et al., 2014)	"Infrared Thermography Assessment of Thermal Bridges in Building Envelope: Experimental Validation in a Test Room Setup"	Italy	Quantitative aspect of analysis was used, infrared thermography used in the field measurement with the objective of evaluating the energy losses through a building. External walls, ceiling and floor were evaluated. Further continuation of the 2012 study.	The results of the study showed that the methods of the study are dependable to quantify the incidence of thermal bridges in the envelope thermal losses.
(O'Grady et al., 2016)	"Infrared thermography technique as an in-situ method of assessing heat loss through thermal bridging"	Ireland	A method for determining actual rate of heat flow due to the thermal bridge in a building through the use of infrared thermography solely without using heat flow meters (HFM) and other calculation methods. Involved calculating rate of heat flow for each pixel on an infrared line produced by a thermal image.	Through this study it was found that linear thermal transmittance could be calculated which mirror the real thermal performance of the thermal bridge
(Smusz & Korzeniowski, 2018)	"Experimental investigation of thermal bridges in building at real conditions"	Poland	Applied infrared thermography in winter season under actual conditions of the building to study the effect of thermal bridges on heat losses through the building envelope. 2D numerical calculations were carried out with COMSOL software.	Through this study it was concluded that a fast and simple in-situ infrared thermography inspections can be applied to study the actual losses of heat in a building

Literature Source	Title	Location	Criteria used	Key findings
(Kaymaz, 2019)	"Monitoring thermal bridges by infrared thermography"	Turkey	Visualization of thermal bridges as well as thermal pattern generalization through the use of infrared thermography of exposed surfaces. An apartment block was considered for the study focusing on the external components from inside and outside the building.	Through this research she concluded that infrared thermography can be practically used on site for thermal bridge diagnostics
(Ramenah, 2024)	"Applying infrared thermography to a latest residential building in France: case study, verifying dwelling national thermal regulations RT 2012 mainly thermal bridges assessment"	France	Highlighted the assessment of balcony to wall thermal bridge using infrared thermography. A latest high-performance apartment was considered for the study.	Demonstrated that thermal imaging is a method of quality assurance for buildings by determining the position and magnitude of thermal bridges.
(Carramiñana et al., 2024)	"Influence of balcony thermal bridges on energy efficiency of dwellings in a warm semi arid dry Mediterranean Climate"	Spain	A comprehensive analysis of thermal bridges was carried out, with particular attention to balconies and slab edges in two buildings. Thermographic images were captured to qualitatively evaluate the thermal bridges, while a thermal transmittance flowmeter was used to measure their thermal transmittance. Additionally, the total annual energy requirements of the buildings were assessed using computer simulations.	This study revealed that thermal bridges accounted for roughly 40% of a residential building's total annual energy consumption, with the most significant thermal bridges identified at balcony facades and slab edge junctions.

CHAPTER 3 METHODOLOGY

This research uses a mixed method approach, combining both qualitative and quantitative methods to study and analyze thermal bridges in residential buildings. The study is primarily quantitative as it involves collecting measurable data and analyzing numerical data from thermal imaging and simulations, but it also includes quantitative aspects as well, as we use need to interpret and understand thermal patterns from the thermal images. The methodological framework structured around the research design, philosophical paradigms and practical execution are explained below.

3.1 Research Design

This research follows a mixed method design, where qualitative data such as thermal images supports the quantitative analysis gathered from simulations. The research begins with a thorough literature review of the subject, followed by thermographic inspection of certain residential buildings. Heat loss is then quantified through simulation software THERM, energy performance through OpenStudio and is verified with the thermal images.

3.2 Philosophy of Research

3.2.1 Ontology

This is the nature of reality, this research aligns with a realist ontology, understanding thermal bridges as an objective phenomenon influenced by material properties, geometry and environmental conditions. However, their detection and interpretation depend on observations and tools (infrared camera) as well as contextual factors (building design).

3.2.2 Epistemology

This is how knowledge is acquired, this research aligns with post positivism, as while objective truth exists, observations and measurements are influenced by the tools and our own interpretation. There are also limitations for our methods and tools, such as the accuracy of infrared camera, ambient conditions of the environment.

3.2.3 Axiology

This is concerned with the ethics involved in research, as this research concerns energy efficiency in buildings, the identification and prioritization of problems may be influenced by the authors background in the field.

3.3 Research Methodology

The surface temperature of the external building elements is typically consistent. However, thermal bridges disturb this consistency by lowering the surface temperatures on the interior side and raising them on the exterior side. These temperature variations can be clearly identified and captured using infrared imagery. In this study, a thermal imaging camera will be employed to detect thermal bridges and produce thermal patterns of exposed surfaces. Indoor and outdoor temperatures, along with relative humidity, will be measured/logged using a data logger. A residential building will be considered focusing on the external envelope components mainly the balcony slab and roof/wall junction. The external wall system components with infill masonry walls will be examined from inside and outside of the building. Thermal bridge is defined by linear thermal transmittance ψ.

$$\psi = L_{2D} - \sum_{j=1}^{k} Uj \cdot lj \text{ ....(i)}$$

where,

L_{2D} – thermal coupling coefficient of the component separating the two environments,

Uj – overall heat transfer coefficient

lj – length over which the value Uj applies

K – number of 1D components

Overall heat transfer coefficient (U) is given by,

$$U = \frac{1}{\frac{1}{ha}+\frac{l1}{k1}+\frac{l2}{k2}+\cdots+\frac{1}{hb}} \text{ ....(ii)}$$

where,

U = overall heat transfer coefficient (in W/m^2-K)

h_a,h_b = film coefficient (in W/m^2-K)

l_1,l_2… = thickness of material (in m)

$k_1, k_2 \ldots$ = thermal conductivity (in W/m-K)

For verification and validation of the results a two-dimensional numerical calculation need to be carried out. THERM is such a software which can be used for this. The results from the infrared calculations and the simulations are compared to verify the results.

Ambient temperatures will be measured for calculation of linear thermal transmittance as well as comparison with the results to increase the reliability of the calculated linear thermal transmittances. An infrared imaging camera will be used to determine thermal bridges. As the indoor environment can have a better controlled environment due to control over factors such as solar radiation and wind, the thermal imaging will be taken from the indoors maintaining the proper distance between object and camera as well as maintaining the emissivity settings.

The energy performance of the building will be carried out through building energy modelling (BEM) software OpenStudio. The impact of correction of the thermal bridging through certain measures such as an introduction of insulation material will be simulated to figure out the extent of reduction which can be achieved.

The methodology of the research study can be summarized into:

Selection of Case Study

After extensive literature review regarding thermal bridges and the identification of clear objectives of the research study, the selection of buildings for case study for thermographic inspections is carried out. Buildings representing a typical housing typology of the study region are selected.

Data Collection

Primary and secondary data were collected for this study. For primary data thermographic images were captured of the selected buildings focusing on areas in the buildings where thermal bridges would typically be present based on literature review carried out in the beginning of this research process. Thermographic inspection was focused on the building envelope components (building components exposed to the outdoor environment) excluding components only connected to interior environment. Similarly, temperature data was logged using data loggers for temperature analysis of indoor and outdoor conditions. This temperature data is required for use in 2D simulation in THERM. For secondary data, weather files are required for simulation in BEM software (OpenStudio). This were acquired from energy plus library. Material thermal properties were acquired from secondary sources, for this study ASHRAE handbook fundamentals was the source for various properties for example thermal conductivity, specific heat and density. The building geometry and material dimensions were acquired from architectural drawings and measurement at the site.

Simulation

THERM and OpenStudio are two simulation software which have been used in this study. They serve different purposes, THERM is a 2D heat transfer analysis software to assess the heat transfer of building components whereas, OpenStudio is a building energy modelling (BEM) software to assess the energy performance of a building. The primary and secondary data acquired have been used during the simulation process in this research. THERM helps us to validate the thermographic images captured of various building components which have been inspected as well as help us quantify the additional heat loss accumulated due to thermal anomalies like linear thermal bridges. OpenStudio helps us quantify the total energy a building requires for its functioning annually as well as breakdown which sources consume how much energy.

Analysis

Thermal images acquired from the thermographic inspection were analyzed in detail to figure out thermal patterns of thermal bridges in the building envelope and pinpoint specific areas where the thermal bridge location was prominent in all the inspected buildings. The study of the thermal images helps us to generalize the common locations of thermal bridges in similar typology of buildings, which helps us further analyze the additional heat flows through these locations from the use of heat transfer software like THERM.

Methodology Framework

The methodology framework has been shown in Figure 12.

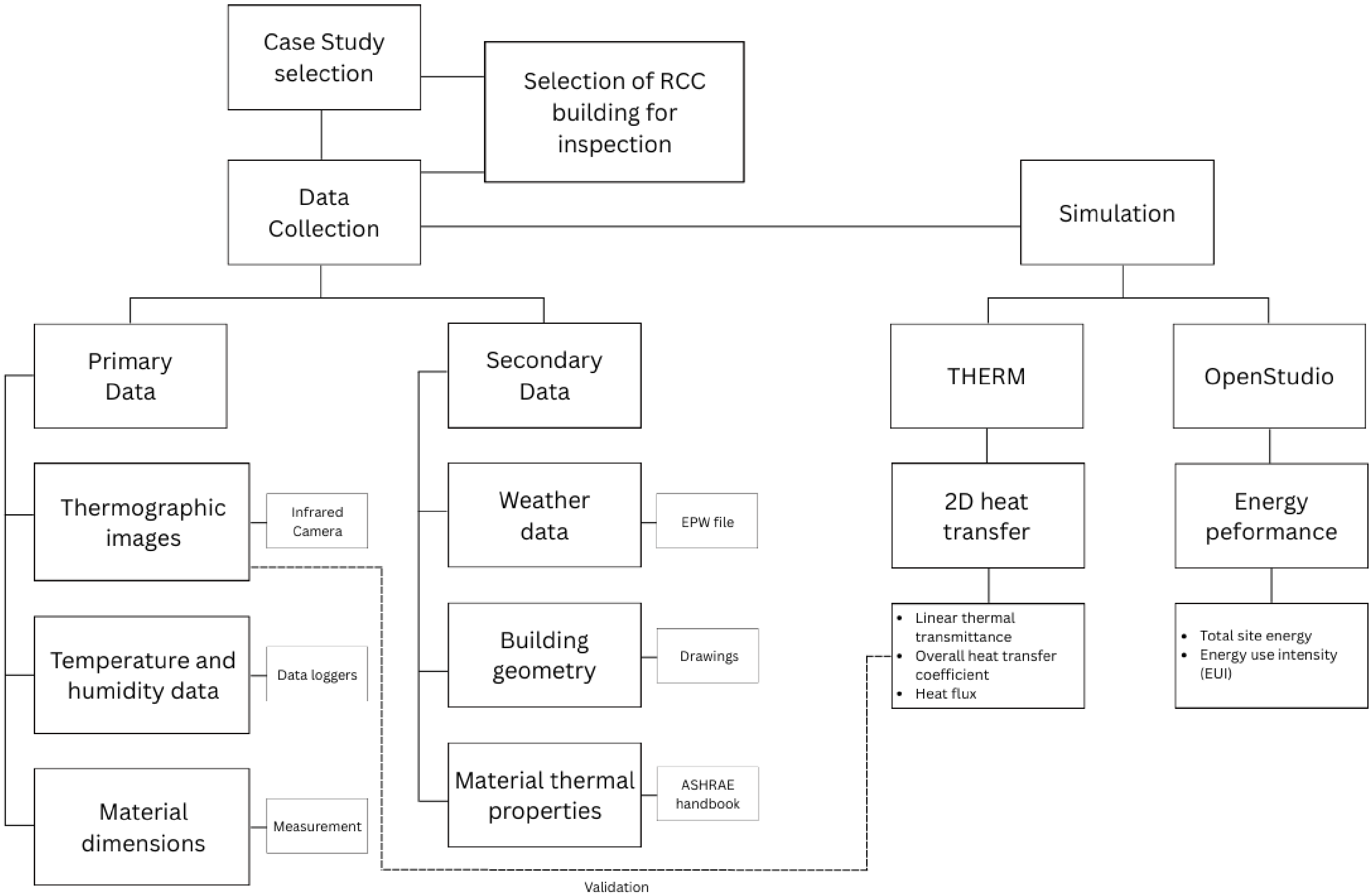

Figure 12: Research methodology Framework

CHAPTER 4 CASE STUDY

4.1 Introduction

A reinforced concrete structural frame consisting of columns, beams and slabs combined with infill masonry walls made of brick masonry with cement plaster and paint surface finishing, along with transparent elements such as window/door frame, glazing and window sill form a considerable part of the typology in Kathmandu, Nepal which is in a temperate region. The RC framed structure is very widespread in this region which may be considered suitable to assess thermal bridge.

According to National Population and Housing Census 2021 (National Statistics Office, 2023) approximately 54.10% of buildings in Kathmandu are RCC framed structures, 92.09% have outer walls of cement bonded bricks or stones and 86.78% have RCC roofs. The rapid urbanization of Kathmandu has replaced traditional materials such as timber, mud with reinforced cement concrete and brick or cement blocks with cement masonry due to its perceived durability and modernity as well as their strength and earthquake resistance. However, these buildings often lack thermal performance considerations increasing the energy inefficiency of these buildings. The RCC buildings typically have uninsulated slab projections such balconies, exposed columns and beams as well as poorly detailed window and wall junctions which also increase the likelihood of thermal bridges. Thermal insulation is rarely used in residential buildings in Kathmandu or in Nepal in general due to the cost consideration as well as due to the lack of awareness of thermal performance or energy efficiency. Also, the absence of strict building codes on insulation for any building typology in Nepal the use of thermal insulation is minimal. These make RCC buildings susceptible to energy loss, reinforcing the importance of thermal bridge detection and mitigation strategies. The standard procedure of building construction process of RCC framed buildings also simplifies the modelling procedure in THERM as well as OpenStudio compared to other building structures such as steel framed buildings or load bearing structures.

Kathmandu represents the warm temperate climate of Nepal, the main climatic condition in the Hilly region. In summers the outdoor temperatures range from 20 to 24°C while in the winter the mean temperature drops to 2°C. The temperature during the winter does not drop down drastically (Bodach et al., 2014). In the temperate climate of Kathmandu, during winters the low temperature may cause significant heat loss due to the presence of thermal bridges increasing the heating demand. Similarly, in summer due to the heat gain cooling demands are also increased. During monsoon there is high humidity in the region which may lead to condensation and mold risks due to the presence of thermal bridges. Identifying and mitigating thermal bridges in RCC structures could help improve indoor thermal comfort and energy efficiency.

For this case study, thermographic inspection with an IR camera is used to study 6 RCC framed structured buildings in different locations of Kathmandu (Figure 13) for a general assessment to identify common areas where thermal bridging may be prominent. Thermographic inspection of the whole building focusing on wall/slab joints, roof/wall joints, window/door frame junctions and balcony slab junctions are carried out.

Given Kathmandu's construction trends of the use RCC structured buildings, these buildings offer the most relevant case study for identifying and mitigating thermal bridging in Nepal's urban housing field. Due to the lack of use of insulation practices in these buildings, the issue of heat loss as well as energy loss is a serious issue to address. Focusing on RCC buildings ensures that the findings of this study are applicable to the majority of Kathmandu's urban building stock.

Data logging for indoor and outdoor ambient temperature and relative humidity were carried out only in one building, since the structures and the climate is similar. Similarly, the 2-dimensional heat transfer analysis using the software THERM will be used for a common general location of thermal bridge which can be further used similarly for other locations of thermal bridges.

The architectural characteristics of the building were studied from the existing drawings as well as from site evaluation. The one building selected for the purpose of data logging as well as for energy modelling simulation was a RCC building which represent the typical residential typology in Kathmandu and hence the result obtained could be generalized for similar buildings.

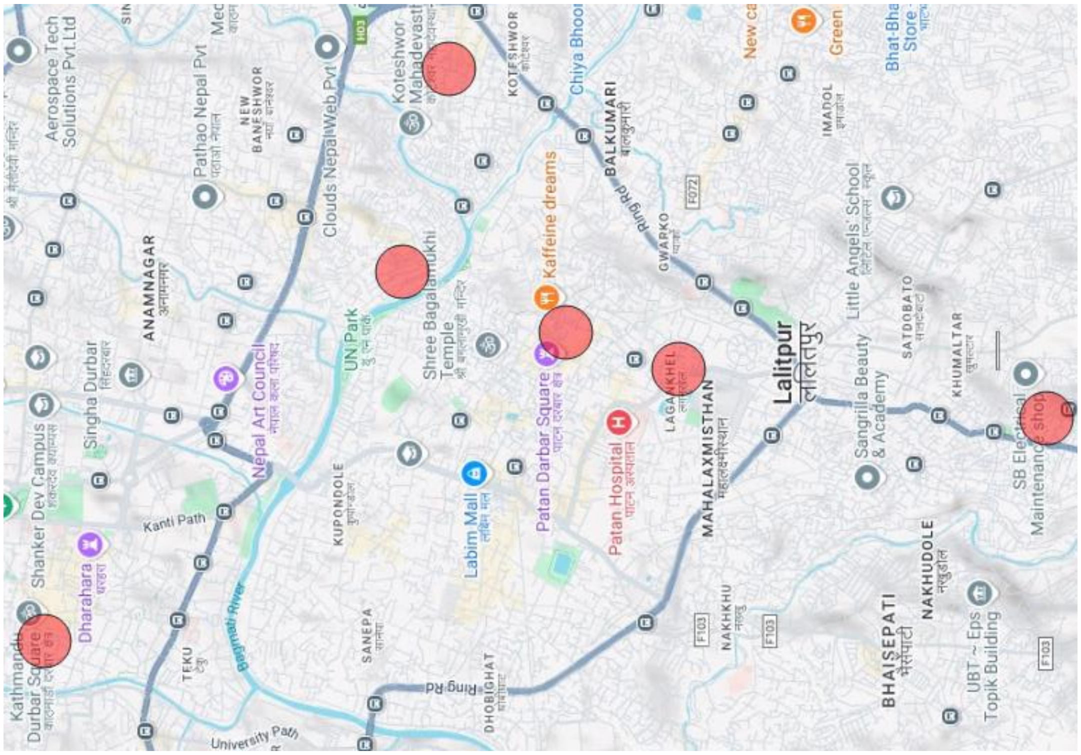

Figure 13: Location of buildings surveyed for thermographic inspection

4.2 Description of Selected Buildings

In total 6 buildings where selected for thermographic inspection for a general localization of thermal bridges in the building envelope. All of the 6 buildings selected for inspection where RCC framed structures with brick masonry which where chosen randomly with variations in the age of the building, the quality of the building materials as well as variation in the economic capability of the respective owners of the buildings. All 6 of the selected building were constructed using conventional RCC frame structure with brick infill walls, which are representative of the region's dominant building typology. The buildings varied in height, age and exterior finishes. None of the buildings featured application of thermal insulation or energy efficiency measures except use of energy efficient lighting (LED) or equipment. Table 2 gives a brief description of the buildings selected for thermographic inspection.

These buildings were selected to represent a range of construction practices, orientations, and finishes typically found in Kathmandu's residential areas. Building 1 in Koteshwor is approximately 15 years old and is a three and a half floor RCC building with cement brick walls. This building has balconies with exposed balcony slab. The exterior building envelope is cement plastered with an exterior paint finish. Building 2 is similarly a RCC building with cement brick walls located in Shankhamul similarly with a cement plaster and a exterior paint finish. The window frames in this building is wooden in contrast to the first building which have aluminium framed windows. Building 3 located in Basantapur is also a RCC building with cement brick infill walls but the exterior envelope is left exposed and not plastered or painted. The window frame of this building is also wooden. This is the oldest building among the building which were investigated. Building 4 in Khumaltar is the newest building among the investigated buildings which was built approximately 5 years ago. This is also a RCC framed building with cement plaster and a paint finish. The window frames as well as the door frames are constructed of aluminium. In all the other buildings the door frame was wooden. Building 5 in Lagankel is also a RCC framed building with cement brick walls along with cement plaster and paint finish. All the doors and windows are wooden framed. Finally, building 6 located in Mangalbazar is also RCC framed with cement brick walls with cement plaster and paint finish. The window and door frames of this building are also wooden. These building collectively illustrate the diversity in construction age, façade treatment and material usage prevalent in Kathmandu’s residential architecture, particularly among middle income households.

The building envelope components of the selected buildings where inspected with a thermal camera focusing on the components most likely to display thermal anomalies based on extensive literature review.

Table 2: Description of the buildings selected for thermographic inspections

S.No.	**Location**	**Age**	**Wall Material**	**Roof Type**	**Number of floors**	**Window and door frame**	**Thermal bridge focus area**
1	Koteshwor	~15	Cement Brick	RCC Slab	$3\frac{1}{2}$	Aluminium and Wooden	Roof wall junction, window/door

S.No.	Location	Age	Wall Material	Roof Type	Number of floors	Window and door frame	Thermal bridge focus area
							frames, balcony wall junction
2	Shankhamul	~18	Cement Brick	RCC Slab	$2\frac{1}{2}$	Wooden	Roof wall junction, window/door frames
3	Basantapur	~20	Cement Brick	RCC Slab	3	Wooden	Roof wall junction, window/door frames, balcony wall junction
4	Khumaltar	~5	Cement Brick	RCC Slab	$2\frac{1}{2}$	Aluminium	Roof wall junction, window/door frames
5	Lagankhel	~10	Cement Brick	RCC Slab	$3\frac{1}{2}$	Wooden	Roof wall junction, window/door frames, balcony wall junction
6	Mangalbazar	~18	Cement Brick	RCC Slab	4	Wooden	Roof wall junction, window frames

Figure 14: Photos of the 6 inspected RCC buildings for thermographic inspection

4.3 Energy modelling inputs

Thermographic inspection of various building envelope components gives a general identification of areas prone to thermal bridges. A common location of areas where there is a difference in the temperature distribution in the building envelope of the inspected buildings will be the basis for further simulation processes.

Only one of the 6 buildings inspected was used as a base model for both THERM and OpenStudio analysis. For this data loggers for indoor ambient temperature along with relative humidity as well as outdoor ambient temperature was also measured for the said single building. Figure 15 and Figure 16 shows the plan and elevation of the building selected for the base model to be simulated as well as the measure of the indoor and outdoor ambient temperature. The figure also shows areas where thermal images are inspected. The composition of the external building envelope consists of brick masonry walls of 4-inch thickness along with concrete columns of size 10 inches by 12 inches. The window frames are composed of aluminium and the door frames are wooden.

THERM 7.8 version is used for the 2D analysis and OpenStudio 1.9.0 version is used for the energy performance analysis.

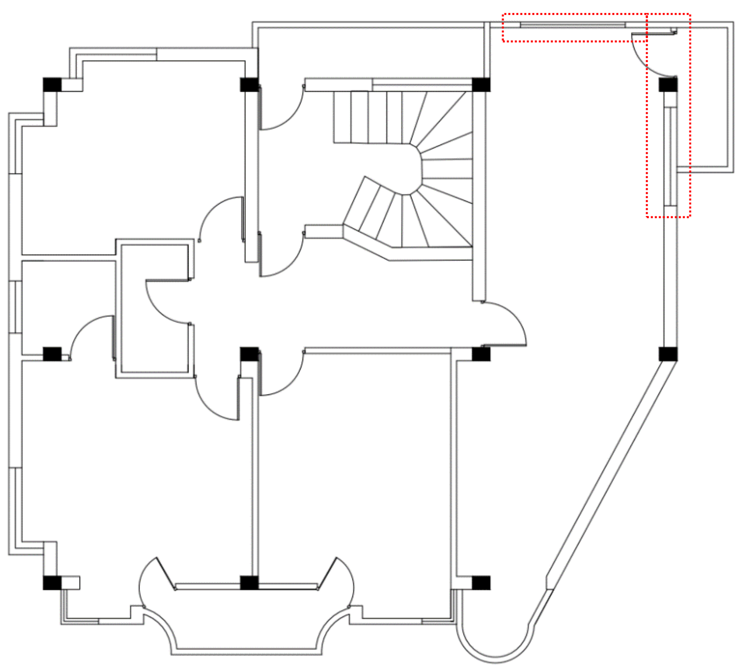

Figure 15: Floor plan showing areas where IR images where captured as well as where indoor data was logged

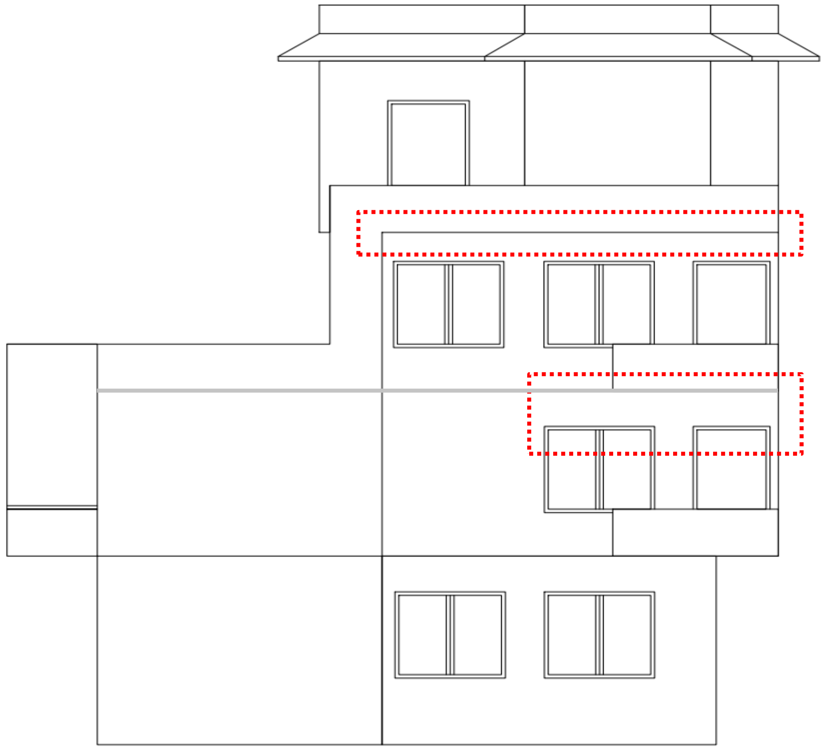

Figure 16: Elevation of selected building for simulation and areas where IR inspection were conducted

In OpenStudio modelling, various parameters are required before simulation, the 3D model of the building can be constructed in the OpenStudio application itself or SketchUp software can be used with the OpenStudio plugin. The OpenStudio application cannot make complex structures hence, SketchUp is used for the modelling of the building. All the parameters required for simulation in OpenStudio such as construction materials, construction sets, schedule sets, loads (people, lighting, equipment), spaces, thermal zones have to be specified before simulation. The parameters which have been entered are mentioned in the Appendix section of this report. In THERM simulation, thermal properties of the material and boundary condition need to be specified. In this software only, a section of a building component is simulated to analyze the heat transfer mechanism of that component. Temperature and humidity data need to be specified as well in this software whereas in OpenStudio the EPW file need to be entered which is acquired through the EnergyPlus library.

CHAPTER 5 DATA COLLECTION

The data collection process for this study involves both primary and secondary data sources to ensure a comprehensive assessment of thermal bridges in residential buildings. Primary data included thermal images, temperature and humidity measurements as well as building dimensions, while secondary data consists of climate data and material thermal properties as well as building energy modeling input files.

5.1 Primary Data Collection

Primary data was gathered through on-site inspection, thermographic inspection to capture real world thermal anomalies along with climate monitoring (temperature and humidity).

5.1.1 Thermal Imaging

To identify and analyze thermal bridges in the building envelope, infrared thermography (IRT) process was used. A Trotec EC060V infrared camera was deployed to capture thermal images of various building envelope components. The camera specifications are as follows:

- Detector type = Microbolometer UFPA
- Detector Spectral range = 8~14 microns
- Detector Resolution = 160 x 120 pixels
- Temperature range = -20°C ~ 250°C
- Accuracy = +2°C
- Digital image = 640 x 480 pixels
- Emissivity = 0.01 to 1.00
- Thermal sensitivity = 0.08°C

Figure 17: TROTEC IR Camera

Thermal images were captured from inside as well as from outside the building. However, to minimize the influence of external environmental factors such as solar radiation and wind, the primary focus was on indoor thermal imaging. The thermal images were captured from an optimal distance ranging between 2-4 meters.

Thermal images to be taken were focused on roof wall junctions, window/door frame connections and balcony slabs which are areas prone to thermal bridging according to various literature. The thermal images where mostly captured after sunset usually are 5PM and in the early morning before 7AM. As this thermal camera also captures digital images, the digital images were captured simultaneously of the same location after thermal image capture. Each thermal image was analyzed for temperature gradients, cold spots and heat loss patterns to determine the presence of thermal bridging. These images provided a visual representation of thermal bridges, allowing for a qualitative assessment of their impact on the building's energy performance. The images captured during the inspection have been described in the analysis and findings portion of this report as well as in the Appendix section of this report.

5.1.2 Ambient Temperature and Relative Humidity logging

To quantify heat loss through thermal bridges, it is necessary to measure both indoor and outdoor temperatures, relative humidity measurement is also necessary for mold and condensation prediction. Data was recorded using high precision data loggers

- HOBO MX2300 Series External Temperature Logger – Outdoor ambient temperature
- T&D TR-76Ui Temperature and Humidity Logger – Indoor ambient temperature and relative humidity

HOBO MX2304, ext temp model data logger was used for logging outdoor ambient temperature. The external sensors of this logger measures temperature from -40°C to 100°C. The accuracy of the device is ±0.25°C from -40 to 0°C, ±0.2°C from 0 to 70°C and ±0.25°C from 70 to 100°C. This data logger can store a maximum of 84,650 measurements. The rate of logging in this device can be used from 1 second to 18 hours. This device requires an application "HOBO connect app" to download and view the recorded data and can be navigated through a phone or a computer.

T&D TR-76Ui data logger was used for logging indoor ambient temperature and humidity. This data logger uses a THA-3001 sensor and has a range of measurement of 0 to 55°C for temperature and 10 to 95% for humidity. The accuracy of the device is ±0.5°C for temperature and 5% RH at 25°C. This device also measures CO2 concentration levels of a room in ppm. The logging capacity of this device is 8000 data sets. The recording interval of this device ranges from 1,2,5,10,15,20,30 seconds or 1,2,5,10,15,20,30,60 minutes. This logger has an LCD display which helps to see the temperature, humidity and CO2 data at any particular time. This device requires a software "CO2 Recorder for Windows" to download and view the recorded data, only through a computer.

Outdoor temperature data logger was placed on a shaded external surface to avoid direct sunlight whereas indoor data logger was placed at least 1.2m away from direct airflow sources like windows. Both indoor and outdoor data loggers were logged at an interval of 1 hour over a time period of 10 consecutive days to capture variations in thermal behavior. This outdoor and indoor temperature is required for simulation in THERM to understand the two-dimensional heat transfer analysis in thermal bridge locations.

The indoor and outdoor ambient temperature measurement were recorded for only one of the 6 buildings which were inspected for thermographic inspection. Building 1 located in Koteshwor was the building selected for the collection of this data, assuming that the structure and the climate data would be similar in all the inspected buildings. The temperature

Figure 18: HOBO and T&D data logger

variation of the indoor and outdoor temperature measurements has been discussed in the analysis and findings section of this report whereas the temperature data of the indoor and outdoor data for 10 days at an interval of 1 hour has been tabulated in the Appendix section of this report.

5.2 Secondary Data Collection

5.2.1 Climatic Data

To simulate the building's energy performance, climate data was obtained from:

- Energy Plus Weather Data Library (EPW and DDY files)

The EPW file can be acquired through various channels some of which are the Energyplus website, onebuilding website or similar sites. For the simulation in OpenStudio application, the EPW file was acquired from the onebuilding website. The EPW files consists of various data for climatic study of a particular region. Global horizontal radiation, direct normal radiation, diffuse horizontal radiation, wind speed, wind direction, dry bulb temperature, dew point temperature, relative humidity, pressure and snow depth are some to the data that are within this EPW file. This weather file is used by energy modellers and building consultants in simulations where a building's energy performance is assessed. Through energy simulation we can learn a building's annual energy use, heating and cooling loads, annual peak electrical demand among other outputs.

The EPW acquired for simulation in OpenStudio was for a period of 15 years from 2009 to 2023. The station of the EPW file was the Tribhuvan international airport in Kathmandu. TMY3 (typical meteorological Year 3) is the source through which this weather file was derived from. This TMY is more useful in predicting future energy use.

DDY (Design Day) files are additional weather information which is useful for energy modelling. This file describes extreme climatic conditions expected for a particular location and is used for the sizing of HVAC systems. This DDY file is used for the ideal air loads in the OpenStudio simulation.

5.2.2 Material thermal properties

The thermal properties of different building envelope materials were collected for use in THERM as well as in the OpenStudio simulations. The properties of these different materials were referenced from the ASHRAE Handbook fundamentals. ASHRAE Handbook fundamentals is a globally recognized reference in building science to acquire data on thermal properties of various materials. The materials included in the thermal analysis such as concrete, brick, cement mortar etc were matched as closely as possible with those available in the ASHRAE material property tables. This approach ensured that the inputs for simulation in THERM and OpenStudio were based on scientifically validated values, enhancing the accuracy and credibility of the study.

For simulation in THERM as well as in OpenStudion various thermal properties of building materials are needed. Thermal conductivity, specific heat capacity and density are some of the thermal properties which are required for simulation, these properties were acquired from a secondary source the ASHRAE Handbook fundamentals. These properties can only be acquired from a secondary source as actual data of these properties in our context in not available. Thermal properties are the foundational inputs for simulation in THERM as well as in OpenStudio, for proper and accurate quantification of heat transfer and energy performance. The compilation of these thermal properties is a critical component of this study. The use of standardized values from ASHRAE allows for consistency and comparability with international studies.

Table 3: Building envelope materials and their source

S.No.	Materials	Source
1	Brick	ASHRAE Handbook
2	Plaster	ASHRAE Handbook
3	Concrete	ASHRAE Handbook
4	Cement Mortar	ASHRAE Handbook
5	Tile	ASHRAE Handbook
6	Expanded polystyrene	ASHRAE Handbook
7	Rockwool	ASHRAE Handbook
8	Gypsum plaster	ASHRAE Handbook

5.2.3 Building geometry and construction details

The building geometry and construction details are essential for simulation in THERM as well as in OpenStudio. The dimensions of the building will be collected through architectural drawings as well as measurement at the location where possible. Thickness of materials will also be measured at the site where possible and checked from drawings as well.

The different building construction materials used such as the envelope material have been figured out through architectural drawings as well as through site inspection. The frame types of windows and doors, the dimensions of the slab projections, thickness of walls all were measured at the site. The lack of insulation used in all the buildings is also a notable detail which is the common theme in most residential buildings in Kathmandu. The thermal properties of these construction materials are then acquired through secondary sources. Similarly, the building dimensions and the thickness of these materials are also figured out through the drawings as well as verified through measurements at the site. These dimensions are required to be entered in the simulation software both THERM and OpenStudio for modelling to acquire heat transfer and energy performance quantification respectively. The data of the building geometry have been entered in the simulation software, the thickness of the various building materials have been tabulated in the analysis and findings sections of this study.

The data collection framework for building geometry and construction details consisted of referring to original architectural drawings and detailed site measurements. For proper quality assurance measures the measurements where taken more than once, cross verification with drawings was also carried out. As the case study was focused on RCC framed structures with brick masonry as infill walls, there was a general idea about the materials and construction details, only the dimensions and size of the materials needed to be figured out. Brick masonry thickness, slab thickness, floor height, room dimensions, type of window and door frame, type of glass, floor finishing material and thickness were some of the parameters which were needed for simulation, all these were acquired through site measurements and relevant drawings.

5.3 Summary of Data Collected

Table 4 summarizes all the data collected for this study as well as the purpose of the data for this study. The study uses a combination of primary and secondary data for various objectives required from thermal image for thermal bridge identification to temperature data, thermal properties and building dimensions for simulation and modelling. This study employed a very detailed data collection approach to ensure comprehensive analysis of thermal bridging phenomena in residential buildings. This research systematically gathered both primary and secondary data, each serving a specific purpose for analytical purposes. The multi source approach compensated for individual method limitations, while the systematic collection of data ensured data quality and relevance throughout the research phase. The use of primary and secondary data provided both ground truth as well as the contextual understanding essential for thermal performance assessment.

Table 4: Summary of Data Collected

Data Type	**Instruments Used**	**Purpose**
Thermal Images	Trotec EC060V IR Camera	Detect temperature difference to locate thermal bridges
Indoor temperature and humidity	T&D TR-76Ui Data logger	Measure interior temperature and humidity data
Outdoor temperature	HOBO MX2300 ext temp logger	Measure exterior ambient temperature
Building dimensions	Site measurement and architectural drawings	For simulation in THERM and OpenStudio
Building thermal properties	Literature	For input in simulation software
Climatic data	Energy Plus Weather files (EPW) and DHM data	For input in OpenStudio software

CHAPTER 6 ANALYSIS AND FINDINGS

Thermal images where captured of various building envelope components to identify locations where thermal bridges were most prominent. The outdoor environment is affected by various environmental factors such as solar radiation, wind and other parameters, which severely affect the temperature and humidity data, hence the thermal imaging will only be taken from indoors as the environment can be better controlled.

Through the study of the thermal images captured of the 6 buildings, the roof wall junction was found to be one of the areas where thermal bridges could be prominent.

6.1 Infrared Thermography

This study employed infrared thermography as a primary investigative tool to identify and analyze thermal bridges in residential buildings across Kathmandu Valley. The thermographic survey followed a rigorous protocol to ensure reliable data collection and meaningful interpretation of thermal anomalies in building envelopes.

Thermal images of various building envelope locations were captured along with their digital image. A total of approximately 155 thermal images were captured of different building components from roof wall junction, window frame and wall junction, exterior door frame junction to balcony slab connection. Some image of floor and slab connection were also captured to see if any noticeable difference could be seen. But the main focus was on the roof wall junction and the window frame and wall connection. As the roof wall junction was found to be one of the most prominent areas where the thermal bridges exist through the analysis of thermal images, this roof wall junction is considered for further analysis through the THERM software. The thermographic inspection was carried out in the early morning before 7 am or in the evening between 5 to 7 pm to minimize the effect of solar radiation. Also, majority of the inspection was carried out from indoors to minimize the effect from solar as well as wind effects. To maximize detection accuracy and minimize environmental interference, the inspection was conducted to avoid solar gain effects, hence the tests where performed after sunset or in the early morning. But some images were captured from outside targeting the balcony slab and wall connection to identify potential thermal bridging locations.

Figure 19 shows the thermal images along with their corresponding digital images of roof wall junction of some of the surveyed buildings, this was carried out for precise location referencing, for accurate identification of thermal anomaly positions as well as documentation of material conditions. The thermal images show a noticeable temperature difference at the roof wall junction compared to the surrounding areas, indicating the potential of thermal bridges. The thermal images display a different temperature zone along the horizontal band where the roof slab intersects the masonry wall. The junction exhibited a temperature difference ranging from 1.8°C to 2.5°C relative to the surrounding roof and wall surface areas suggesting increased heat flow through these locations. The multiple images of the roof wall junction of different buildings shows that this was not an isolated occurrence reinforcing the presence of the thermal anomaly of thermal bridge highlighting the potential of a thermal performance issue. The sharp contrast between the roof wall junction and the surrounding areas was visibly distinct which helps us identify a pattern from these images. These potential thermal bridge areas could be the result of material change, in the roof wall junction region, due to the different thermal properties of the RCC roof slab and the brick wall such as thermal conductivity. These may also indicate air leakage due to cracks of poor sealing. The multiple roof wall junction images demonstrated remarkable consistency in thermal bridge occurrence. The thermal bridge anomalies observed in multiple buildings showed that thermal bridge was present regardless of the age of the building.

The results of the thermographic findings demonstrated the prevalence of thermal bridges on RCC buildings in Kathmandu regardless of the age of the building. The results revealed a general construction practice issue. This comprehensive thermographic investigation not only confirmed the hypothesized thermal bridge locations but also provided data to guide subsequent work and mitigation strategy development. The consistent patterns observed across multiple buildings highlight the general nature of thermal bridging in Nepal's residential construction and the significant opportunity for performance improvement through targeted interventions.

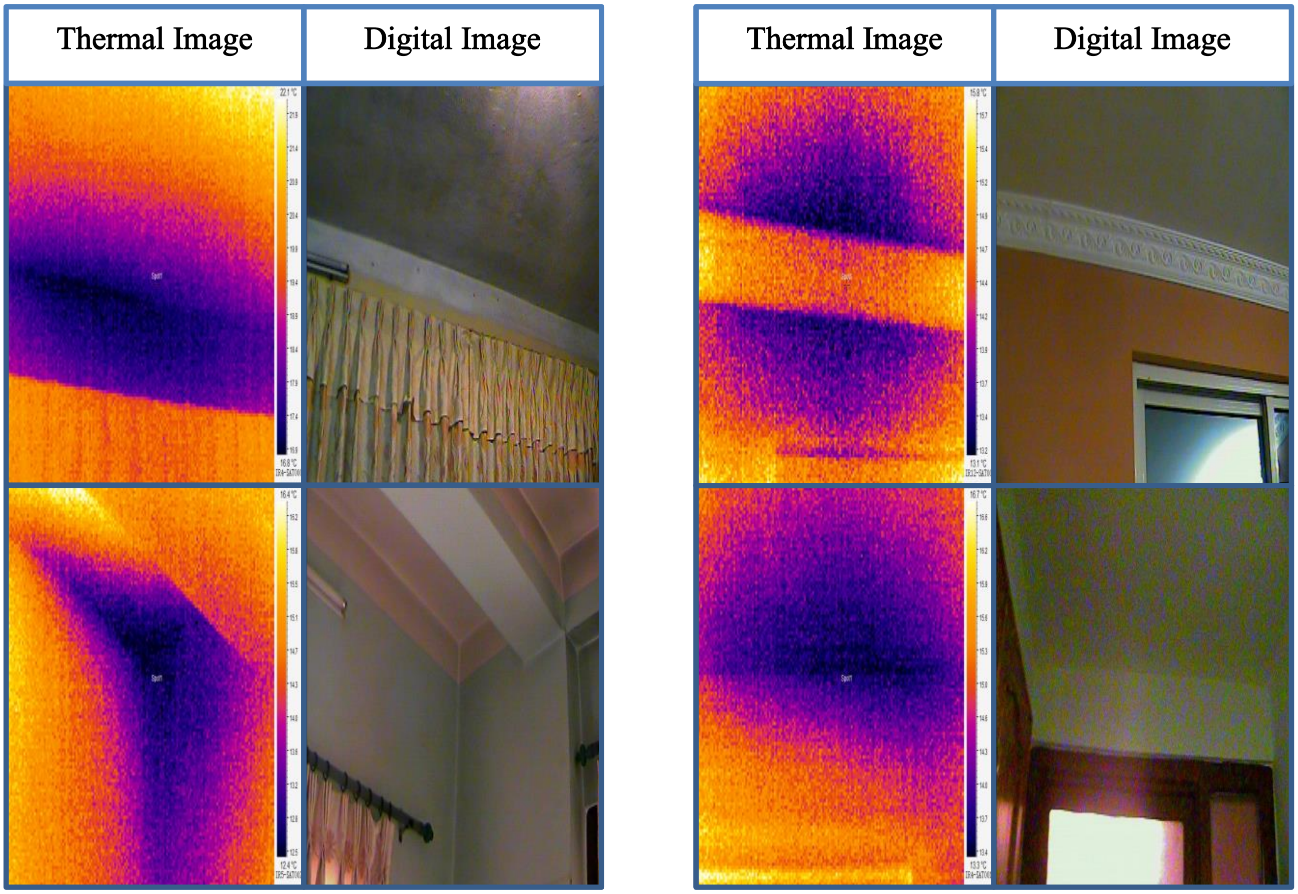

Figure 19: Thermal and digital image of roof wall junction

6.2 Temperature analysis

This study implemented a rigorous temperature monitoring to establish a reliable boundary conditions for thermal analysis and simulation work. Ambient temperature was recorded for both outside and inside with data loggers for a period of 10 days during the winter season, the temperature was logged at an interval of 1 hour. The measurement of indoor and outdoor temperature was recorded with T&D and HOBO data loggers described above in the data collection section. The outside and inside temperature is needed to simulate in the THERM software.

Variation of indoor and outdoor temperature graph is shown in Figure 20. This graph highlights the consistent difference between indoor and outdoor conditions. The graph also illustrates the typical temperature fluctuations observed in Kathmandu during the study period. The indoor and outdoor temperature data has been published in the APPENDIX section. The temperature was logged at an interval of one hour, resulting in 24 data points per day for a period of 10 days. This frequency was chosen to adequately capture the daily temperature cycle, including the peak temperature during the midday and the lowest temperature during the early morning hours.

The indoor temperature measurements were taken in a typical room located in the upper floor of one of the selected RCC buildings, under normal occupancy conditions. Meanwhile, the outdoor temperature readings were recorded on the shaded side of the building façade to minimize solar radiation effects and better represent the ambient air temperature. The recorded temperature serves as an input parameter in the THERM software, to model a 2D heat transfer through construction elements and define the thermal gradient driving the heat flux. The temperature recording using data loggers were only carried out for one of the 6 buildings inspected for thermographic inspection due to the lack of availability of data loggers as well as the time constraints. But as the ambient temperature of the outdoor environment is similar throughout Kathmandu, the variation in temperature would not be massive. Similarly, as the selected buildings were all RCC buildings with brick masonry as infill walls without any thermal insulation, the indoor temperature would also be similar for the buildings.

The maximum temperature recorded for the time period of 10 days for indoor and outdoor ambient temperature was 24°C and 18°C respectively whereas the minimum temperature recorded was 7°C and 12°C respectively. The average temperature of the indoor and outdoor temperature came out to be 18°C and 10°C respectively. The maximum and minimum data for humidity recorded for the indoor environment was 60% and 30% respectively. There were some anomalies seen in the indoor data at certain intervals due to the use of electrical equipment directly beside the data logger but these were very few. The indoor temperature throughout the 10 day period were very stable with rarely any spikes in the temperature from the average value, whereas the outdoor temperature saw few spikes due to the higher temperature during the day time.

This comprehensive temperature monitoring approach generated a strong dataset that significantly enhanced the reliability of both the thermographic analysis and subsequent thermal simulations. The detailed temperature profiles not only served as a critical input for numerical modelling but also provided valuable insights into the actual thermal performance of Kathmandu's typical residential buildings during winter conditions. The methodology and findings establish a strong foundation for future, more extensive temperature monitoring campaigns across different seasons and building typologies.

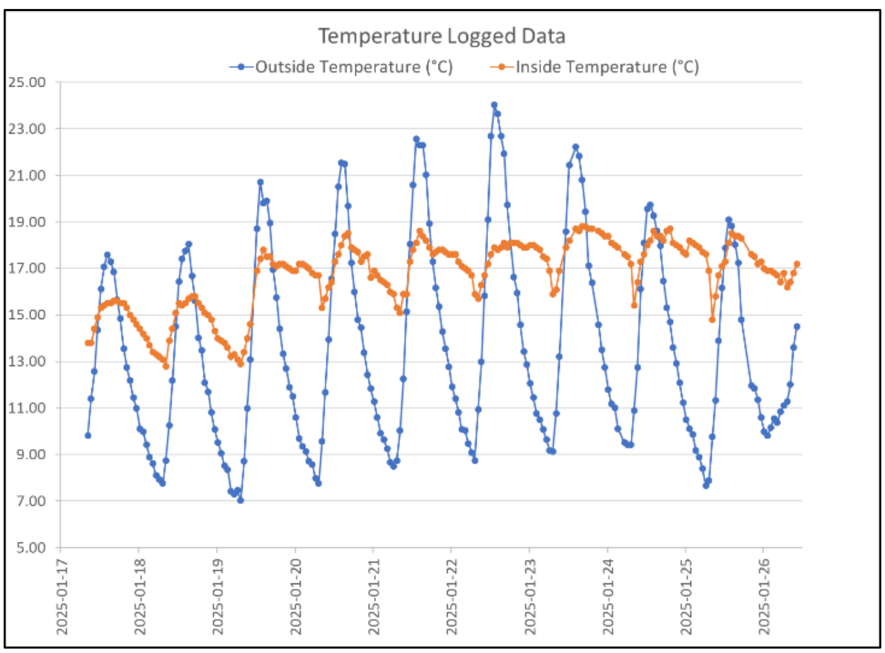

Figure 20: Indoor and outdoor temperature variation

6.3 THERM analysis

THERM software is used for the analysis of thermal bridge in the roof slab and wall junction. The different physical and thermal properties of the building envelope materials have been listed in the Table 5 and Table 6. The thermal properties namely the thermal conductivity, inner and outer film coefficient has been taken from the ASHRAE handbook fundamentals. The outside and inside ambient temperature are taken to be 10°C and 18°C respectively.

Figure 22 shows the drawing of the roof slab and wall junction which is modelled in the THERM software for the 2-dimentional analysis. Figure 23 shows the heat flux distribution along the wall and roof slab obtained from THERM. In the heat flux distribution, the roof wall junction exhibits higher heat flux compared to the surrounding area, this confirms the localized heat transfer and aligns with the thermal images captured from the infrared camera.

The THERM software gives the U-factor of the roof slab and wall section. This U-factor multiplied with the length of the specified section gives the thermal coupling coefficient (L_{2D}). The U-factor produced from the simulation is shown in Figure 21.

Table 5: Physical parameters considered in THERM

Materials	Width (mm)	Thermal conductivity (W/m.K)
Brick	230	0.9
Plaster	12	0.72
Concrete	150	0.5334
Cement mortar	20	0.72
Tile	12	0.6
Expanded polystyrene	10	0.035

Table 6: Boundary parameters considered in THERM

Position of Surface	Direction of Heat Flow	Film Coefficients (W/m^{2}K)
Indoor		
Vertical	Horizontal	8.29
Horizontal	Downward	6.13
Horizontal	Upward	9.26
Outdoor		
Winter	Any	34

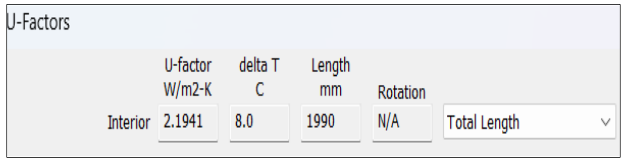

Figure 21: U-factor from THERM

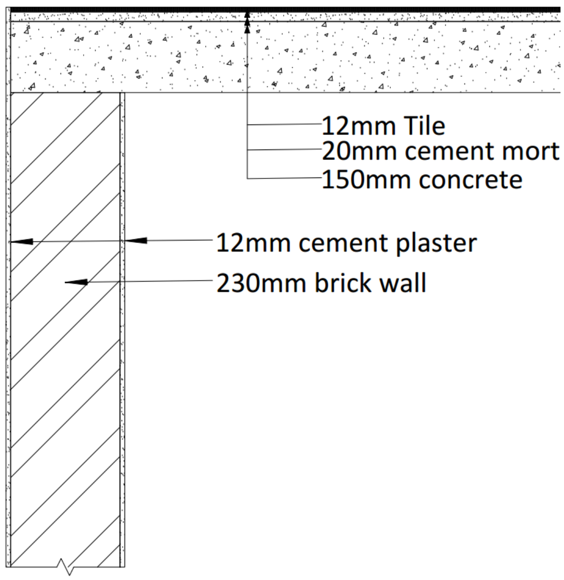

Figure 22: Drawing of roof slab-wall junction (base model)

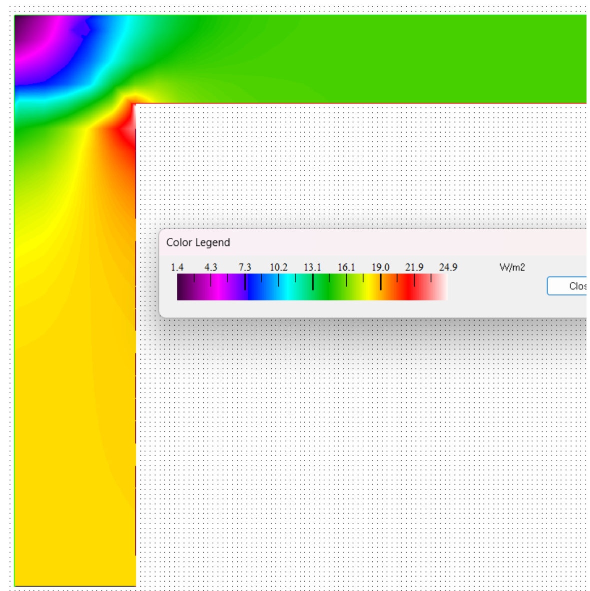

Figure 23: Analysis of roof slab-wall junction (base model) from THERM

$$L_{2D} = \text{U-factor x L} = 2.194 \times 1.99 = 4.366 \text{ W/m}$$

$$U = \frac{1}{\frac{1}{ha}+\frac{l1}{k1}+\frac{l2}{k2}+\frac{1}{hb}} = \frac{1}{\frac{1}{34}+\frac{0.02}{0.72}+\frac{0.012}{0.6}+\frac{0.15}{0.533}+\frac{1}{6.13}} = 1.9289 \text{ W/m}^2\text{-K}$$

$$\psi = L_{2D} - \text{U x L} = 4.366 - 1.9289 \times 1.99 = 0.5275 \text{ W/m-K}$$

The overall heat transfer coefficient (U value) of the same section of roof slab and wall is calculated based on the same material and boundary properties considering the whole section as the slab material, using equation (ii) which was found to be 1.9289 W/m^2-K. The linear thermal transmittance(ψ) was calculated from the equation (i), which comes out to be 0.5275 W/m-K. Multiplying this ψ value with the overall length of the junction of the roof slab and wall junction gives the additional heat loss through this thermal bridge.

Figure 25, Figure 27, Figure 29, Figure 31, Figure 33, Figure 35 and Figure 37 shows the drawing of the roof slab and wall junction of various cases (case 1 to 7 respectively) for simulation in THERM, details of which have been described in Table 7, applied for a section along the roof wall junction from exterior side or the interior side. Figure 26, Figure 28, Figure 30, Figure 32, Figure 34, Figure 36 and Figure 38 shows the heat flux distribution along the wall and roof slab of the 7 cases mentioned above from THERM. The U-factor produced from the simulation for the 7 cases is shown in Figure 24.

Table 7: Description of different cases modelled in THERM

Case	**Description**
Base Case	Concrete roof slab with tile and brick wall with plaster
Case 1	300 x 300 mm expanded polystyrene along roof wall junction
Case 2	20mm additional cement plaster of 300mm on exterior face of wall
Case 3	20mm gypsum plaster of 300mm on exterior face of wall
Case 4	Cornice of cement plaster at roof wall junction from interior side
Case 5	Cornice of gypsum plaster at roof wall junction from interior side
Case 6	Cornice with rock wool and cement plaster from interior side at junction
Case 7	Cornice with rock wool and gypsum plaster from interior side at junction

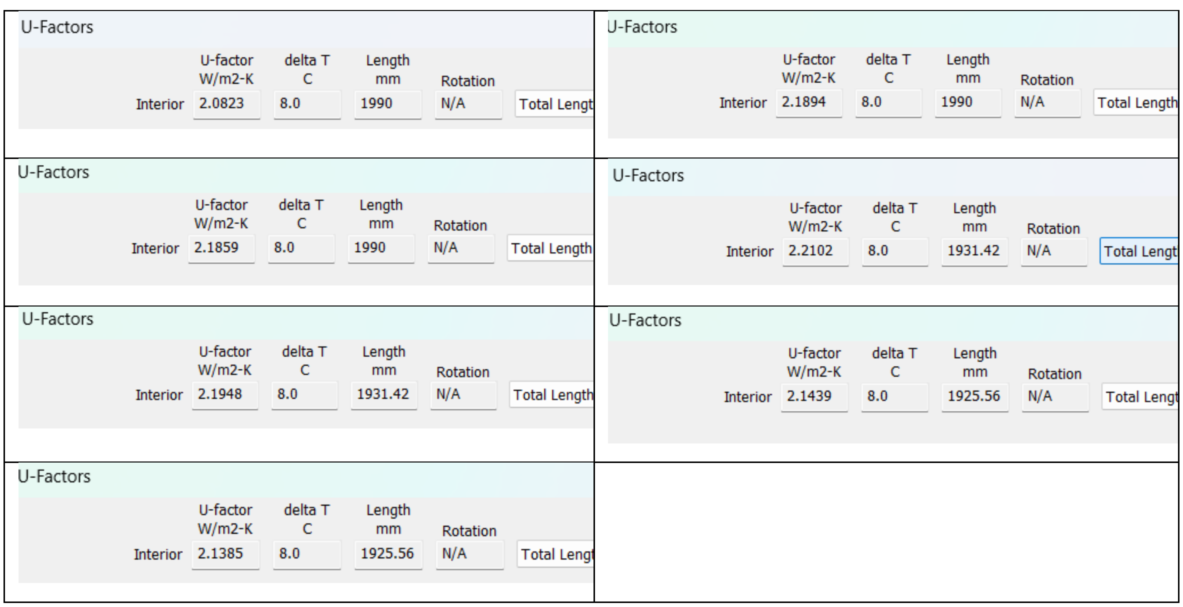

Figure 24: U-factor from THERM from Case 1 to Case 7

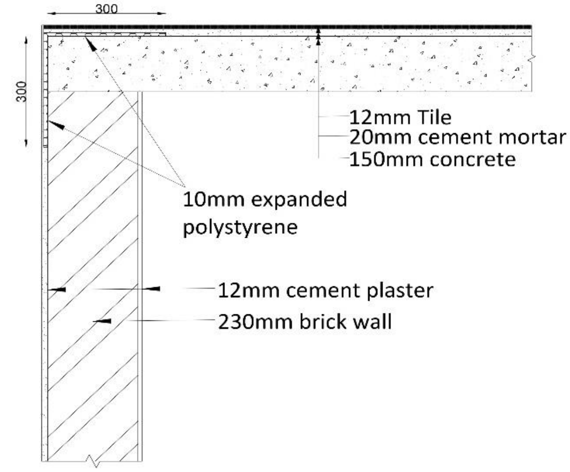

Figure 25: Drawing of roof slab-wall junction (Case 1)

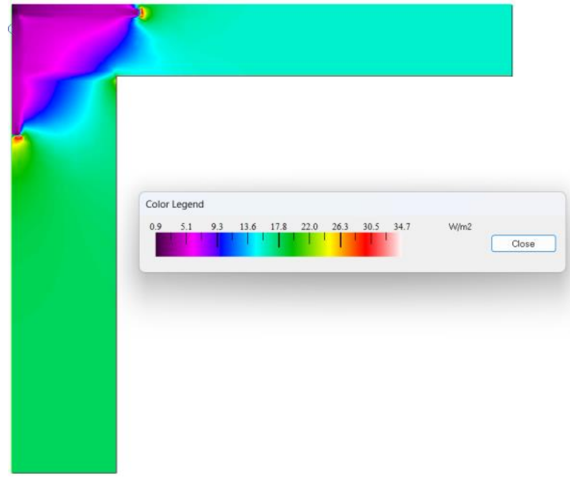

Figure 26: Analysis of roof slab-wall junction (Case 1)

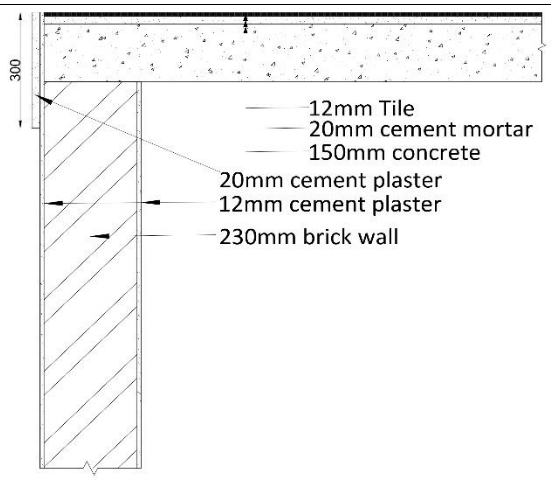

Figure 27: Drawing of roof slab-wall junction (Case 2)

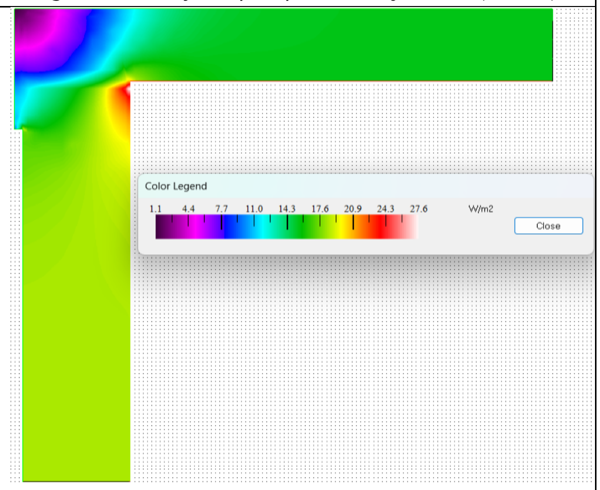

Figure 28: Analysis of roof slab-wall junction (Case 2)

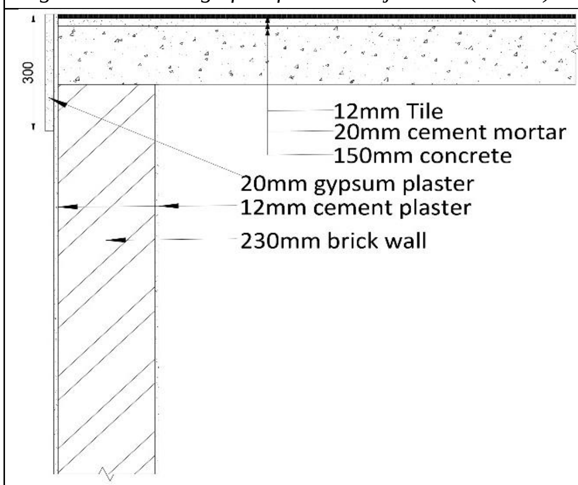

Figure 29: Drawing of roof slab-wall junction (Case 3)

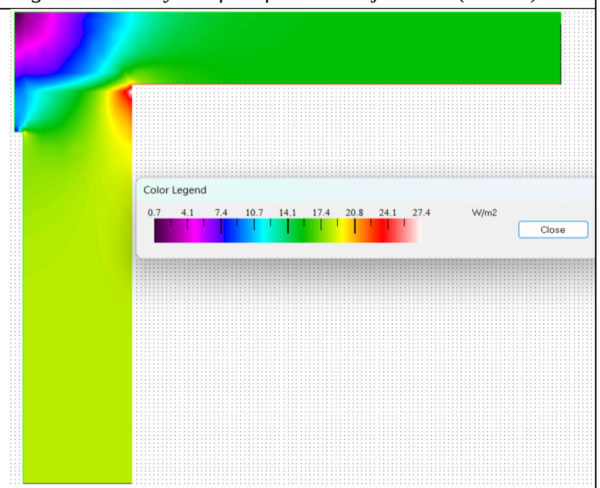

Figure 30: Analysis of roof slab-wall junction (Case 3)

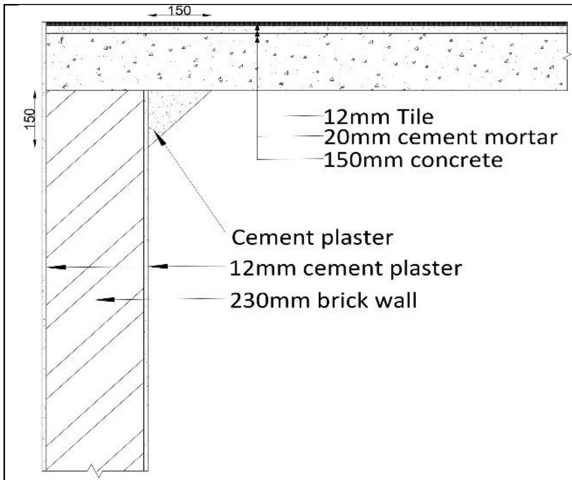

Figure 31: Drawing of roof slab-wall junction (Case 4)

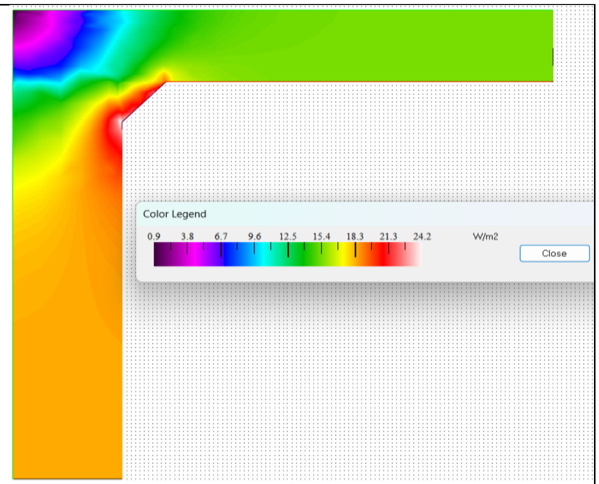

Figure 32: Analysis of roof slab-wall junction (Case 4)

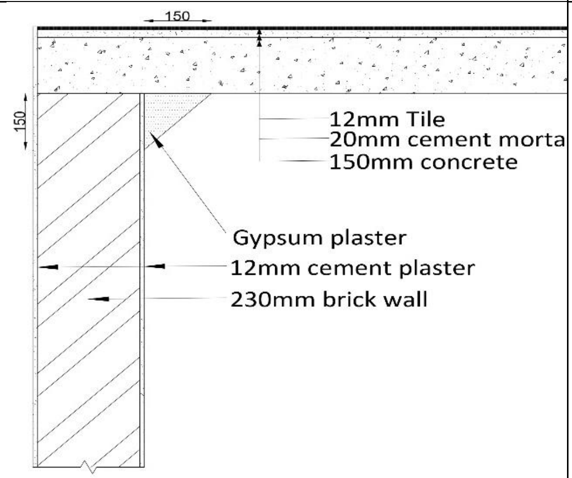

Figure 33: Drawing of roof slab-wall junction (Case 5)

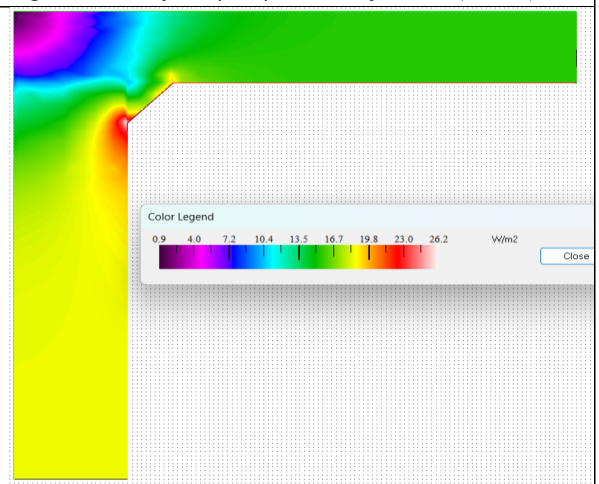

Figure 34: Analysis of roof slab-wall junction (Case 5)

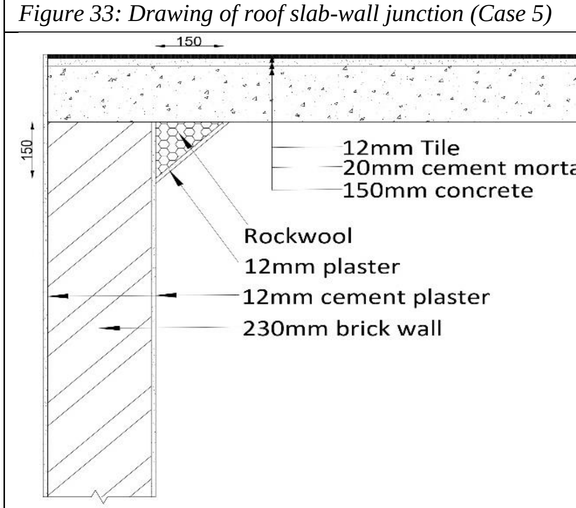

Figure 35: Drawing of roof slab-wall junction (Case 6)

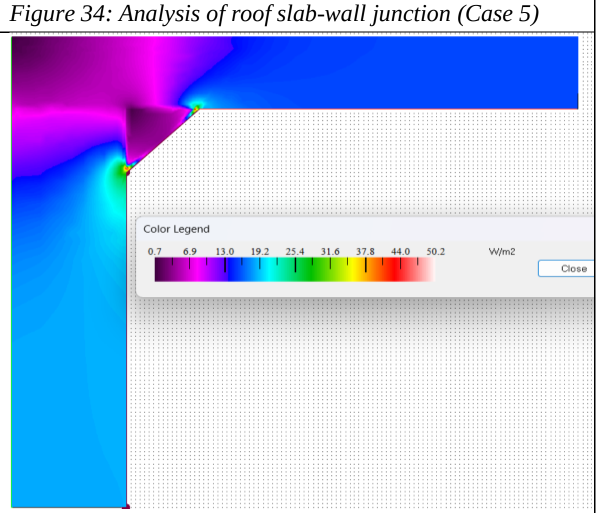

Figure 36: Analysis of roof slab-wall junction (Case 6)

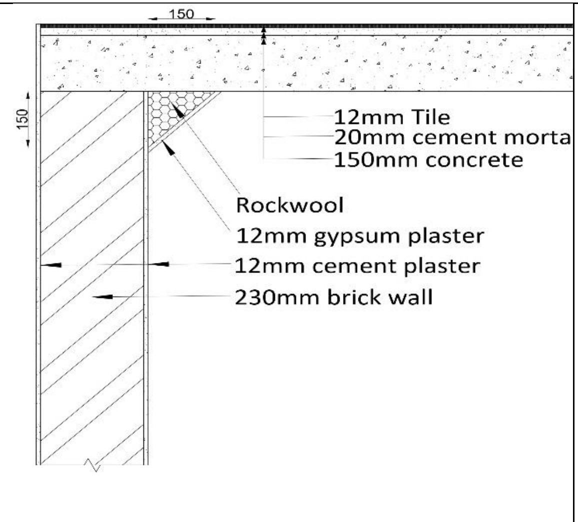

Figure 37: Drawing of roof slab-wall junction (Case 7)

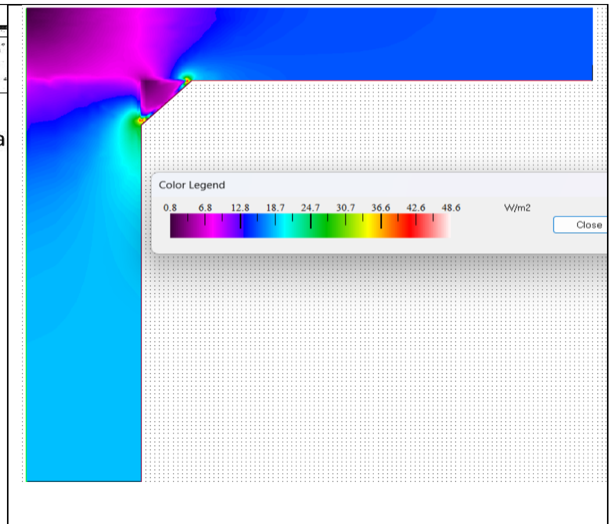

Figure 38: Analysis of roof slab-wall junction (Case 7)

The figures of the heat flux distribution patterns above of cases 1 to 7 shows how different materials and construction assemblies used impacts the heat flux distribution of the components. The roof wall junction showed higher heat flux compared to the surrounding areas for the base case, to rectify this thermal anomaly different material and composition were applied along the building components. The results show that using insulation materials such as EPS and rockwool reduce the heat flux at the junctions whereas only using cement or gypsum plaster only does not make a huge impact. From the heat flux distribution patterns in the figures above, it is seen that case 1, case 6 and case 7 showed decrease in the heat flux at the junction of the roof wall area. In these cases insulation materials where used hence the reduction could be seen. However, in the other cases where different techniques where applied without using insulation only slight decrease in heat flux was seen.

$$L_{2D} = \text{U-factor x L} = 2.0823 \text{ x } 1.99 = 4.1437 \text{ W/m-K}$$

$$U = \frac{1}{\frac{1}{ha}+\frac{l1}{k1}+\frac{l2}{k2}+\frac{1}{hb}} = \frac{1}{\frac{1}{34}+\frac{0.02}{0.72}+\frac{0.012}{0.6}+\frac{0.15}{0.533}+\frac{1}{6.13}} = 1.9289 \text{ W/m}^2\text{-K}$$

$$\psi = L_{2D} - \text{U x L} = 4.1437 - 1.9289 \text{ x } 1.99 = 0.3051 \text{ W/m-K}$$

The linear thermal transmittance(ψ) for the Case 1 was also calculated from the equation (i), which comes out to be 0.305 W/m-K. There was a reduction of a value of 0.2224 W/m-K for the linear thermal transmittance which is a reduction of approximately 42%.

Similarly, for case 7 the linear thermal transmittance came out to be 0.2781 W/m-K, which was a reduction of 0.2494 W/m-K approximately 47.2% reduction. These two cases showed the best improvements and are different in the mitigation design as case 1 is insulated from the exterior side where case 7 is insulated from the interior side. The same process was followed for other cases from 2 to 7 and the summary is shown in Table 8.

Table 8: Summary of various parameters of two models simulated

Case	**U-factor (W/m^2-K)**	**Length (m)**	**U value (W/m^2-K)**	**L_{2D} (W/m-K)**	**ψ (W/m-K)**
Base case	2.194	1.99	1.9289	4.366	0.5275
Case 1	2.0823	1.99	1.9289	4.1437	0.3051
Case 2	2.1894	1.99	1.9289	4.3569	0.5184
Case 3	2.1859	1.99	1.9289	4.3499	0.5114
Case 4	2.2102	1.931	1.9289	4.2679	0.429
Case 5	2.1948	1.931	1.9289	4.2381	0.399
Case 6	2.1439	1.925	1.9289	4.127	0.2885
Case 7	2.1385	1.925	1.9289	4.116	0.2781

The linear thermal transmittance values of different cases from Table 8 shows that case 2 and case 3 showed almost no improvement in rectifying the thermal anomaly of linear thermal bridge at the roof wall junction. In these two cases no insulation material was used and a thicker plaster layer was applied along the junction from the exterior surface, in case 2 with cement plaster and in case 3 with gypsum plaster. These measures did not give significant results hence where not further explored in OpenStudio simulation. In case 4 and case 5 a cornice was applied from the interior side with cement plaster and gypsum plaster as shown in Figure 31and Figure 33, these measures yielded only a slight improvement in the linear transmittance value, hence where also not explored further for simulation in OpenStudio. Case 1 with the application of EPS and cases 6 & 7 with the application of cornice with rockwool with cement and gypsum plaster respectively showed considerable improvement in lowering the value of linear transmittance. Case 6 and 7 were similar with the difference being the plaster material of cement and gypsum, hence only one of them where further explored in OpenStudio. Case 7 with cornice with rockwool and gypsum plaster and case 1 with the use of EPS from the exterior side where further explored in OpenStudio for energy performance evaluation.

The THERM simulation followed a systematic approach to ensure consistent and reliable results. The base geometry for all the cases where the same meaning using of 150mm slab and 230mm brick, similarly the boundary conditions were kept the same as well with indoor temperature being 18°C and outdoor temperature being 10°C. The film coefficient for the outer and inner surfaces where also kept the same. The findings from the simulation using various different strategies showed that surface treatment alone cannot adequately address the thermal bridge effects as the just using plaster material from both inside and outside showed. Material thermal conductivity was seen as the major factor in reducing the transmittance values. This two-dimensional analysis provides technical justification for the selected mitigation strategies and lays a solid foundation for the further whole building energy performance evaluation in OpenStudio. The results showed that there is a need for improving junction detailing in RCC buildings as well as the need for the importance of workmanship. This study also shows that modelling for analysis such as heat transfer is a valuable tool to access heat loss.

6.4 OpenStudio Analysis

OpenStudio building energy modelling software is used for the evaluation of a building's energy performance. Similarly, to the THERM analysis the thermal properties of the building materials have been acquired from the ASHRAE handbook fundamentals. The building dimensions have been taken from site measurements as well as from the relevant building drawings. The model is drawn in Sketchup with the use of the OpenStudio plugin, then for simulation the OpenStudio application is used.

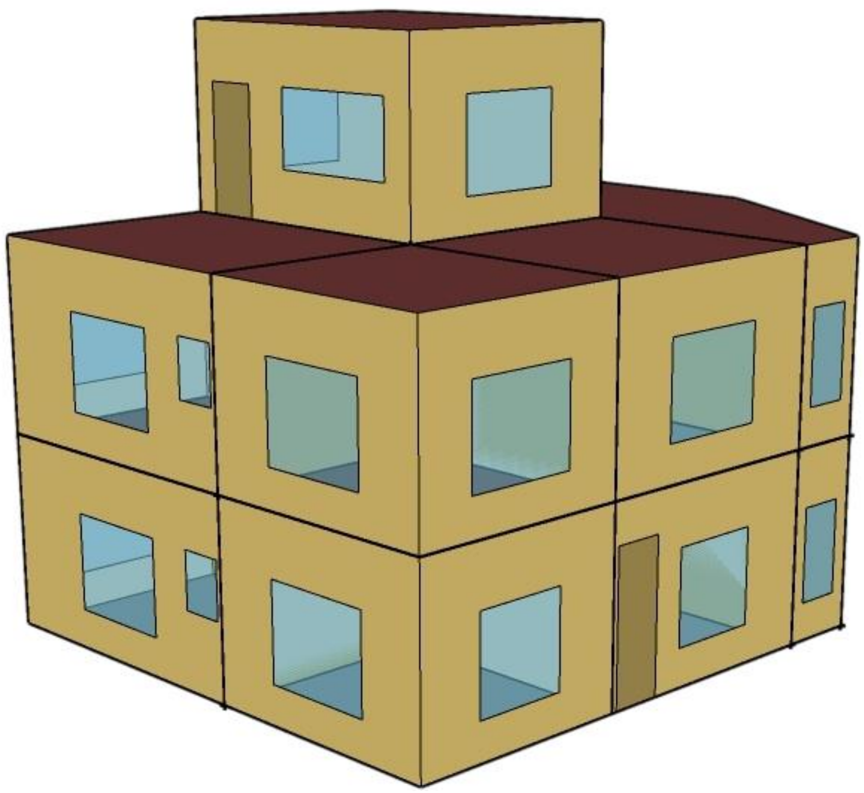

Figure 39: 3D model of the building simulated in OpenStudio

Figure 39 shows the 3D model of the building which is simulated in OpenStudio for energy performance assessment. The model which is simulated is a residential 2 and a half storey building, each floor of 3.04m height.

Table 9 describes the different materials used in different building components of the building modelled for simulation. Table 10 lists the various thermal properties of the different building materials considered in the simulated model. These were applied to the base case model which was first simulated to generate the energy performance results. In Case 1 (case mentioned in THERM analysis) for simulation, a 300mm x 300mm section of expanded polystyrene (EPS) is applied along the length of the roof slab and wall junction, the detail of which is as shown in Figure 25. This EPS has been applied on the roof slab and wall junction of the top floor as well as the first floor in areas where slab is exposed to the exterior environment. Similarly, in case 7 (mentioned in THERM analysis), a section of rockwool is applied from the interior side of the room at the roof wall junction. A section of 150mm x 150mm but rectangular as shown in Figure 37 has been applied, this has been applied in areas where slab is exposed to the exterior environment similar to case 1. All 3 cases, the base case, case 1 and case 7 have been modelled with the ideal air loads function in the OpenStudio application for the HVAC system. In all the three cases every other parameter was kept the same only the roof wall junction was separately modified. The lighting schedule, equipment schedule, people schedule, infiltration, wall, roof, door, window materials were kept the same. Similarly, the space types, thermal zones and the ideal air loads were also kept the same, the intention was to only check what rectifying the thermal bridge locations with different materials would impact the energy performance of the building. Only case 1 and 7 were simulated in OpenStudio as these cases showed decrease in the linear thermal transmittance and U-factor values, case 6 and 7 had similar results and had similar construction assembly so only one of these was chosen. Case 1 was chosen as it was applied from the exterior side and was different to the other cases.

Table 9: Building component description

Building Component	Description
Exterior Wall	• 12mm cement plaster • 230mm brick wall • 12mm cement plaster
Interior Wall	• 12mm cement plaster • 110mm brick wall • 12mm cement plaster
Floor Slab	• 12mm plaster and punning • 150mm reinforced concrete

Building Component	Description
Roof Slab	• 12mm tile • 12mm cement plaster • 150mm reinforced concrete
Window	• 3mm clear glass
Door	• 50mm Wood

Table 10: Thermal properties of different building components considered in OpenStudio

Material	Thermal conductivity (W/m-K)	Density (kg/m3)	Specific heat (KJ/kg.K)
Concrete	0.5334	2400	0.8
Brick	0.9	1920	0.8
Plaster	0.72	1860	0.84
Tile	0.6	2380	1
Glass	1.38	2200	-
Wood	0.18	660	1.63
Expanded polystyrene	0.035	20	1.5
Rockwool	0.04	64	1.2
Gypsum	0.38	1120	0.84

The various input parameters that need to be supplied in the OpenStudio application such as construction sets, loads, spaces, space types, thermal zones have been published in the APPENDIX section.

Figure 40, Figure 41 and Figure 42 shows the results of the simulation of the base case, Case 1 and Case 7 respectively. The total site energy reduced from 9,103 kWh to 8867 kWh and 8806 kWh, reducing by a value of 236 kWh (2.59%) and 297 kWh (3.26%) annually. Similarly, the EUI reduced from 43.24 kWh/m^2 to 42.12 and 41.83 kWh/m^2, reducing by a value of 1.12 kWh/m^2 (2.59%) and 1.41 kWh/m^2 (3.26%) annually.

Model Summary

Building Summary

Data	Value
Building Name	Building 1
Total Site Energy	9,103 kWh
Total Building Area	211 m^2
Total Site EUI	43.24 kWh/m^2
OpenStudio Standards Building Type	n/a

Figure 40: Summary of the total site energy and EUI of the base case

Model Summary

Building Summary

Data	Value
Building Name	Building 1
Total Site Energy	8,867 kWh
Total Building Area	211 m^2
Total Site EUI	42.12 kWh/m^2
OpenStudio Standards Building Type	n/a

Figure 41: Summary of the total site energy and EUI of Case 1

Model Summary

Building Summary

Data	Value
Building Name	Building 1
Total Site Energy	8,806 kWh
Total Building Area	211 m^2
Total Site EUI	41.83 kWh/m^2
OpenStudio Standards Building Type	n/a

Figure 42: Summary of the total site energy and EUI of Case 7

Annual Overview

End Use - view table

End Use	Consumption (kWh)
Heating	5,278
Cooling	1,161
Interior Lighting	989
Exterior Lighting	0
Interior Equipment	1,675
Exterior Equipment	0
Fans	0
Pumps	0
Heat Rejection	0
Humidification	0
Heat Recovery	0
Water Systems	0
Refrigeration	0
Generators	0

Figure 43: Breakdown of total site energy of the base model

Annual Overview

End Use - view table

End Use	Consumption (k
Heating	5,025
Cooling	1,178
Interior Lighting	989
Exterior Lighting	0
Interior Equipment	1,675
Exterior Equipment	0
Fans	0
Pumps	0
Heat Rejection	0
Humidification	0
Heat Recovery	0
Water Systems	0
Refrigeration	0
Generators	0

Annual Overview

End Use - view table

End Use	Consumption (k
Heating	5,108
Cooling	1,031
Interior Lighting	989
Exterior Lighting	0
Interior Equipment	1,675
Exterior Equipment	0
Fans	0
Pumps	0
Heat Rejection	0
Humidification	0
Heat Recovery	0
Water Systems	0
Refrigeration	0
Generators	0

Figure 44: Breakdown of total site energy of Case 1 and Case 7

Figure 43 and Figure 44 details the breakdown of the total site energy of the base and modified model respectively by different building components such as heating, cooling, lighting and equipment among others. Similarly, other results from the simulation such as district heating, cooling, zone temperature etc have been published in the APPENDIX. In the breakdown of the total energy use of the simulated building, it is seen that the interior lighting and interior equipment has the same values 989 kWh and 1675 kWh respectively for all the 3 cases (base, case 1 and case7). This is because the lighting and interior equipment schedules were kept the same in all cases. The schedules for heating and cooling were also kept constant for all the cases but the output of energy consumption for heating and cooling loads was dependent on the temperature of the indoor environment which changed due to the change in the roof wall junction material. These schedules were developed based on typical occupancy patterns and appliance usage in Nepalese residential buildings. The application of insulation materials in case 1 and 7 lead to a change in the indoor temperature due to which heating and cooling loads changed from the base case. The electricity consumption of the building simulation is kept in the APPENDIX of this report, the annual electricity consumption of the building aligns with the lighting and equipment energy consumption given by the simulation model. As the simulated building in question does not have any HVAC systems ideal air loads were assumed for the purpose of seeing how rectification of thermal bridges leads to a change in the cooling and heating loads due to minimization of heat loss and gain through the building envelope.

The current study focused on a single building representing a common typology of buildings in the study region, future research could investigate the cost effectiveness of the measures used considering the local material and the labour costs. Also look into alternative insulation materials which are more suited to Nepal’s construction practices. Also, combined measures that integrate thermal bridge mitigation with other energy efficiency strategies.

The reduction of 236 kWh and 297 kWh appears modest and may not warrant the additional cost to apply them in reality, but it is a first step towards reducing energy consumption of a building, scaling this to the total residential buildings in Kathmandu may make a massive difference in energy conservation in a large scale. As the construction sector of Kathmandu continues to grow year by year, implementing such measures during the design phase as well as in retrofitting of existing structures contribute significantly to Nepal’s sustainable development goals.

CHAPTER 7 DISCUSSIONS

The findings of this study highlight the significance of the impact of thermal bridges on the energy performance of residential buildings in Kathmandu, Nepal. The use of infrared thermography (IRT) proved to be an effective method for identifying thermal anomalies, particularly at roof wall junctions.

The calculated linear thermal transmittance (ψ value) for the base model without the use of any insulation materials, in 2D simulation software THERM, showed a value of 0.5275 W/m-K which is higher than the Passivhaus standard (<0.01 W/m-K) as well as other thermal bridging guides (<0.3 W/m-K). This indicates additional heat loss through linear thermal bridges. Several cases using various materials and techniques where modelled in THERM to analyze the impact of these materials on the linear thermal transmittance values. Case 1 using a 300 x 300 mm EPS material along the wall and slab showed a reduction in the ψ value to 0.3051, similarly in Case 6 and 7 with the use of rockwool as an insulation material with cement plaster and gypsum plaster respectively from the interior face, a reduction to 0.2885 W/m-K and 0.2781 W/m-K was observed.

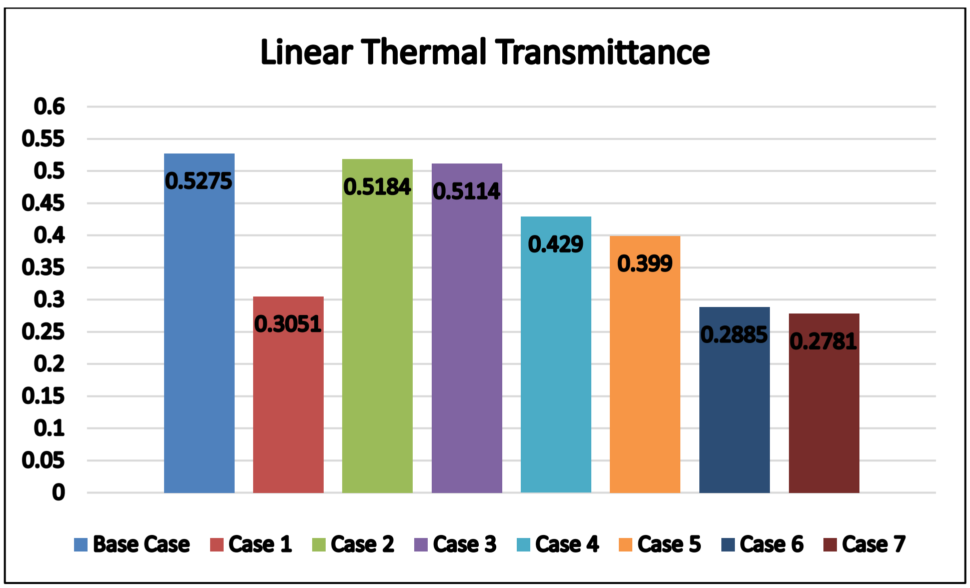

Figure 45: Linear Thermal Transmittance for different cases

Figure 45 shows the different linear thermal transmittance variation for different cases simulated in THERM from base case to case 1 to 7. The use of insulation materials EPS and rockwool significantly reduce the linear thermal transmittance values. EPS applied from the exterior side and rockwool applied for the interior side both reduced the value which indicates that additional heat loss through this thermal bridge could be reduced. Other cases used double plaster or cornice with cement or gypsum plaster did not reduce the value significantly. The results indicate that the use of insulation materials helps to reduce the additional heat loss through a thermal bridge in our case the roof wall junction.

The OpenStudio simulation revealed a decrease in the total site energy and EUI compared to the base model by 2.59% and 3.26% for Case 1 and Case 7 models. In all the three cases base, case 1 and case 7 all the building parameters as well as the internal heat gains parameters such as lighting, equipment were kept the same the only difference was in the case 1 a 300 x 300 mm EPS section was used from the exterior side, whereas in case 7 a cornice (a right-angled triangular section of height and width 150mm) was used with rockwool followed by gypsum plaster. The value of total site energy reduced from 9103 kWh to 8867 and 8806 kWh respectively for case 1 and case 7, similarly, the EUI reduced from 43.24 kWh/m^2 to 1.12 and 1.41 kWh/m^2 respectively.

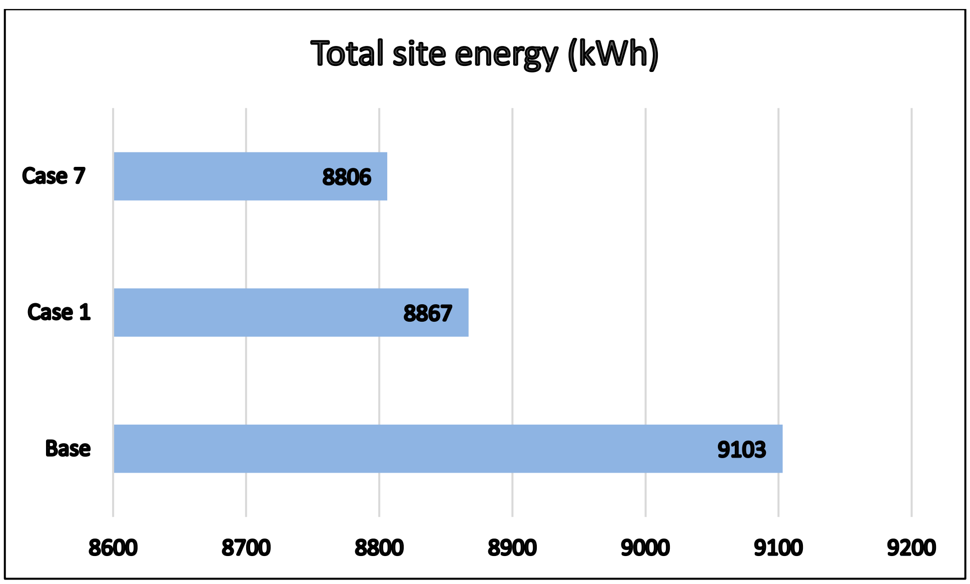

Figure 46: Total site energy for different cases

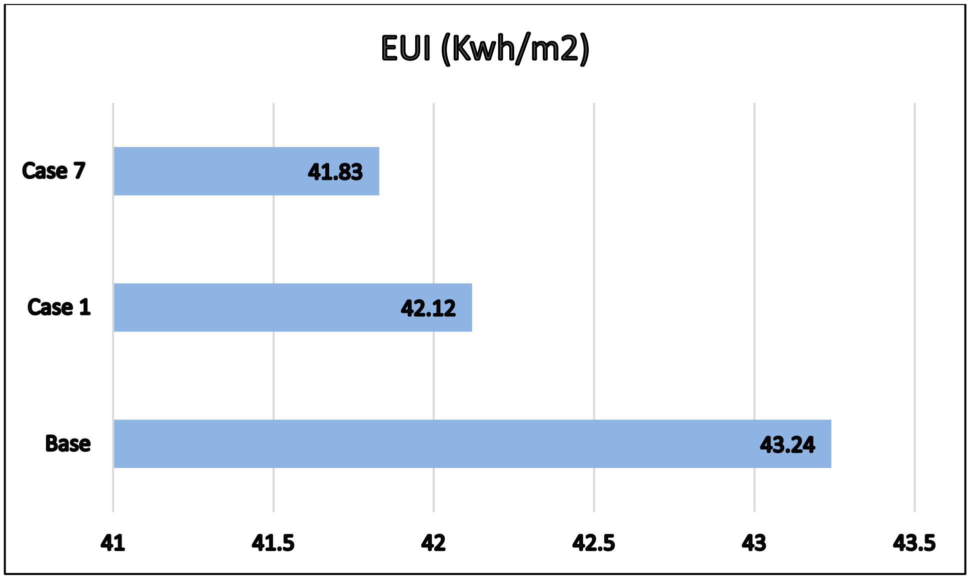

Figure 47: Total EUI for different cases

Figure 46 and Figure 47 shows the change in the energy performance of the building in terms of total site energy and total EUI. There is noticeable reduction in the total site energy and the total EUI of the building with the application of insulation materials only at the junction of the roof wall section. Only case 1 and case 7 were simulated along with the base case as the THERM results showed reduction in the linear thermal transmittance values in these cases. The total site energy reduced by a value of 236 kWh and 297 kWh for case 1 and case 7 respectively. This is the annual total site energy reduction of the simulated building.

According to the national population and housing census (2021) among the total 542,892 households in Kathmandu, 293,725 houses are reinforced cement concrete buildings which is approximately 54.10% of the total buildings in Kathmandu. Similarly, among the total building structure (316,730) in Kathmandu 258,138 are residential buildings, which is approximately 81.5% of the total building structures. If we quantify the energy saved from one building to the total number of residential buildings in Kathmandu, we could get the total energy saving potential from the rectification of thermal bridge at roof wall junction, this is assuming the roof wall junction length is same for all buildings. The exposed roof wall junction for each residential building may not be the same, the length could be lower or higher depending on the design of the building. The total energy which could be saved assuming the same length of the roof wall junction could amount to 76,666,986 kWh annually taking the reduction from case 7 as the basis. This assuming that the exposed surface of the roof wall junction for all the buildings in Kathmandu is the same as well as ideal air loads condition being taken for heating and cooling loads. This is not the actual case in reality, the length of the exposed roof wall junction could be lower or higher than the building which has been simulated, similarly the heating and cooling loads of buildings varies on the occupants of each buildings and the type of systems used which is different for each building.

According to energy synopsis report (2024), the total energy residential sector consumes is 323.46 PJ, out of which 4.99% is contributed by electricity which amounts to 4.48 billion kWh. The amount of 76,666,986 kWh saved with the use of insulation in our building model for the total residential buildings in Kathmandu amounts to 1.71% savings in electricity consumption for the whole of the country of Nepal annually with assumption mentioned above of certain parameters.

The linear thermal transmittance value that was found out through the THERM simulation and further calculations, give the additional heat loss from a building envelope through thermal anomalies, linear thermal bridges in this case. This linear thermal transmittance multiplied by the length of thermal anomaly location gives the additional heat loss from this junction. The sum of this overall heat transfer coefficient (U value) multiplied by the area of the clear field (eg wall), linear thermal transmittance multiplied by the length of the junction and point thermal transmittance give the total heat transfer value (loss or gain) through a building envelope. In this research, linear thermal transmittance value is of concern and in most researches point thermal transmittance is largely ignored. By finding out the linear thermal transmittance value, heat loss through linear thermal bridges can be figured out. The total length of the roof wall junction which is exposed to the environment for the simulated building is 52.48m, so the additional heat loss through this junction is 27.68 W/K. This is the additional heat loss from the roof wall junction in the case study building. The effect of these additional heat losses through thermal bridges may not be felt due to fact that the building envelope materials in our context of Nepal do not use external insulation materials. The effect of thermal bridges increases with the application of insulation materials on the external envelope surfaces, but this does not mean that heat loss through thermal bridges should be ignored as heat loss through these thermal bridges increases additional energy consumption for heating and cooling purposes as well as leading to condensation risks and mold growth. The additional heat losses through the thermal bridges shows that even in non-insulated building envelopes which are common in our context, these contribute measurably to energy efficiency.

The validity of this research was reinforced through a dual approach involving both empirical measurements using infrared thermography and simulations via THERM and OpenStudio. The alignment between thermographic observations and simulation outputs supports the reliability of the findings.

Regarding the use of insulation materials to rectify the thermal bridging anomalies in the roof wall junction. EPS was used from the outside in one case and rockwool was used in another case from the inside at the junction of the roof and wall slab. These materials have very low thermal conductivity and their use significantly reduce the linear thermal transmittance. The use of either material or other materials can be explored in further future researches. The choice between the proper insulation materials and its use from the exterior face or the interior face depends on the cost analysis of the materials as well as the manpower available to perform these tasks. EPS and rockwool may both be economical in terms of the price and may be easily available as well but the use of these as building materials may not be prevalent, especially EPS, rockwool are common used in buildings in our context in false ceilings and in partition walls so use of these materials in thermal bridge locations may be feasible but EPS application from the exterior side may lack the required manpower even if the cost of this material is lower than rockwool.

This study has demonstrated that thermal bridges in Kathmandu’s RCC buildings is a phenomenon which needs to be examined as they compromise energy efficiency as well as indoor comfort. Through the use of infrared thermography, numerical simulation and finally energy modelling, the research has shown the importance of analyzing thermal bridges. Regarding Nepal’s ever-growing urbanization where energy demand is critical this study shows the need to take the thermal bridging seriously.

CHAPTER 8 CONCLUSION

This study highlights the critical role of thermal bridges in the energy efficiency of residential buildings, particularly in the context of Nepal's temperate climate. By employing infrared thermography and numerical simulation (THERM), the research successfully identified and quantified thermal bridges in a key area such as a roof-wall junction, similarly this can be carried out for balcony slabs, and window frames. The analysis revealed that roof-wall junctions are particularly susceptible to thermal bridging, with a calculated linear thermal transmittance (ψ value) of 0.5275 W/m-K. For passivhaus standard the linear thermal transmittance should be below 0.01 W/m-K. From other thermal bridging guides like the Building Envelope Thermal bridging guide by BC Housing, linear thermal transmittance greater than 0.3 W/m-K is considered poor in terms of building performance. With the application of EPS as an insulation material along the thermal bridge section the ψ value reduced by 42% to 0.3051 W/m-K, showing the effectiveness of the targeted intervention.

The OpenStudio simulation further validated these findings, revealing a 2.59% and 3.26% reduction in the total site energy as well as the EUI after the application of the EPS and rockwool insulation. While this improvement may seem very minute, it represents a meaningful step toward energy efficiency, especially in the context of Nepal’s growing building stock.

Given the lack of empirical data on thermal bridges in Nepal, this research hopefully provides valuable insights for building professionals. These findings emphasize the need for improved building envelope design, including enhanced insulation and careful consideration of thermal bridging in construction practices. Addressing thermal bridges can reduce energy consumption, mitigate heat loss, and improve indoor comfort, contributing to more sustainable and energy-efficient buildings. The manual released by building energy efficiency in Nepal ((BEEN), 2024), gives only a brief introduction about thermal bridges without going into much detail, hence the outcomes of this research may give a better and clear understanding on thermal bridges and its impact on energy efficiency in a building. The study hopes to give a clarity regarding the analysis of thermal bridging from the calculation of parameters that define thermal bridges to clearly explaining these different parameters.

This study hopes to not only fill a gap in localized thermal performance research but also provide a replicable framework for future studies regarding thermal bridging concept. As cities like Kathmandu continue to grow, prioritizing energy efficient design will be essential to balancing modernization with environmental conservation. The rising cost of energy should also indicate the need to lower energy consumption by even the slightest amount. As energy is directly related to carbon emissions as well, energy conservation and mitigation is a broader issue in which even the minute of improvements should be taken into account.

In conclusion, this study highlights the critical role that thermal bridges play in the energy performance of residential buildings in Kathmandu. Combining empirical data from infrared thermography with simulation-based analysis through THERM and OpenStudio, offers a comprehensive understanding of heat loss mechanisms at roof wall junctions. This thermal bridging is a blind spot for which solutions are technically and economically viable. The implementation strategies applied showed measurable improvements in the energy performance, the broader implications highlight the need for greater awareness to address thermal bridging effects. Addressing this thermal anomaly may lead to the reduction of energy consumption, enhance occupant well being and advance the sustainable development goals of the country as well as the target set for net zero emissions by 2045. Integrating thermal bridge assessment into building practices holds significant potential in the energy efficiency field of a building.

CHAPTER 9 RECOMMENDATION

The findings of this study provide a strong foundation for further investigation into thermal bridging and its impacts on building energy performance in Nepal. Future research could build upon these results through several key paths of investigation, encompassing broader climatic and typological studies, advanced measurement techniques and more advanced analytical approaches. Further research could significantly enhance our understanding of thermal bridging phenomena and their mitigation strategies.

Expanded Building Typologies and Climatic Condition

Future research should expand on these findings by exploring additional building typologies and climates, as well as developing localized solutions to minimize thermal bridging in Nepal and similar regions, including traditional brick masonry structures, stone masonry structures as well as rammed wall constructions. Each typology presents a unique thermal bridging challenge that may require specific solutions. Additionally, research could move beyond Kathmandu's climate to investigate thermal bridging in Nepal's diverse climatic zones from subtropical Terai to the cold Himalayan regions as well as their specific and unique building construction practices. These could yield climate specific design guidelines for thermal bridging mitigation.

Localized Material Characterization

The thermal properties of the building materials where taken from ASHRAE standard, future research may make use of instruments such as a heat flow meter and other advanced instruments to measure actual properties like thermal conductivity and resistances of various building materials. These would give accurate and context specific data.

Comprehensive Thermal bridge mapping

This study primarily focused on roof wall junction, in the future thermal bridging analysis of other thermal bridging areas such as balcony wall junction, window wall connection as well as foundation wall connections can be carried out as well.

Seasonal Monitoring

The temperature and humidity logging as well as the thermographic inspection was carried out in the winter time during a period of 2 weeks, future research could be carried out in different seasons for a longer time period, to give a more robust and comprehensive finding. A year round monitoring to capture seasonal variations on thermal bridging effects could be carried out.

Hygrothermal and indoor air quality impacts

Thermal bridging major impact is the risk of condensation and mold growth, future research could look at the potential of condensation and mold growth due to thermal bridging effects, this could give a more detailed understanding of how thermal bridges affect not only energy but also the indoor environmental quality.

Advanced Imaging and Detection Technologies

Using a higher resolution camera may give sharper and clearer images along with being more accurate with a more detailed analysis. Infrared thermography is a comprehensive non-destructive technique to detect thermal anomalies in a building and with a better camera, better and more detailed results could be expected. Application of IRT could be a good method for energy efficient retrofits of existing buildings.

Cost Benefit Analysis of Mitigation Strategies

Cost analysis for the use of various techniques for rectifying thermal bridging effect could be carried out not only for new construction of buildings but also in the retrofitting of existing buildings to improve their energy efficiency.

Advanced Simulation Techniques

THERM is a 2D simulation analysis tool in the future 3D thermal modelling could be carried out through software such as ANSYS, COMSOL for a more comprehensive understanding of thermal bridges in a 3D direction. These may also help to understand complex intersections involving multiple building elements.

CHAPTER 10 LIMITATIONS

While this study presents promising results into the thermal bridging effects in Nepalese residential buildings, it is important to acknowledge certain limitations. These limitations vary from methodological constraints, measurement challenges and assumptions that may affect the generalizability of the results.

Environmental and measurement constraints

The outdoor environment is affected by various environmental factors such as solar radiation, wind and other parameters, which severely affect the temperature and humidity data, hence the thermal imaging was mostly taken from indoors as the environment could be better controlled. This limited exterior thermal imaging of balcony slab junctions and thermal inspections from exterior side in general. The infrared camera's low resolution (160 x 120 pixels), is a limitation as clearer and more detailed thermal images could not be captured, where higher resolution camera could capture even minute details and thermal anomalies along with being more accurate with a more detailed analysis.

Material property assumptions

The reliance on ASHRAE standard material properties may not fully capture the local variations in construction materials. Future research could include on site measurement of thermal properties using tools like heat flow meters. Similarly, the long-term changes in the material properties were not accounted for in this research as well as the workmanship quality was ignored, in actual construction practices the quality may deviate from idealized assumptions. These can lead to overestimation or underestimation of heat flows.

Simulation assumptions and sample size

The assumed exposed length of roof wall junctions during the simulation process was assumed to be the same across Kathmandu while estimating the total energy saving potential, which may not hold true due to the architectural diversity of buildings. Similarly, the indoor conditions, occupancy behaviour, lighting and equipment details as well as exact constructions details vary across households, which could influence the actual energy saving potential. The simulation and measurements were conducted on only one typical residential building in Kathmandu. The study also makes no assessment of the urban microclimate effects such as the difference in dense and sparse neighbourhoods. While the findings provide valuable insights, architectural variations across the city could influence thermal bridge behaviour. Similarly, the occupant behaviour differs from person to person and the occupant behaviour specified in the simulation may not capture the real work usage. Building heights, designs and exposed surface areas vary across the building typology, which could lead to either overestimation or underestimation of energy savings. These limitations, however, do not undermine the broader trend observe that thermal bridge correction has a measurable impact on building energy performance.

Seasonal limitations

The data logging for this research was logged for a period of only two weeks during the winter season. This logging of temperature and humidity only captures the conditions during the two-week winter period and not the whole year seasonal condition. The various seasonal changes such as the humidity condition during the monsoon season, temperature during the summer season is not encapsulated during the logging of data.

Economic factors

This study did not address or focus on the real world implementation challenges such as the cost effectiveness of the various mitigation measures, retrofitting feasibility in constructed buildings, maintenance requirements over time etc. These types of considerations are important for adoption of these measures in real world setting, policy development and long-term performance.

Despite these limitations, this research highlights the significance of thermal bridges and its importance in the energy performance of buildings. These limitations highlight important areas for further research regarding thermal bridges.

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APPENDIX 1: Climate Data

S.No.	Date-Time (Nepal Standard Time)	Outside Temperature (°C)	Inside Temperature (°C)	RH
1	01-17-2025 08:17:20	9.82	13.8	59.7
2	01-17-2025 09:17:20	11.41	13.8	60.7
3	01-17-2025 10:17:20	12.57	14.4	58.3
4	01-17-2025 11:17:20	14.37	14.9	57.1
5	01-17-2025 12:17:20	16.13	15.3	56.6
6	01-17-2025 13:17:20	17.07	15.4	55.1
7	01-17-2025 14:17:20	17.59	15.5	48.8
8	01-17-2025 15:17:20	17.29	15.5	47.1
9	01-17-2025 16:17:20	16.86	15.6	47.1
10	01-17-2025 17:17:20	15.66	15.6	47.7
11	01-17-2025 18:17:20	14.84	15.5	48.4
12	01-17-2025 19:17:20	13.55	15.5	48.8
13	01-17-2025 20:17:20	12.74	15.3	49
14	01-17-2025 21:17:20	12.18	15	50.2
15	01-17-2025 22:17:20	11.45	14.8	51.1
16	01-17-2025 23:17:20	10.98	14.6	51.4
17	01-18-2025 00:17:20	10.12	14.4	52
18	01-18-2025 01:17:20	9.99	14.2	52.8
19	01-18-2025 02:17:20	9.44	14	53
20	01-18-2025 03:17:20	8.88	13.7	53.4
21	01-18-2025 04:17:20	8.62	13.4	53.5
22	01-18-2025 05:17:20	8.11	13.3	53.5
23	01-18-2025 06:17:20	7.93	13.2	53.5
24	01-18-2025 07:17:20	7.76	13.1	53.3
25	01-18-2025 08:17:20	8.75	12.8	52.6
26	01-18-2025 09:17:20	10.25	13.9	51.8
27	01-18-2025 10:17:20	12.18	14.4	50.9
28	01-18-2025 11:17:20	14.50	15.1	49.5
29	01-18-2025 12:17:20	16.43	15.5	48.4
30	01-18-2025 13:17:20	17.41	15.4	47.6
31	01-18-2025 14:17:20	17.76	15.5	46.5
32	01-18-2025 15:17:20	18.06	15.7	46.2
33	01-18-2025 16:17:20	16.69	15.8	45.9
34	01-18-2025 17:17:20	15.61	15.8	47.5
35	01-18-2025 18:17:20	14.03	15.5	48.8
36	01-18-2025 19:17:20	13.47	15.3	49.8
37	01-18-2025 20:17:20	12.10	15.1	49.3
38	01-18-2025 21:17:20	11.71	15	49.6

S.No.	Date-Time (Nepal Standard Time)	Outside Temperature (°C)	Inside Temperature (°C)	RH
39	01-18-2025 22:17:20	10.81	14.8	49.7
40	01-18-2025 23:17:20	10.08	14.3	50.3
41	01-19-2025 00:17:20	9.52	14	51.3
42	01-19-2025 01:17:20	9.05	13.9	51.5
43	01-19-2025 02:17:20	8.53	13.8	51.6
44	01-19-2025 03:17:20	8.36	13.6	51.5
45	01-19-2025 04:17:20	7.42	13.2	51.9
46	01-19-2025 05:17:20	7.29	13.3	52
47	01-19-2025 06:17:20	7.46	13.1	52.2
48	01-19-2025 07:17:20	7.03	12.9	52.1
49	01-19-2025 08:17:20	8.71	13.4	51.4
50	01-19-2025 09:17:20	10.98	14	50.6
51	01-19-2025 10:17:20	13.08	14.6	49.7
52	01-19-2025 12:17:20	18.70	16.9	46.5
53	01-19-2025 13:17:20	20.72	17.4	45.8
54	01-19-2025 14:17:20	19.82	17.8	45.4
55	01-19-2025 15:17:20	19.90	17.5	43.2
56	01-19-2025 16:17:20	18.96	17.5	43.9
57	01-19-2025 17:17:20	16.94	17.2	45.6
58	01-19-2025 18:17:20	15.74	17.1	46.6
59	01-19-2025 19:17:20	14.41	17.2	46.9
60	01-19-2025 20:17:20	13.34	17.2	48.7
61	01-19-2025 21:17:20	12.70	17.1	49.8
62	01-19-2025 22:17:20	11.88	17	49.5
63	01-19-2025 23:17:20	11.49	16.9	48.7
64	01-20-2025 00:17:20	10.59	16.9	48.6
65	01-20-2025 01:17:20	9.69	17.2	47.9
66	01-20-2025 02:17:20	9.35	17.2	47.6
67	01-20-2025 03:17:20	9.14	17.1	47.7
68	01-20-2025 04:17:20	8.71	17	47.7
69	01-20-2025 05:17:20	8.58	16.8	47.2
70	01-20-2025 06:17:20	7.98	16.7	47.1
71	01-20-2025 07:17:20	7.76	16.7	47.1
72	01-20-2025 08:17:20	9.56	15.3	48.2
73	01-20-2025 09:17:20	11.67	15.7	48.8
74	01-20-2025 10:17:20	13.94	16.2	47.6
75	01-20-2025 11:17:20	16.56	16.4	48
76	01-20-2025 12:17:20	18.49	17.3	46.7
77	01-20-2025 13:17:20	20.50	17.6	46.1
78	01-20-2025 14:17:20	21.53	18	45.4
79	01-20-2025 15:17:20	21.49	18.4	44.8

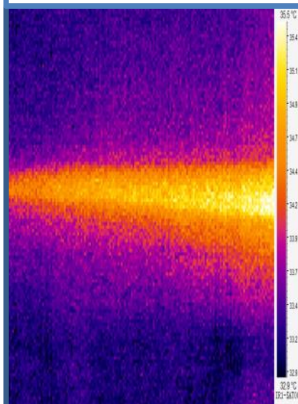
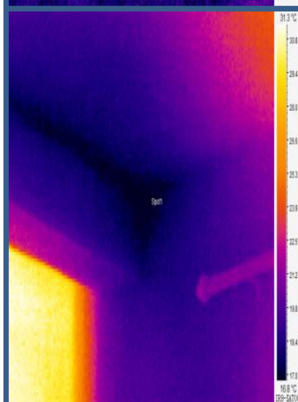
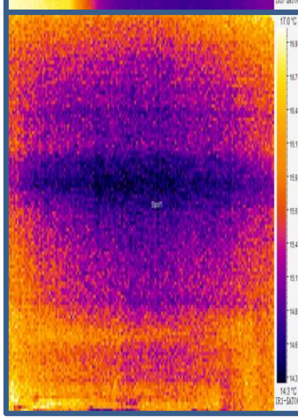
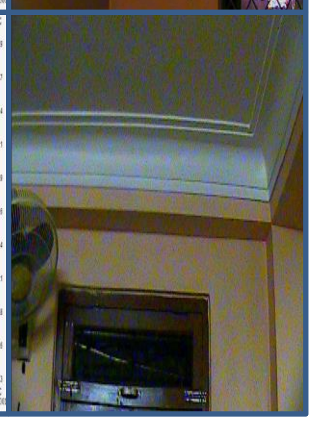
S.No.	Date-Time (Nepal Standard Time)	Outside Temperature (°C)	Inside Temperature (°C)	RH
80	01-20-2025 16:17:20	19.69	18.5	43.8
81	01-20-2025 17:17:20	17.24	17.9	45.9
82	01-20-2025 18:17:20	16.00	17.8	47.3
83	01-20-2025 19:17:20	14.80	17.7	48.3
84	01-20-2025 20:17:20	14.45	17.3	51
85	01-20-2025 21:17:20	13.38	17.5	50
86	01-20-2025 22:17:20	12.44	17.6	49.1
87	01-20-2025 23:17:20	11.84	16.6	49.5
88	01-21-2025 00:17:20	11.28	16.9	48.6
89	01-21-2025 01:17:20	10.59	16.7	48.3
90	01-21-2025 02:17:20	9.91	16.5	48.7
91	01-21-2025 03:17:20	9.65	16.4	48.2
92	01-21-2025 04:17:20	9.26	16.3	47.9
93	01-21-2025 05:17:20	8.66	16	48.1
94	01-21-2025 06:17:20	8.49	15.9	48.1
95	01-21-2025 07:17:20	8.75	15.3	48.4
96	01-21-2025 08:17:20	10.04	15.1	49.1
97	01-21-2025 09:17:20	12.27	15.9	49.5
98	01-21-2025 10:17:20	15.14	15.9	49.2
99	01-21-2025 11:17:20	18.06	17.3	47.2
100	01-21-2025 12:17:20	20.59	17.8	45.7
101	01-21-2025 13:17:20	22.56	18.1	44.6
102	01-21-2025 14:17:20	22.31	18.6	43.4
103	01-21-2025 15:17:20	22.31	18.4	40.3
104	01-21-2025 16:17:20	21.02	18.2	40.8
105	01-21-2025 17:17:20	18.92	17.9	43.9
106	01-21-2025 18:17:20	17.29	17.6	46.6
107	01-21-2025 19:17:20	16.17	17.7	47
108	01-21-2025 20:17:20	15.36	17.8	47.9
109	01-21-2025 21:17:20	14.28	17.8	47.8
110	01-21-2025 22:17:20	13.55	17.7	47
111	01-21-2025 23:17:20	12.78	17.6	47.4
112	01-22-2025 00:17:20	11.92	17.6	47.1
113	01-22-2025 01:17:20	11.41	17.6	46.5
114	01-22-2025 02:17:20	10.81	17.3	46.9
115	01-22-2025 03:17:20	10.08	17.1	46.9
116	01-22-2025 04:17:20	10.04	17	46.3
117	01-22-2025 05:17:20	9.48	16.9	46.5
118	01-22-2025 06:17:20	9.09	16.7	46.8
119	01-22-2025 07:17:20	8.75	15.9	47.1
120	01-22-2025 08:17:20	10.94	15.7	47.6

S.No.	Date-Time (Nepal Standard Time)	Outside Temperature (°C)	Inside Temperature (°C)	RH
121	01-22-2025 09:17:20	13.00	16.3	48.4
122	01-22-2025 10:17:20	15.83	16.7	47.3
123	01-22-2025 11:17:20	19.09	17.2	46.1
124	01-22-2025 12:17:20	22.69	17.6	43.1
125	01-22-2025 13:17:20	24.02	17.9	39.6
126	01-22-2025 14:17:20	23.64	17.8	35.8
127	01-22-2025 15:17:20	22.69	17.9	34.4
128	01-22-2025 16:17:20	21.92	18.1	34.8
129	01-22-2025 17:17:20	19.73	17.9	37.6
130	01-22-2025 18:17:20	18.10	18.1	39.9
131	01-22-2025 19:17:20	16.64	18.1	42.2
132	01-22-2025 20:17:20	15.96	18.1	43.6
133	01-22-2025 21:17:20	14.58	18	43.8
134	01-22-2025 22:17:20	13.43	17.9	42.6
135	01-22-2025 23:17:20	12.87	17.9	42
136	01-23-2025 00:17:20	12.05	18	39.4
137	01-23-2025 01:17:20	11.45	18	40
138	01-23-2025 02:17:20	10.77	17.9	39.5
139	01-23-2025 03:17:20	10.51	17.8	40
140	01-23-2025 04:17:20	10.08	17.5	40.1
141	01-23-2025 05:17:20	9.65	17.4	40.1
142	01-23-2025 06:17:20	9.18	16.9	40.1
143	01-23-2025 07:17:20	9.14	15.9	39.3
144	01-23-2025 08:17:20	10.77	16.1	41.1
145	01-23-2025 09:17:20	13.21	16.9	39.6
146	01-23-2025 11:17:20	18.57	17.9	39.3
147	01-23-2025 12:17:20	21.45	18.2	38
148	01-23-2025 14:17:20	22.22	18.7	33.4
149	01-23-2025 15:17:20	21.83	18.6	30.3
150	01-23-2025 16:17:20	20.80	18.8	31.6
151	01-23-2025 17:17:20	19.43	18.8	32.8
152	01-23-2025 18:17:20	17.11	18.7	38.1
153	01-23-2025 19:17:20	16.39	18.7	40.3
154	01-23-2025 21:17:20	14.58	18.6	41.8
155	01-23-2025 22:17:20	13.51	18.5	40.5
156	01-23-2025 23:17:20	12.74	18.4	41
157	01-24-2025 00:17:20	11.79	18.4	40.8
158	01-24-2025 01:17:20	11.19	18.1	41
159	01-24-2025 02:17:20	11.02	18	41.3
160	01-24-2025 03:17:20	10.12	17.9	41.3
161	01-24-2025 05:17:20	9.52	17.6	41.5

S.No.	Date-Time (Nepal Standard Time)	Outside Temperature (°C)	Inside Temperature (°C)	RH
162	01-24-2025 06:17:20	9.44	17.5	41.6
163	01-24-2025 07:17:20	9.44	17.2	42
164	01-24-2025 08:17:20	10.89	15.4	43
165	01-24-2025 09:17:20	12.74	16.4	42.9
166	01-24-2025 10:17:20	16.13	17.3	41.7
167	01-24-2025 11:17:20	18.10	17.6	40
168	01-24-2025 12:17:20	19.56	18	39.2
169	01-24-2025 13:17:20	19.73	18.2	37.5
170	01-24-2025 14:17:20	19.26	18.6	37.6
171	01-24-2025 15:17:20	18.62	18.4	37.3
172	01-24-2025 16:17:20	17.97	18.4	35.3
173	01-24-2025 17:17:20	16.47	18.2	35.8
174	01-24-2025 18:17:20	15.31	18.6	37.8
175	01-24-2025 19:17:20	14.71	18.7	38.3
176	01-24-2025 20:17:20	13.60	18.1	38
177	01-24-2025 21:17:20	12.91	18	39
178	01-24-2025 22:17:20	12.10	17.9	39.5
179	01-24-2025 23:17:20	11.24	17.7	40.4
180	01-25-2025 00:17:20	10.51	17.6	40.9
181	01-25-2025 01:17:20	10.12	18.2	40.1
182	01-25-2025 02:17:20	9.86	18.1	40.1
183	01-25-2025 03:17:20	9.18	18	40.2
184	01-25-2025 04:17:20	8.88	17.9	40.1
185	01-25-2025 05:17:20	8.41	17.7	40.2
186	01-25-2025 06:17:20	7.68	17.6	40
187	01-25-2025 07:17:20	7.89	16.9	40.1
188	01-25-2025 08:17:20	9.78	14.8	41.6
189	01-25-2025 09:17:20	11.32	15.8	40.8
190	01-25-2025 10:17:20	13.90	16.7	39.7
191	01-25-2025 11:17:20	16.17	17.1	38.8
192	01-25-2025 12:17:20	17.89	17.3	37.7
193	01-25-2025 13:17:20	19.09	18.1	34.5
194	01-25-2025 14:17:20	18.83	18.5	35.3
195	01-25-2025 15:17:20	18.02	18.4	37.4
196	01-25-2025 16:17:20	17.24	18.4	38.1
197	01-25-2025 17:17:20	14.80	18.3	43.9
198	01-25-2025 20:17:20	11.97	17.6	48.9
199	01-25-2025 21:17:20	11.84	17.5	48.6
200	01-25-2025 22:17:20	11.37	17.2	48.7
201	01-25-2025 23:17:20	10.59	17.3	48
202	01-26-2025 00:17:20	9.99	17	48.4

S.No.	Date-Time (Nepal Standard Time)	Outside Temperature (°C)	Inside Temperature (°C)	RH
203	01-26-2025 01:17:20	9.82	16.9	48.4
204	01-26-2025 02:17:20	10.16	16.9	48.3
205	01-26-2025 03:17:20	10.55	16.8	48.5
206	01-26-2025 04:17:20	10.38	16.7	48.9
207	01-26-2025 05:17:20	10.85	16.4	49
208	01-26-2025 06:17:20	11.11	16.8	48.6
209	01-26-2025 07:17:20	11.28	16.2	49.5
210	01-26-2025 08:17:20	12.01	16.4	49.3
211	01-26-2025 09:17:20	13.60	16.8	48.2
212	01-26-2025 10:17:20	14.50	17.2	47

APPENDIX 2: Thermal Images

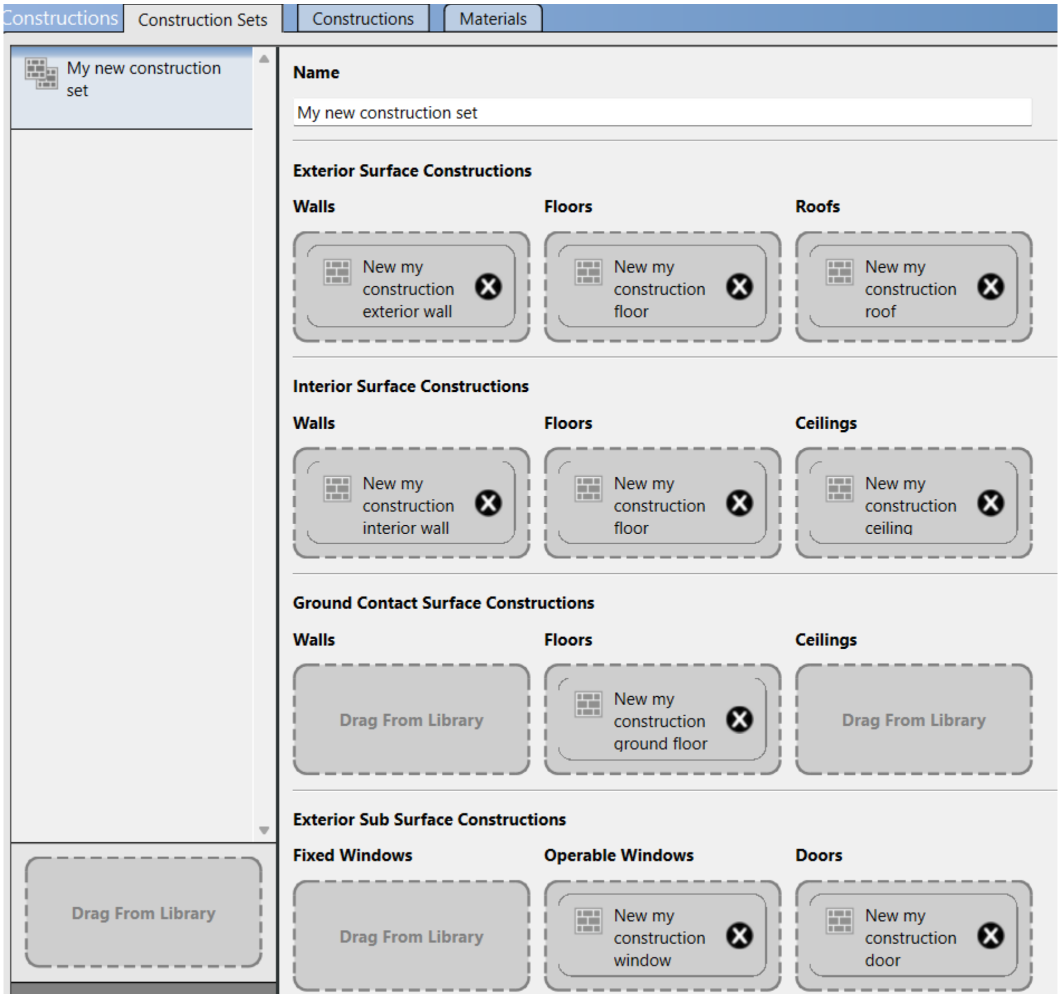
Thermal Image	Digital Image
	
	
	

APPENDIX 3: Electricity Consumption

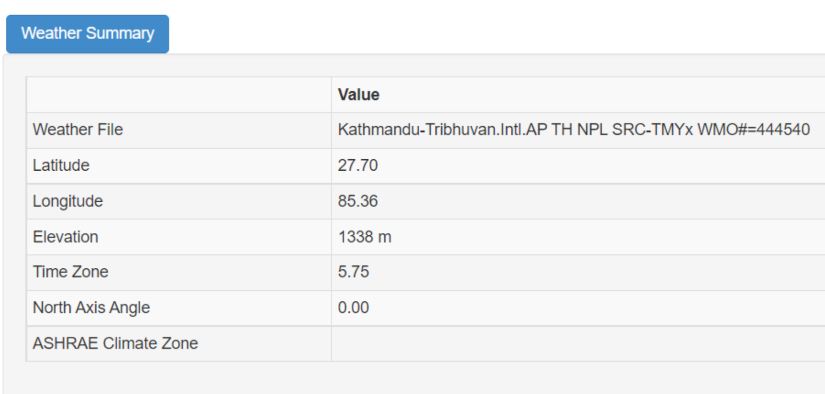
Month	**Units (kWhr)**
January 2023	191
February 2023	188
March 2023	205
April 2023	168
May 2023	188
June 2023	203
July 2023	216
August 2023	218
September 2023	222
October 2023	215
November 2023	194
December 2023	203

APPENDIX 4: OpenStudio properties

Construction Sets



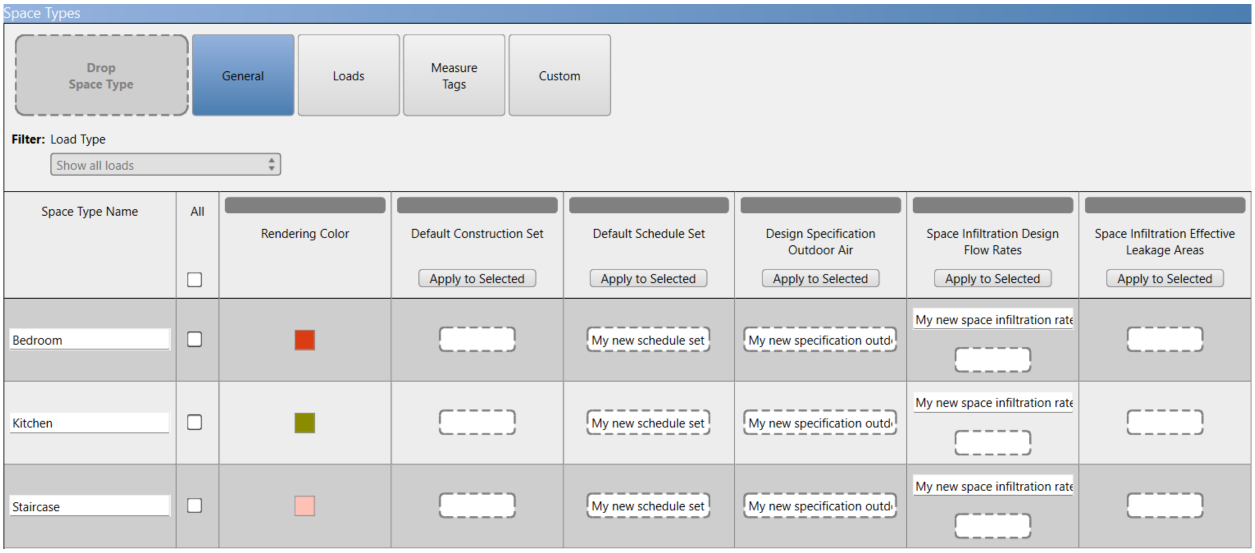
Weather file detail

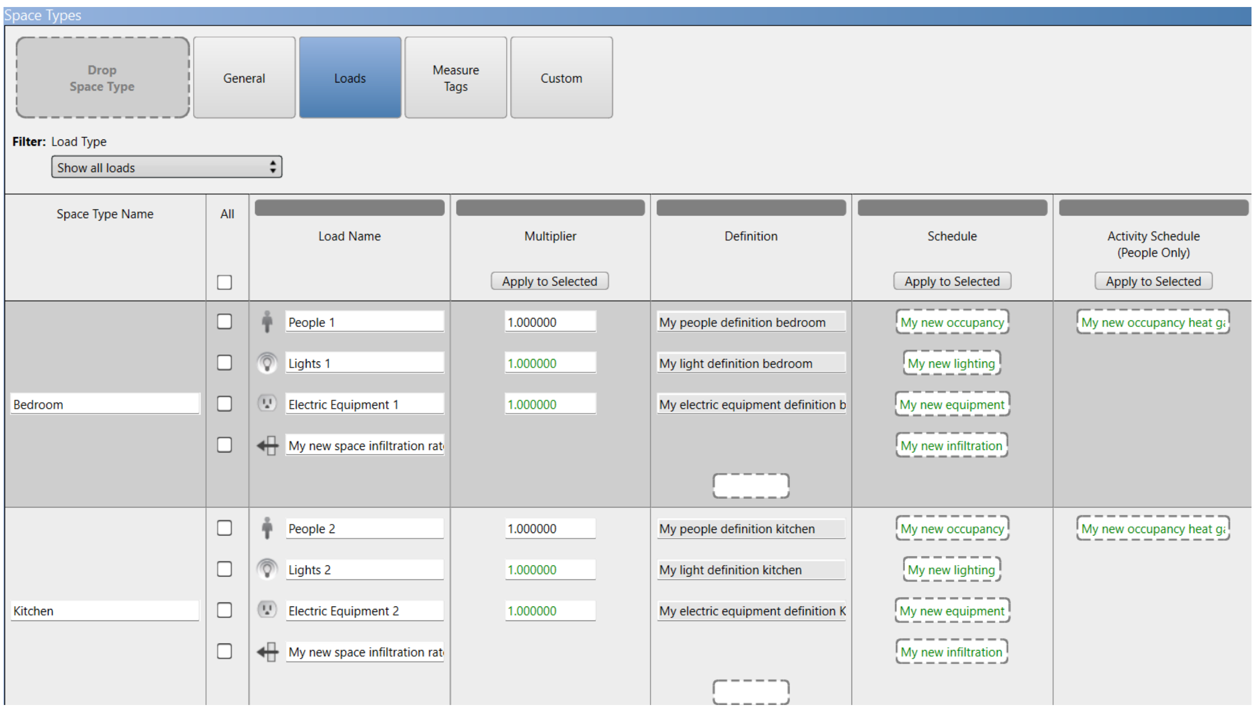


Weather Summary

	Value
Weather File	Kathmandu-Tribhuvan.Intl.AP TH NPL SRC-TMYx WMO#=444540
Latitude	27.70
Longitude	85.36
Elevation	1338 m
Time Zone	5.75
North Axis Angle	0.00
ASHRAE Climate Zone	

Space Types



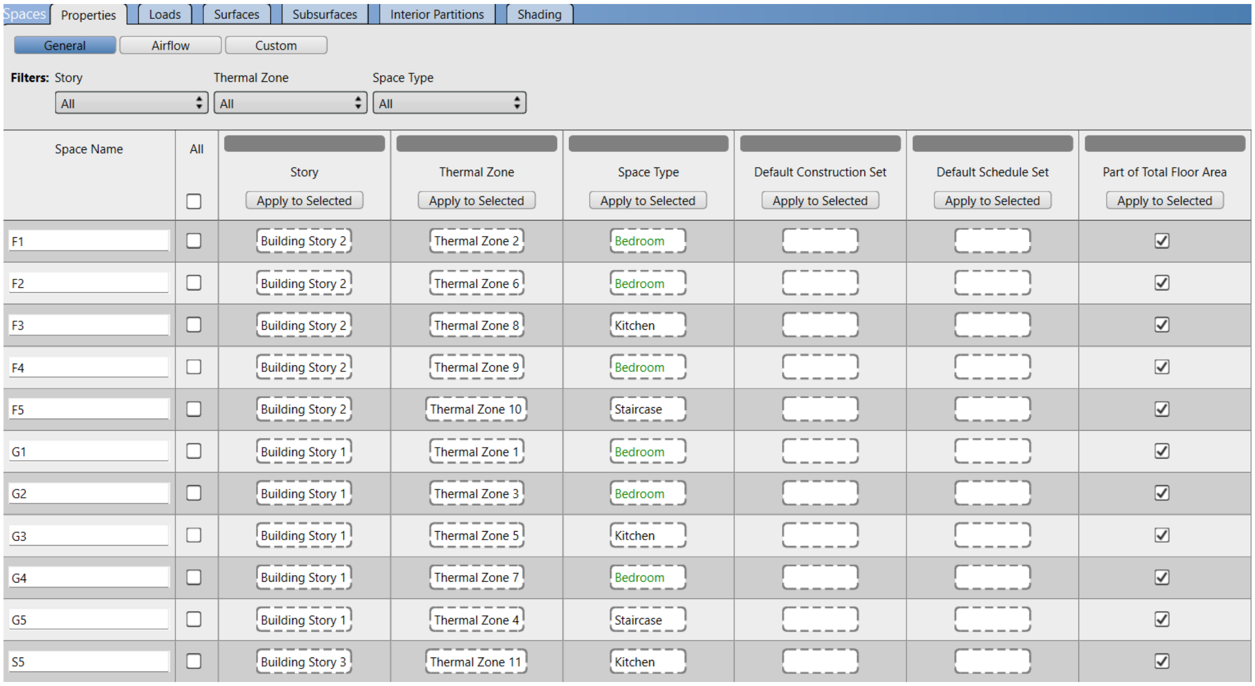


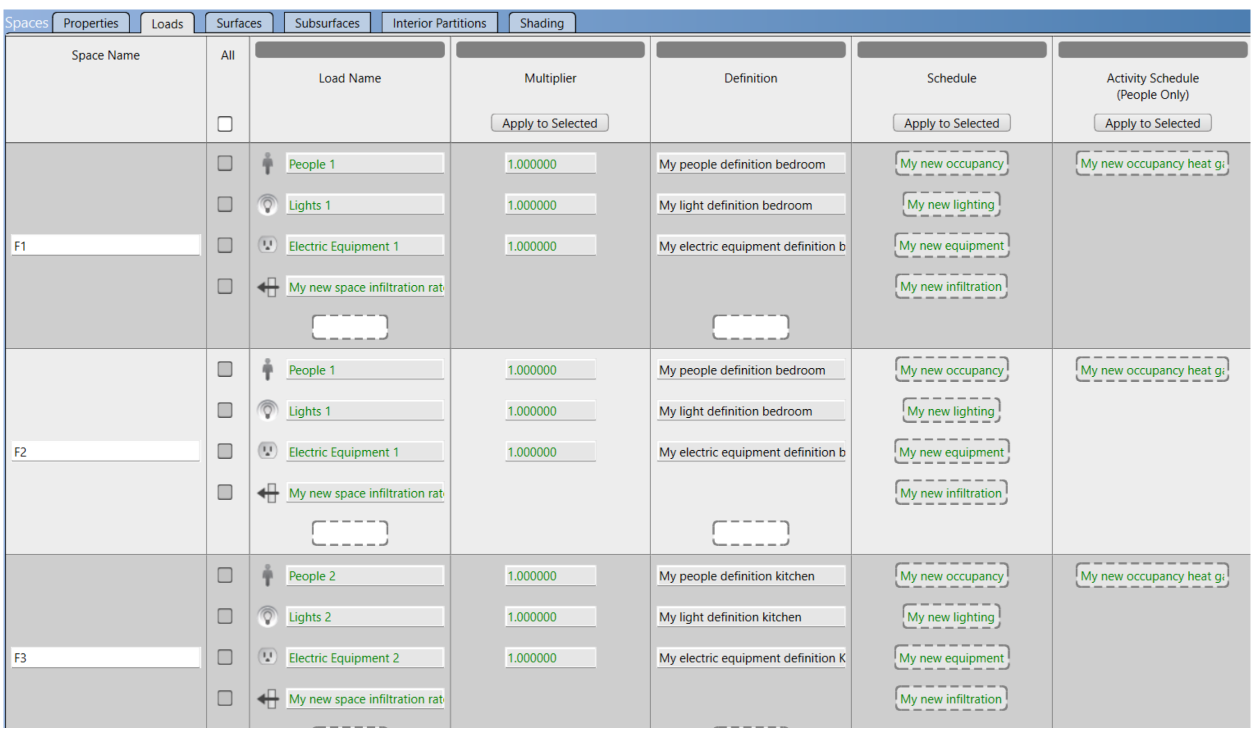
Window wall

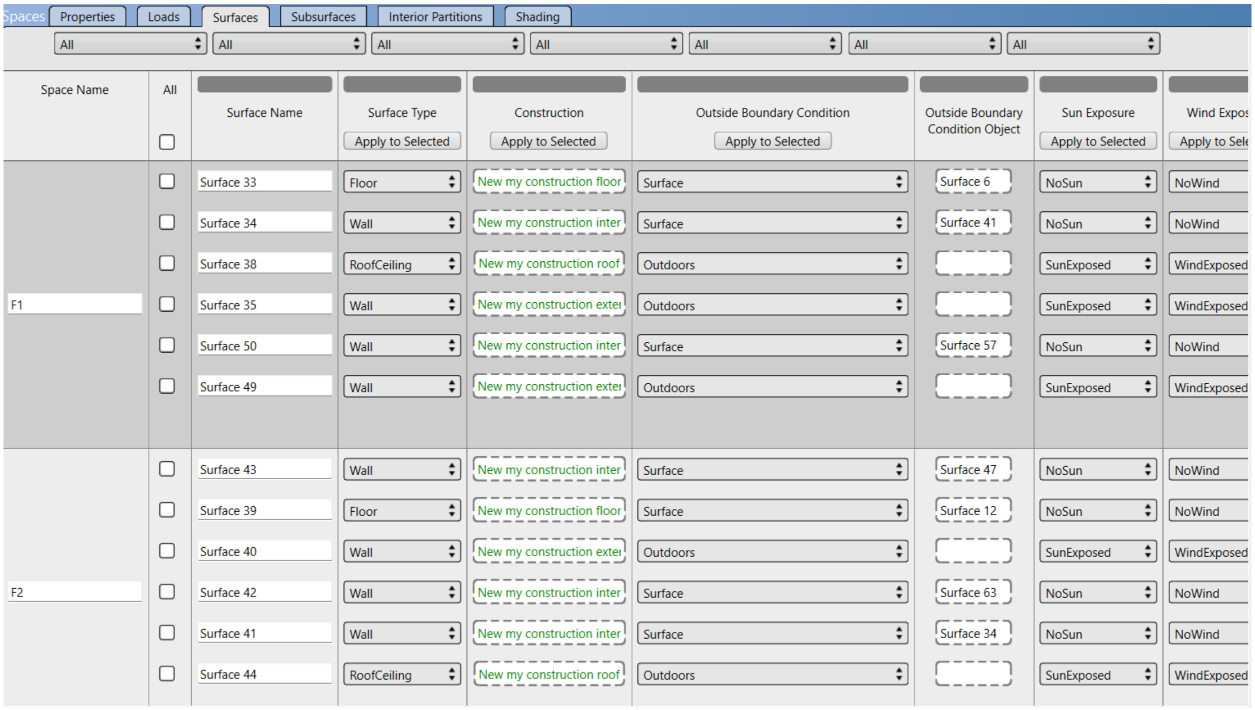
Window-to-Wall and Skylight-to-Roof area Ratios

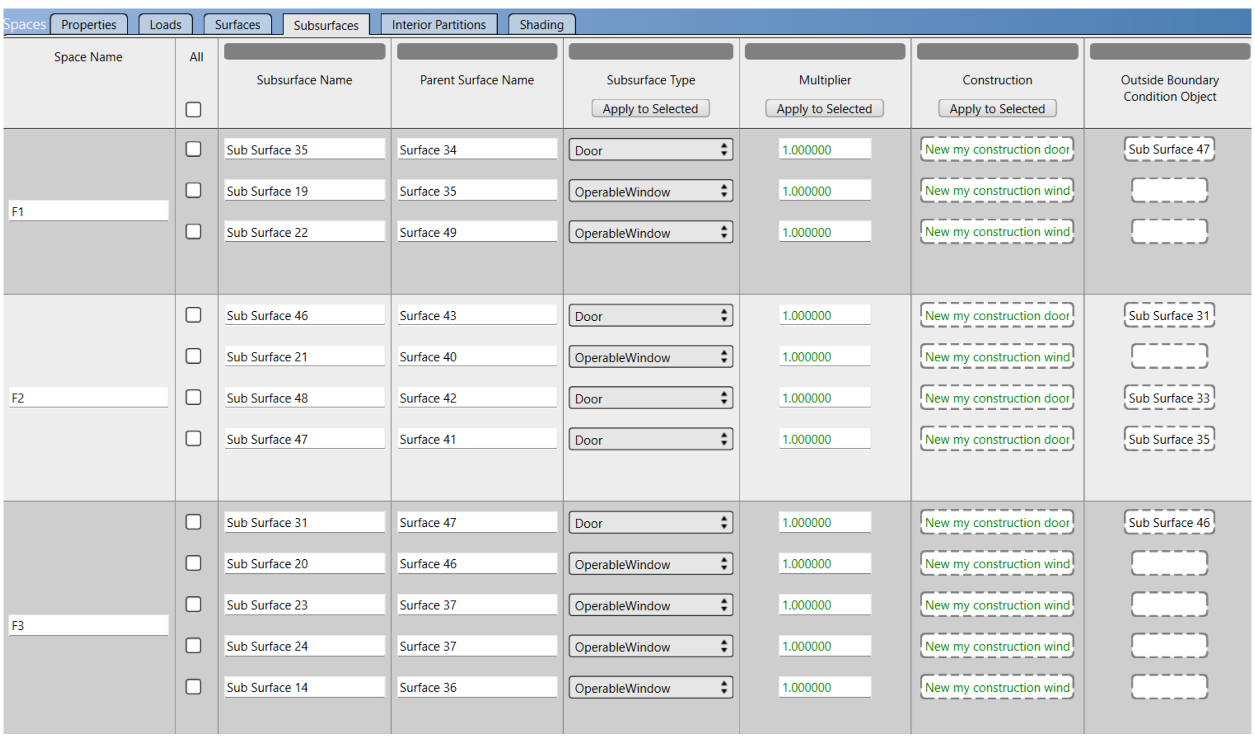
Description	Total (%)	North (%)	East (%)	South (%)	West (%)
Gross Window-Wall Ratio	19.81	23.25	12.32	22.2	21.41
Gross Window-Wall Ratio (Conditioned)	19.73	24.42	12.32	22.2	21.41
Skylight-Roof Ratio	0.0				

Spaces

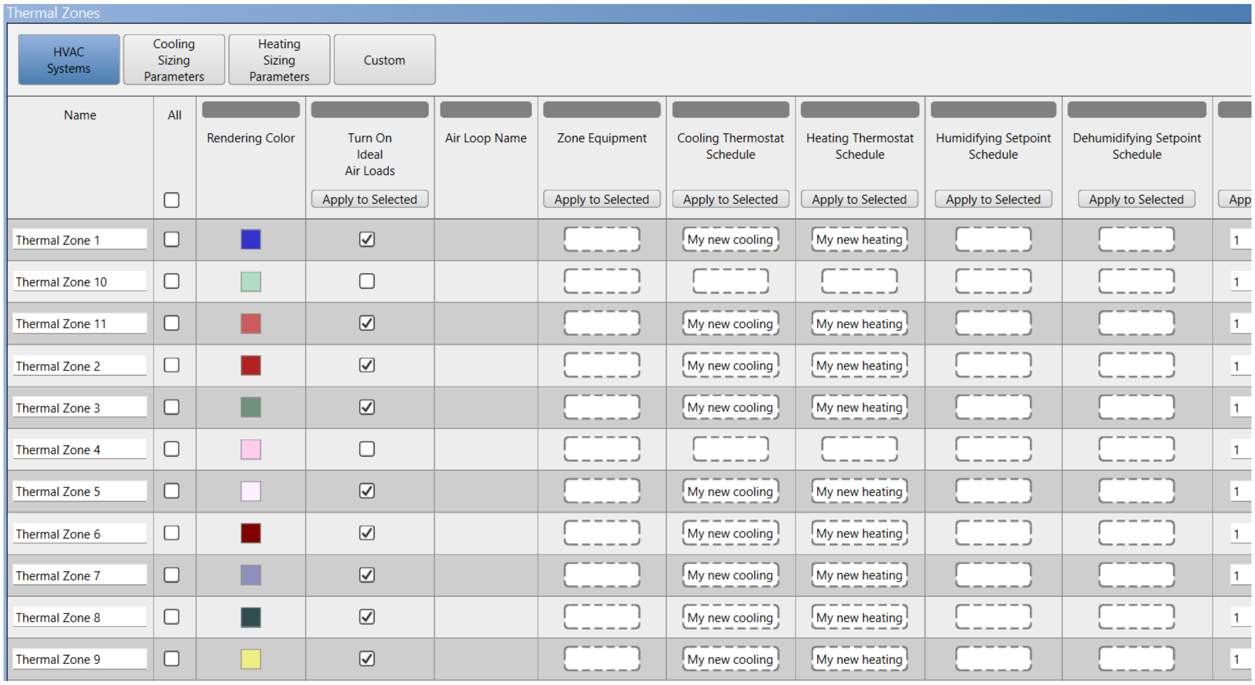

Spaces
Properties
Loads
Surfaces
Subsurfaces
Interior Partitions
Shading
General
Airflow
Custom
Filters: Story
Thermal Zone
Space Type
All
All
All
Space Name
All
Story
Thermal Zone
Space Type
Default Construction Set
Default Schedule Set
Part of Total Floor Area
Apply to Selected
F1
Building Story 2
Thermal Zone 2
Bedroom
F2
Building Story 2
Thermal Zone 6
Bedroom
F3
Building Story 2
Thermal Zone 8
Kitchen
F4
Building Story 2
Thermal Zone 9
Bedroom
F5
Building Story 2
Thermal Zone 10
Staircase
G1
Building Story 1
Thermal Zone 1
Bedroom
G2
Building Story 1
Thermal Zone 3
Bedroom
G3
Building Story 1
Thermal Zone 5
Kitchen
G4
Building Story 1
Thermal Zone 7
Bedroom
G5
Building Story 1
Thermal Zone 4
Staircase
S5
Building Story 3
Thermal Zone 11
Kitchen


Spaces
Properties
Loads
Surfaces
Subsurfaces
Interior Partitions
Shading
Space Name
All
Load Name
Multiplier
Definition
Schedule
Activity Schedule (People Only)
Apply to Selected
F1
People 1
1.000000
My people definition bedroom
My new occupancy
My new occupancy heat g
Lights 1
1.000000
My light definition bedroom
My new lighting
Electric Equipment 1
1.000000
My electric equipment definition b
My new equipment
My new space infiltration rat
My new infiltration
F2
People 1
1.000000
My people definition bedroom
My new occupancy
My new occupancy heat g
Lights 1
1.000000
My light definition bedroom
My new lighting
Electric Equipment 1
1.000000
My electric equipment definition b
My new equipment
My new space infiltration rat
My new infiltration
F3
People 2
1.000000
My people definition kitchen
My new occupancy
My new occupancy heat g
Lights 2
1.000000
My light definition kitchen
My new lighting
Electric Equipment 2
1.000000
My electric equipment definition K
My new equipment
My new space infiltration rat
My new infiltration


Spaces
Properties
Loads
Surfaces
Subsurfaces
Interior Partitions
Shading
All
Space Name
All
Surface Name
Surface Type
Apply to Selected
Construction
Apply to Selected
Outside Boundary Condition
Apply to Selected
Outside Boundary Condition Object
Sun Exposure
Apply to Selected
Wind Expos
Apply to Sele
F1
Surface 33 | Floor | New my construction floor | Surface | Surface 6 | NoSun | NoWind
Surface 34 | Wall | New my construction inter | Surface | Surface 41 | NoSun | NoWind
Surface 38 | RoofCeiling | New my construction roof | Outdoors | SunExposed | WindExposed
Surface 35 | Wall | New my construction exter | Outdoors | SunExposed | WindExposed
Surface 50 | Wall | New my construction inter | Surface | Surface 57 | NoSun | NoWind
Surface 49 | Wall | New my construction exter | Outdoors | SunExposed | WindExposed
F2
Surface 43 | Wall | New my construction inter | Surface | Surface 47 | NoSun | NoWind
Surface 39 | Floor | New my construction floor | Surface | Surface 12 | NoSun | NoWind
Surface 40 | Wall | New my construction exter | Outdoors | SunExposed | WindExposed
Surface 42 | Wall | New my construction inter | Surface | Surface 63 | NoSun | NoWind
Surface 41 | Wall | New my construction inter | Surface | Surface 34 | NoSun | NoWind
Surface 44 | RoofCeiling | New my construction roof | Outdoors | SunExposed | WindExposed

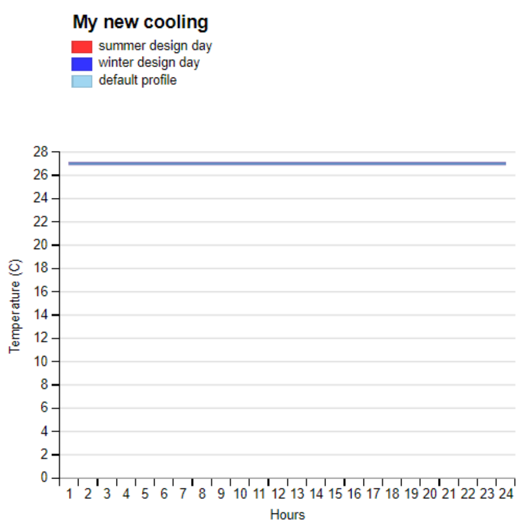

Spaces
Properties
Loads
Surfaces
Subsurfaces
Interior Partitions
Shading
Space Name
All
Subsurface Name
Parent Surface Name
Subsurface Type
Apply to Selected
Multiplier
Apply to Selected
Construction
Apply to Selected
Outside Boundary Condition Object
F1
Sub Surface 35 | Surface 34 | Door | 1.000000 | New my construction door | Sub Surface 47
Sub Surface 19 | Surface 35 | OperableWindow | 1.000000 | New my construction wind
Sub Surface 22 | Surface 49 | OperableWindow | 1.000000 | New my construction wind
F2
Sub Surface 46 | Surface 43 | Door | 1.000000 | New my construction door | Sub Surface 31
Sub Surface 21 | Surface 40 | OperableWindow | 1.000000 | New my construction wind
Sub Surface 48 | Surface 42 | Door | 1.000000 | New my construction door | Sub Surface 33
Sub Surface 47 | Surface 41 | Door | 1.000000 | New my construction door | Sub Surface 35
F3
Sub Surface 31 | Surface 47 | Door | 1.000000 | New my construction door | Sub Surface 46
Sub Surface 20 | Surface 46 | OperableWindow | 1.000000 | New my construction wind
Sub Surface 23 | Surface 37 | OperableWindow | 1.000000 | New my construction wind
Sub Surface 24 | Surface 37 | OperableWindow | 1.000000 | New my construction wind
Sub Surface 14 | Surface 36 | OperableWindow | 1.000000 | New my construction wind

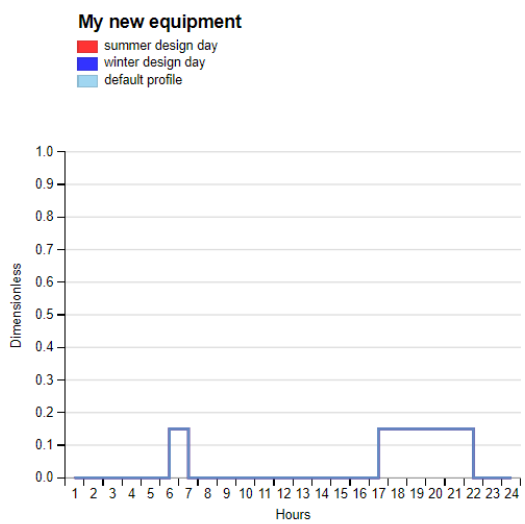
Thermal Zones

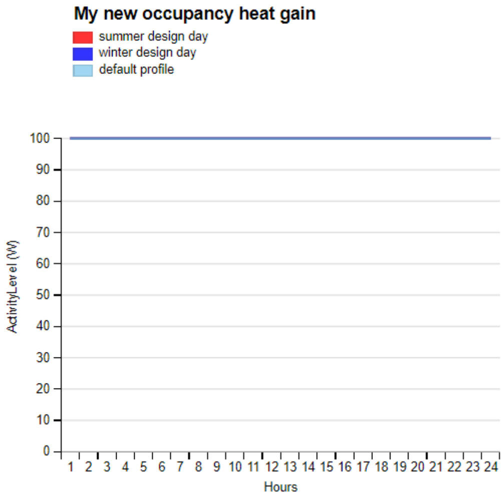


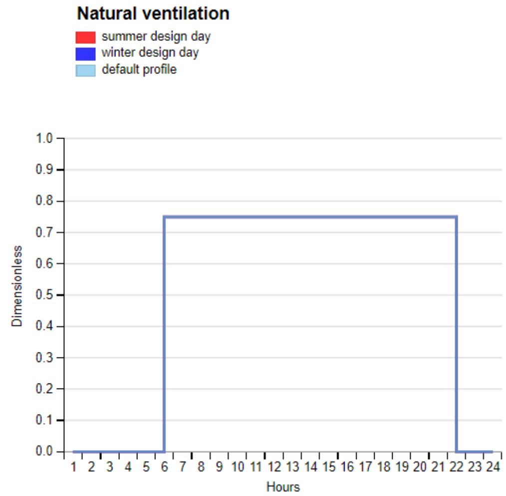
Name	All	Rendering Color	Turn On Ideal Air Loads	Air Loop Name	Zone Equipment	Cooling Thermostat Schedule	Heating Thermostat Schedule	Humidifying Setpoint Schedule	Dehumidifying Setpoint Schedule	App
	☐		Apply to Selected		Apply to Selected	Apply to Selected	Apply to Selected	Apply to Selected	Apply to Selected	App
Thermal Zone 1	☐		☑			My new cooling	My new heating			1
Thermal Zone 10	☐		☐							1
Thermal Zone 11	☐		☑			My new cooling	My new heating			1
Thermal Zone 2	☐		☑			My new cooling	My new heating			1
Thermal Zone 3	☐		☑			My new cooling	My new heating			1
Thermal Zone 4	☐		☐							1
Thermal Zone 5	☐		☑			My new cooling	My new heating			1
Thermal Zone 6	☐		☑			My new cooling	My new heating			1
Thermal Zone 7	☐		☑			My new cooling	My new heating			1
Thermal Zone 8	☐		☑			My new cooling	My new heating			1
Thermal Zone 9	☐		☑			My new cooling	My new heating			1

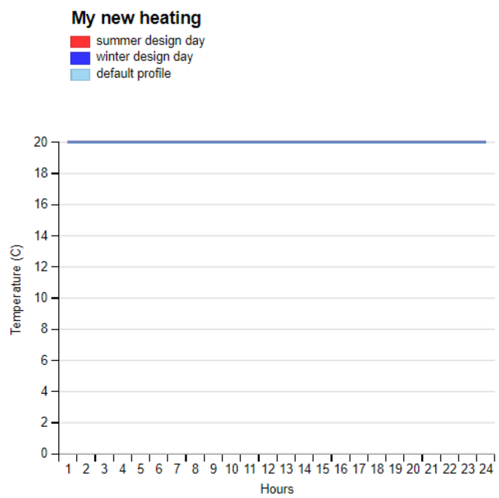
Schedule

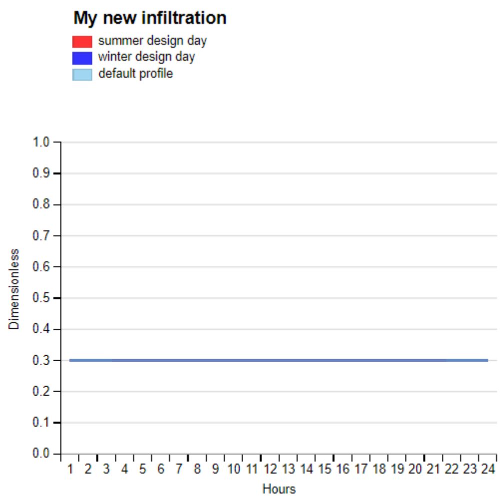


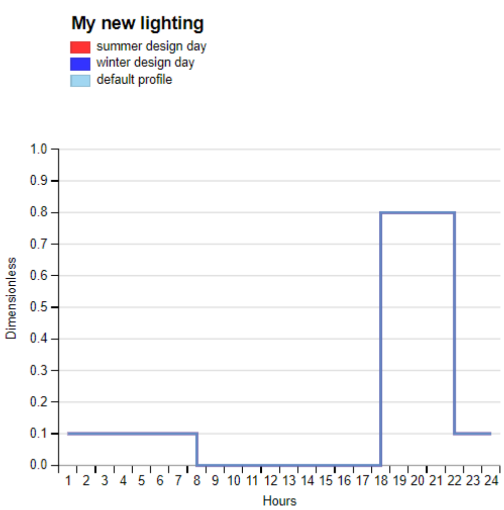


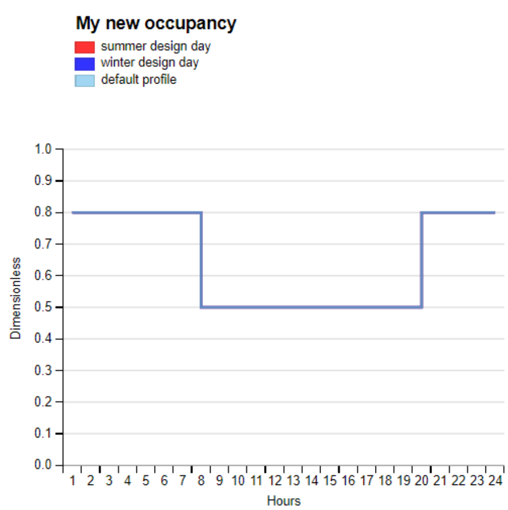

My new occupancy heat gain
summer design day
winter design day
default profile
ActivityLevel (W)
Hours


Natural ventilation
summer design day
winter design day
default profile
Dimensionless
Hours


My new heating
summer design day
winter design day
default profile
Temperature (C)
Hours


My new infiltration
summer design day
winter design day
default profile
Dimensionless
Hours


My new lighting
summer design day
winter design day
default profile
Dimensionless
Hours


My new occupancy
summer design day
winter design day
default profile
Dimensionless
Hours

Space Type Summary

Space Type Summary

Bedroom
(6 spaces and 6 thermal zones)

Definition	Value	Unit	Inst. Multiplier
My people definition bedroom	2	people	1.0
My electric equipment definition bedroom	250	W	1.0
My light definition bedroom	55	W	1.0
My new space infiltration rate	0.0003	m^3/h/ext surf area m^2	
My new specification outdoor air (outdoor air method Sum)	25.4852	m^3/h/person	

Kitchen
(3 spaces and 3 thermal zones)

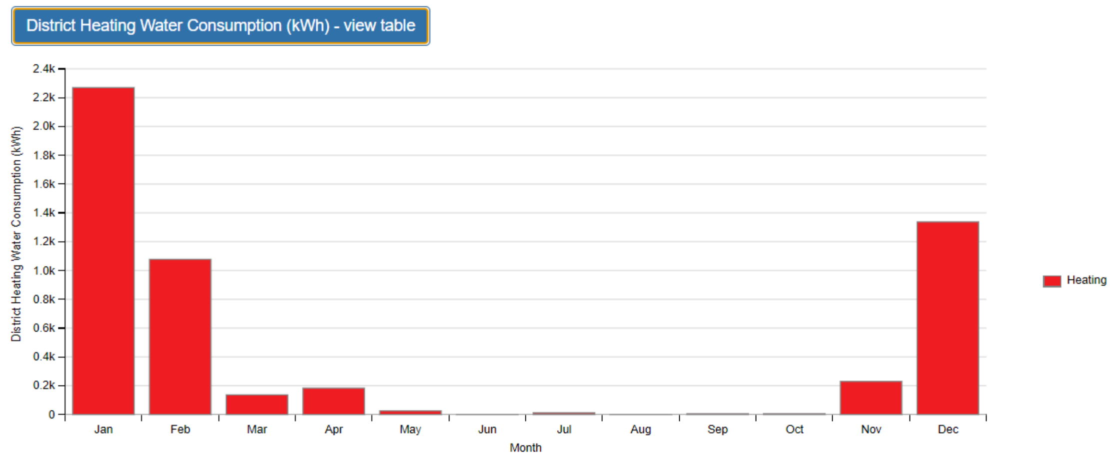
Definition	Value	Unit	Inst. Multiplier
My people definition kitchen	4	people	1.0
My electric equipment definition Kitchen	1,200	W	1.0
My light definition kitchen	85	W	1.0
My new space infiltration rate 1	0.0003	m^3/h/ext surf area m^2	
My new specification outdoor air (outdoor air method Sum)	25.4852	m^3/h/person	

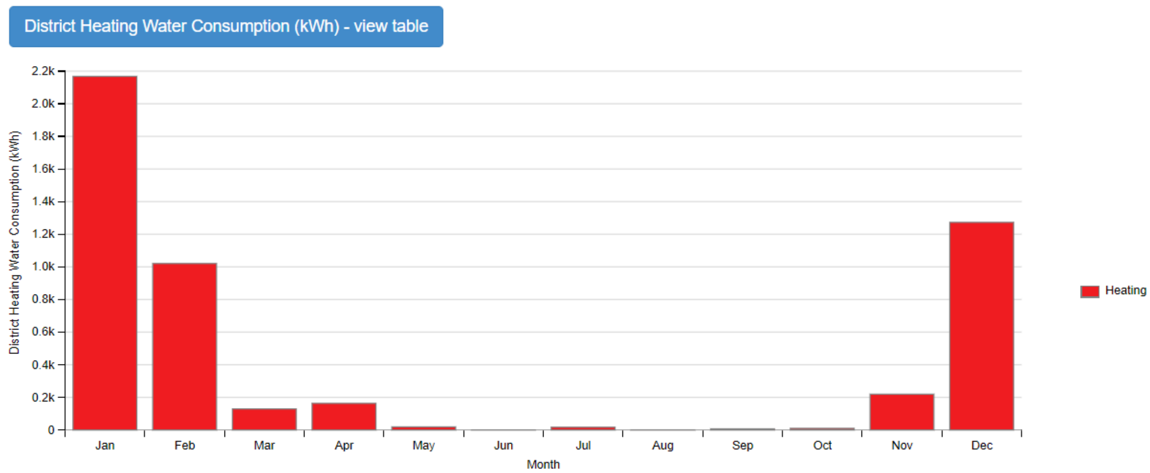
Staircase
(2 spaces and 2 thermal zones)

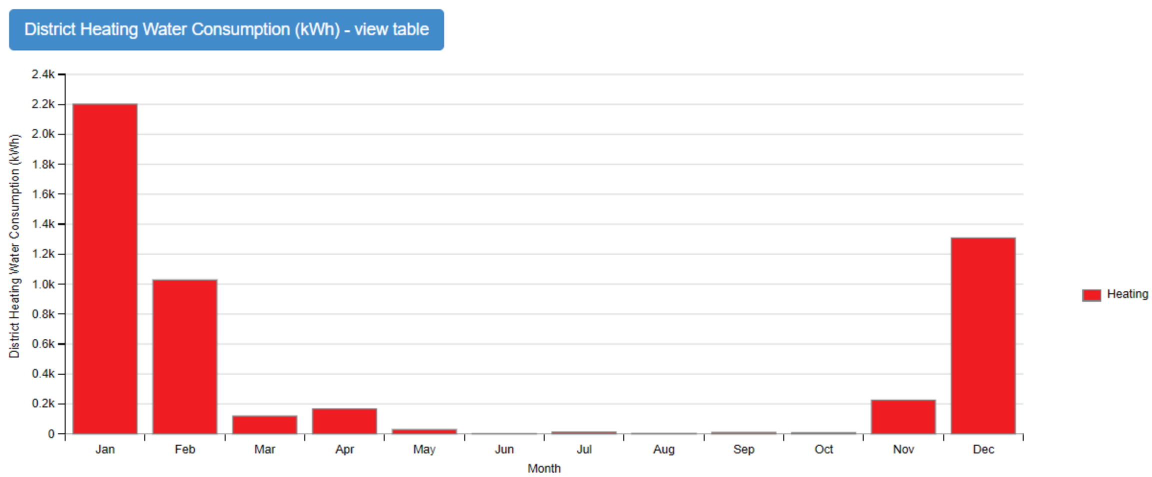
Definition	Value	Unit	Inst. Multiplier
My people definition kitchen	4	people	1.0
My light definition staircase	30	W	1.0
My new space infiltration rate 2	0.0003	m^3/h/ext surf area m^2	
My new specification outdoor air (outdoor air method Sum)	25.4852	m^3/h/person	

APPENDIX 5: OpenStudio Simulation Results

District heating consumption of base, case 1 and case 7 respectively

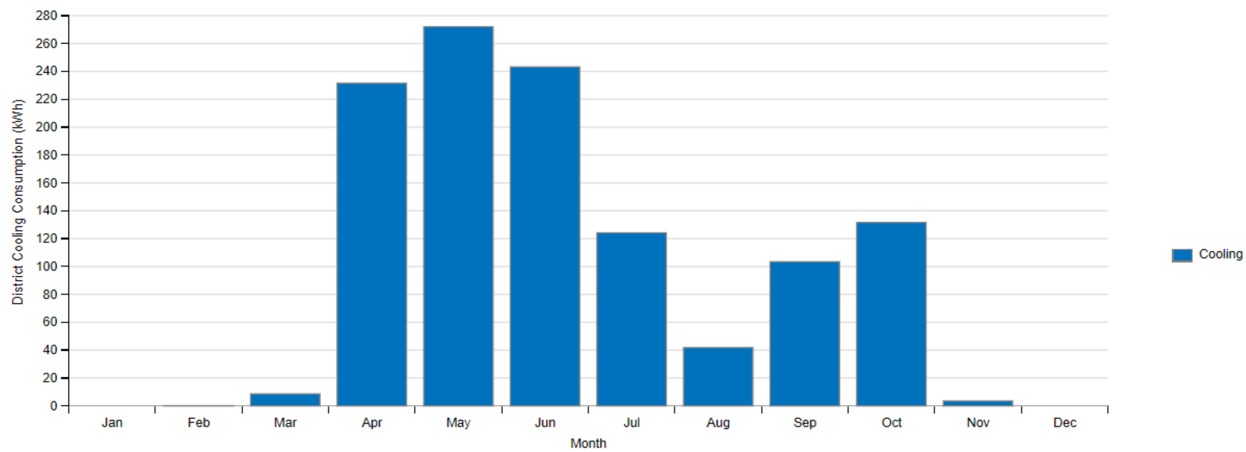




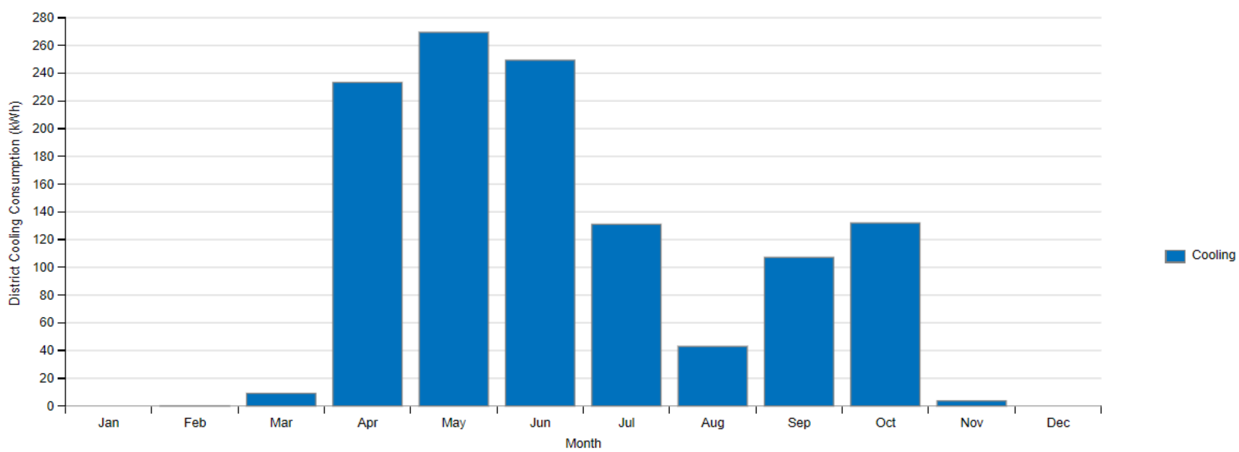


District cooling consumption of base, case 1 and case 7 respectively

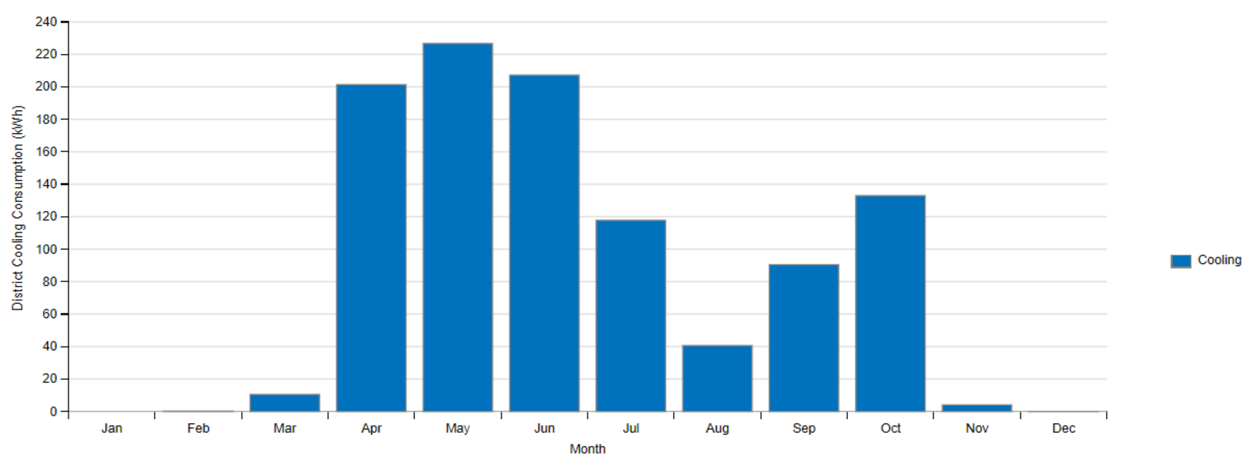
District Cooling Consumption (kWh) - view table



District Cooling Consumption (kWh) - view table



District Cooling Consumption (kWh) - view table



Zone Temperature of base, case 1 and case 7respectively

Zone Conditions

Temperature (Table values represent hours spent in each temperature range)

Zone	Unmet Htg (hr)	Unmet Htg - Occ (hr)	< 13 (C)	13-16 (C)	16-18 (C)	18-20 (C)	20-21 (C)	21-22 (C)	22-23 (C)	23-24 (C)	24-26 (C)	26-28 (C)	28-30 (C)	>= 30 (C)	Unmet Clg (hr)	Unmet Clg - Occ (hr)	Mean Temp (C)
THERMAL ZONE 1	0	0	0	0	0	84	1622	1002	1198	1699	2479	676	0	0	0	0	23.1 (C)
THERMAL ZONE 10	0	0	0	0	51	670	692	841	941	913	2675	1754	223	0	0	0	23.9 (C)
THERMAL ZONE 11	0	0	0	0	0	200	2442	783	921	1118	2102	1194	0	0	0	0	23.0 (C)
THERMAL ZONE 2	0	0	0	0	0	71	1717	818	977	1251	2565	1361	0	0	0	0	23.4 (C)
THERMAL ZONE 3	0	0	0	0	0	63	1472	1052	1407	2111	2356	299	0	0	0	0	23.0 (C)
THERMAL ZONE 4	0	0	0	0	13	920	883	1112	1092	1451	3096	193	0	0	0	0	22.9 (C)
THERMAL ZONE 5	0	0	0	0	0	243	2525	839	1046	1449	2141	517	0	0	0	0	22.6 (C)
THERMAL ZONE 6	0	0	0	0	0	74	1495	811	1105	1288	2764	1223	0	0	0	0	23.5 (C)
THERMAL ZONE 7	0	0	0	0	0	278	2716	830	1085	1510	1928	413	0	0	0	0	22.5 (C)
THERMAL ZONE 8	0	0	0	0	0	250	2435	721	821	1068	2232	1233	0	0	0	0	23.0 (C)
THERMAL ZONE 9	0	0	0	0	0	303	2609	687	805	1111	2287	958	0	0	0	0	22.8 (C)

Zone Conditions

Temperature (Table values represent hours spent in each temperature range)

Zone	Unmet Htg (hr)	Unmet Htg - Occ (hr)	< 13 (C)	13-16 (C)	16-18 (C)	18-20 (C)	20-21 (C)	21-22 (C)	22-23 (C)	23-24 (C)	24-26 (C)	26-28 (C)	28-30 (C)	>= 30 (C)	Unmet Clg (hr)	Unmet Clg - Occ (hr)	Mean Temp (C)
THERMAL ZONE 1	0	0	0	0	0	78	1626	989	1202	1684	2502	679	0	0	0	0	23.1 (C)
THERMAL ZONE 10	0	0	0	0	34	647	692	820	956	919	2603	1855	234	0	0	0	23.9 (C)
THERMAL ZONE 11	0	0	0	0	0	166	2359	770	895	1080	2201	1289	0	0	0	0	23.1 (C)
THERMAL ZONE 2	0	0	0	0	0	84	1646	853	956	1199	2632	1390	0	0	0	0	23.5 (C)
THERMAL ZONE 3	0	0	0	0	0	71	1458	1063	1404	2093	2373	298	0	0	0	0	23.0 (C)
THERMAL ZONE 4	0	0	0	0	12	913	882	1099	1100	1431	3127	196	0	0	0	0	22.9 (C)
THERMAL ZONE 5	0	0	0	0	0	238	2516	850	1038	1443	2154	521	0	0	0	0	22.7 (C)
THERMAL ZONE 6	0	0	0	0	0	77	1504	826	1130	1230	2776	1217	0	0	0	0	23.5 (C)
THERMAL ZONE 7	0	0	0	0	0	270	2701	842	1076	1508	1940	423	0	0	0	0	22.5 (C)
THERMAL ZONE 8	0	0	0	0	0	248	2387	729	795	1049	2263	1289	0	0	0	0	23.1 (C)
THERMAL ZONE 9	0	0	0	0	0	253	2550	710	791	1052	2332	1072	0	0	0	0	22.9 (C)

Zone Conditions

Temperature (Table values represent hours spent in each temperature range)

Zone	Unmet Htg (hr)	Unmet Htg - Occ (hr)	< 13 (C)	13-16 (C)	16-18 (C)	18-20 (C)	20-21 (C)	21-22 (C)	22-23 (C)	23-24 (C)	24-26 (C)	26-28 (C)	28-30 (C)	>= 30 (C)	Unmet Clg (hr)	Unmet Clg - Occ (hr)	Mean Temp (C)
THERMAL ZONE 1	0	0	0	0	0	59	1611	1090	1388	1722	2307	583	0	0	0	0	23.0 (C)
THERMAL ZONE 10	0	0	0	0	38	642	680	871	1149	1281	2941	1102	56	0	0	0	23.5 (C)
THERMAL ZONE 11	0	0	0	0	0	172	2382	866	1109	1188	1961	1082	0	0	0	0	22.9 (C)
THERMAL ZONE 2	0	0	0	0	0	80	1675	893	1229	1399	2369	1115	0	0	0	0	23.3 (C)
THERMAL ZONE 3	0	0	0	0	62	238	336	1032	1643	2436	2770	243	0	0	0	0	23.3 (C)
THERMAL ZONE 4	0	0	0	0	18	857	893	1163	1393	1811	2545	80	0	0	0	0	22.7 (C)
THERMAL ZONE 5	0	0	0	0	0	208	2545	974	1176	1419	1987	451	0	0	0	0	22.6 (C)
THERMAL ZONE 6	0	0	0	0	0	88	1485	863	1372	1495	2564	893	0	0	0	0	23.3 (C)
THERMAL ZONE 7	0	0	0	0	0	213	2773	944	1244	1489	1756	341	0	0	0	0	22.4 (C)
THERMAL ZONE 8	0	0	0	0	0	200	2480	785	1000	1191	2041	1063	0	0	0	0	22.9 (C)
THERMAL ZONE 9	0	0	0	0	0	255	2573	783	1039	1226	2065	819	0	0	0	0	22.7 (C)

Zone humidity of base, Case 1 and Case 7 respectively

Humidity (Table values represent hours spent in each Humidity range)

Zone	< 30 (%)	30-35 (%)	35-40 (%)	40-45 (%)	45-50 (%)	50-55 (%)	55-60 (%)	60-65 (%)	65-70 (%)	70-75 (%)	75-80 (%)	>= 80 (%)	Mean Relative Humidity (%)
THERMAL ZONE 1	55	234	817	1107	944	820	562	394	364	378	577	2508	62.6 (%)
THERMAL ZONE 10	5	24	54	103	130	180	228	266	300	378	573	6519	88.1 (%)
THERMAL ZONE 11	39	225	752	1011	953	857	761	562	450	486	663	2001	61.4 (%)
THERMAL ZONE 2	64	368	894	1098	941	835	631	457	400	471	696	1905	60.1 (%)
THERMAL ZONE 3	42	214	671	1070	1029	830	621	357	354	299	455	2818	63.9 (%)
THERMAL ZONE 4	0	1	12	30	50	81	112	144	181	233	283	7633	93.0 (%)
THERMAL ZONE 5	25	119	614	983	978	898	714	437	421	429	589	2553	64.0 (%)
THERMAL ZONE 6	48	262	914	1109	991	827	579	437	423	485	774	1911	60.5 (%)
THERMAL ZONE 7	29	121	626	962	953	820	796	431	421	389	526	2686	64.3 (%)
THERMAL ZONE 8	37	198	774	991	904	923	766	562	512	502	717	1874	61.3 (%)
THERMAL ZONE 9	37	206	749	972	900	882	799	528	447	492	749	1999	61.7 (%)

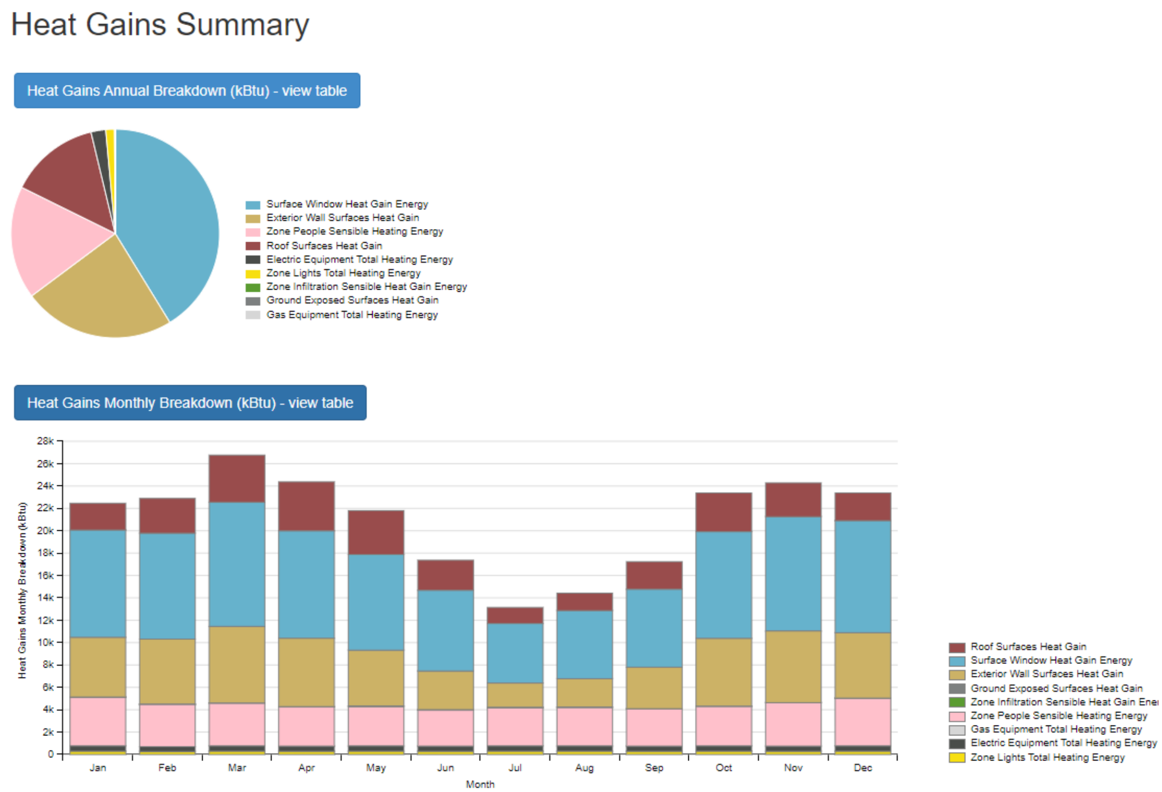
Humidity (Table values represent hours spent in each Humidity range)

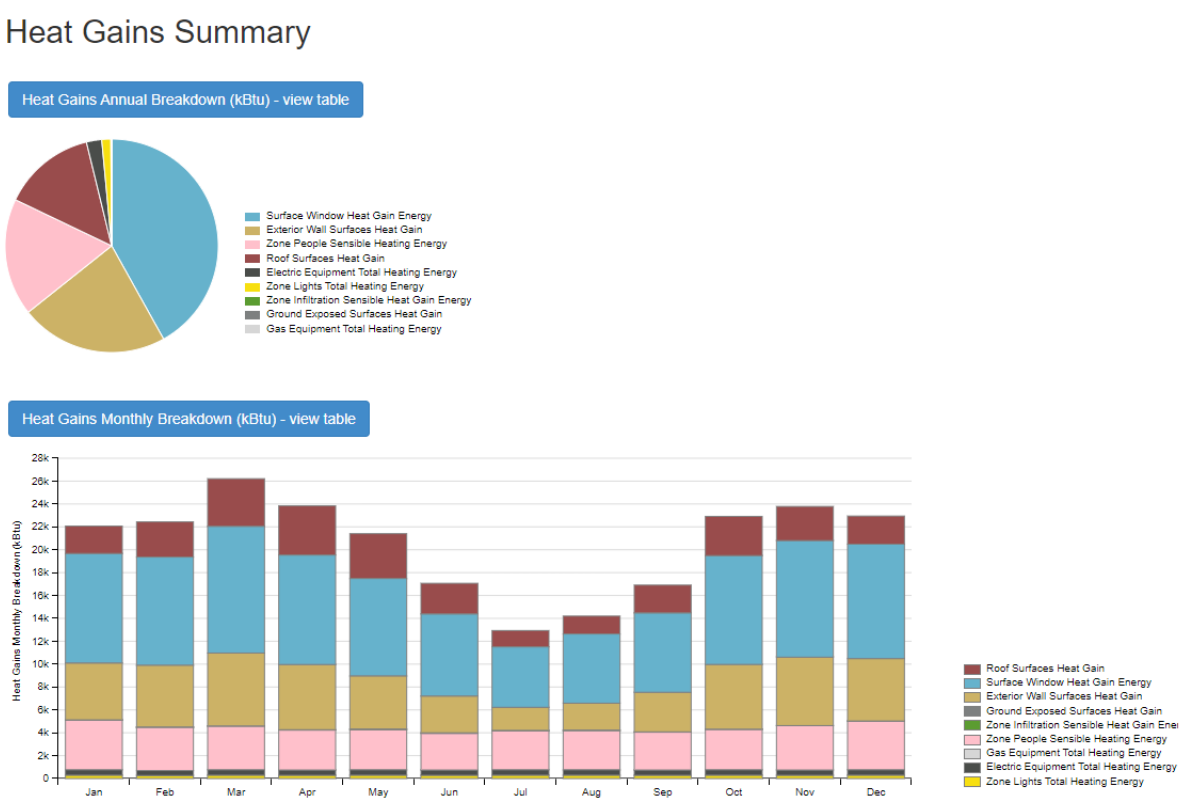
Zone	< 30 (%)	30-35 (%)	35-40 (%)	40-45 (%)	45-50 (%)	50-55 (%)	55-60 (%)	60-65 (%)	65-70 (%)	70-75 (%)	75-80 (%)	>= 80 (%)	Mean Relative Humidity (%)
THERMAL ZONE 1	56	230	817	1100	962	814	561	399	363	381	579	2498	62.6 (%)
THERMAL ZONE 10	5	23	57	104	139	181	240	283	325	390	603	6410	87.7 (%)
THERMAL ZONE 11	47	254	736	1008	931	840	771	591	467	466	661	1988	61.3 (%)
THERMAL ZONE 2	67	369	885	1098	953	826	622	491	406	489	726	1828	59.9 (%)
THERMAL ZONE 3	42	213	673	1061	1037	829	621	360	349	306	460	2809	63.8 (%)
THERMAL ZONE 4	0	1	12	33	48	83	116	138	198	235	274	7622	92.9 (%)
THERMAL ZONE 5	27	119	618	984	972	909	705	431	432	427	597	2539	63.9 (%)
THERMAL ZONE 6	45	245	884	1128	1022	814	571	455	434	494	812	1856	60.5 (%)
THERMAL ZONE 7	28	119	631	954	970	827	783	436	419	396	538	2659	64.3 (%)
THERMAL ZONE 8	36	203	779	997	908	926	756	576	514	513	739	1813	61.1 (%)
THERMAL ZONE 9	38	225	769	963	914	904	794	525	457	517	774	1880	61.3 (%)

Humidity (Table values represent hours spent in each Humidity range)

Zone	< 30 (%)	30-35 (%)	35-40 (%)	40-45 (%)	45-50 (%)	50-55 (%)	55-60 (%)	60-65 (%)	65-70 (%)	70-75 (%)	75-80 (%)	>= 80 (%)	Mean Relative Humidity (%)
THERMAL ZONE 1	58	243	805	1103	970	803	559	381	344	383	556	2555	62.7 (%)
THERMAL ZONE 10	2	24	57	108	131	176	201	284	371	451	697	6258	86.4 (%)
THERMAL ZONE 11	49	256	737	991	935	846	758	543	451	454	596	2144	61.7 (%)
THERMAL ZONE 2	68	354	876	1124	944	836	590	423	375	474	688	2008	60.3 (%)
THERMAL ZONE 3	9	43	140	288	348	330	302	384	533	695	812	4876	79.0 (%)
THERMAL ZONE 4	0	1	19	58	58	98	104	124	204	286	400	7408	91.5 (%)
THERMAL ZONE 5	27	116	616	983	986	897	715	415	411	414	577	2603	64.0 (%)
THERMAL ZONE 6	45	239	867	1155	1012	827	543	396	402	463	762	2049	60.9 (%)
THERMAL ZONE 7	28	124	632	951	963	831	784	420	412	387	509	2719	64.4 (%)
THERMAL ZONE 8	44	259	734	996	889	872	759	561	429	486	661	2070	61.7 (%)
THERMAL ZONE 9	36	210	747	1008	904	902	754	497	424	485	739	2054	61.8 (%)

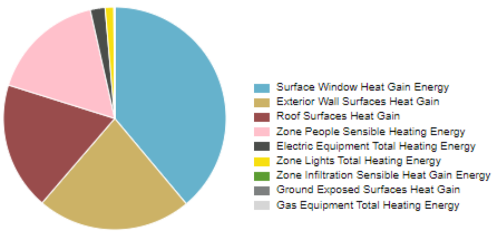
Heat gain of base, Case 1 and Case 7 respectively



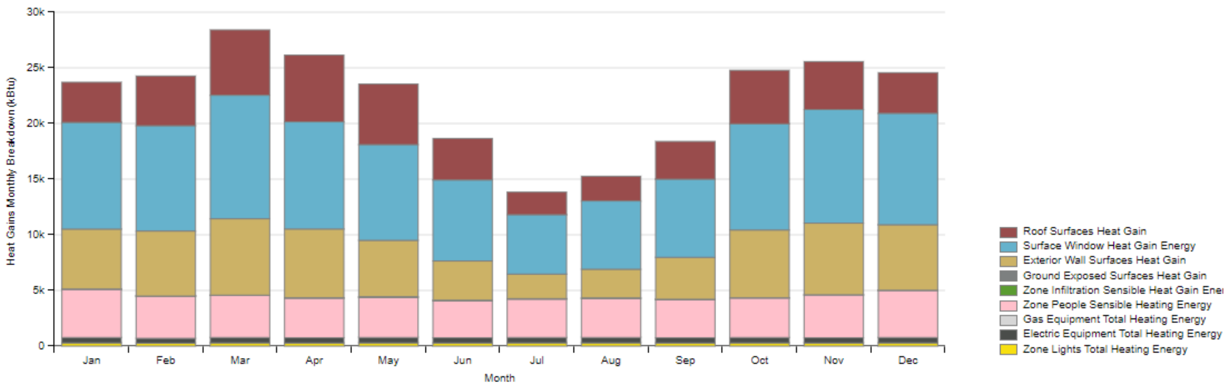


Heat Gains Summary

Heat Gains Annual Breakdown (kBtu) - view table



Heat Gains Monthly Breakdown (kBtu) - view table



Heat Gains Summary

Heat Gains Annual Breakdown (kBtu) - view table

Type	Quantity (kBtu)
Electric Equipment Total Heating Energy	5,716.5
Gas Equipment Total Heating Energy	0.0
Zone Lights Total Heating Energy	3,373.9
Zone People Sensible Heating Energy	43,989.4
Zone Infiltration Sensible Heat Gain Energy	277.0
Surface Window Heat Gain Energy	103,687.5
Exterior Wall Surfaces Heat Gain	59,286.5
Roof Surfaces Heat Gain	35,118.2
Ground Exposed Surfaces Heat Gain	37.5

Heat Gains Summary

Heat Gains Annual Breakdown (kBtu) - view table

Type	Quantity (kBtu)
Electric Equipment Total Heating Energy	5,716.5
Gas Equipment Total Heating Energy	0.0
Zone Lights Total Heating Energy	3,373.9
Zone People Sensible Heating Energy	43,908.6
Zone Infiltration Sensible Heat Gain Energy	263.3
Surface Window Heat Gain Energy	103,388.8
Exterior Wall Surfaces Heat Gain	55,258.1
Roof Surfaces Heat Gain	34,775.1
Ground Exposed Surfaces Heat Gain	36.1

Heat Gains Summary

Heat Gains Annual Breakdown (kBtu) - view table

Type	Quantity (kBtu)
Electric Equipment Total Heating Energy	5,716.5
Gas Equipment Total Heating Energy	0.0
Zone Lights Total Heating Energy	3,373.9
Zone People Sensible Heating Energy	44,413.6
Zone Infiltration Sensible Heat Gain Energy	293.2
Surface Window Heat Gain Energy	103,898.1
Exterior Wall Surfaces Heat Gain	59,855.6
Roof Surfaces Heat Gain	49,513.6
Ground Exposed Surfaces Heat Gain	41.7

Heat Gains Monthly Breakdown (kBtu) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electric Equipment Total Heating Energy	485.5	438.5	485.5	469.9	485.5	469.9	485.5	485.5	469.9	485.5	469.9	485.5
Gas Equipment Total Heating Energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zone Lights Total Heating Energy	286.5	258.8	286.5	277.3	286.5	277.3	286.5	286.5	277.3	286.5	277.3	286.5
Zone People Sensible Heating Energy	4,338.6	3,800.2	3,819.1	3,497.1	3,511.8	3,211.8	3,403.6	3,431.6	3,316.5	3,532.6	3,876.9	4,249.6
Zone Infiltration Sensible Heat Gain Energy	0.0	2.6	9.0	33.0	54.4	49.2	43.6	40.4	25.7	14.8	4.4	0.0
Surface Window Heat Gain Energy	9,592.7	9,471.5	11,107.5	9,601.7	8,551.5	7,219.7	5,320.6	6,092.6	6,970.6	9,532.6	10,210.0	10,016.5
Exterior Wall Surfaces Heat Gain	5,341.8	5,807.1	6,845.8	6,115.4	4,983.0	3,451.0	2,167.0	2,527.3	3,711.8	6,063.9	6,418.3	5,854.0
Roof Surfaces Heat Gain	2,392.6	3,106.7	4,208.6	4,375.5	3,928.1	2,687.0	1,436.5	1,559.4	2,465.5	3,462.6	3,017.3	2,478.6
Ground Exposed Surfaces Heat Gain	21.5	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.6

Heat Gains Monthly Breakdown (kBtu) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electric Equipment Total Heating Energy	485.5	438.5	485.5	469.9	485.5	469.9	485.5	485.5	469.9	485.5	469.9	485.5
Gas Equipment Total Heating Energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zone Lights Total Heating Energy	286.5	258.8	286.5	277.3	286.5	277.3	286.5	286.5	277.3	286.5	277.3	286.5
Zone People Sensible Heating Energy	4,336.8	3,797.8	3,812.1	3,489.0	3,500.4	3,200.3	3,395.0	3,422.6	3,306.7	3,526.3	3,873.7	4,248.0
Zone Infiltration Sensible Heat Gain Energy	0.0	2.3	7.9	31.6	52.3	46.8	41.9	38.3	24.2	13.9	4.0	0.0
Surface Window Heat Gain Energy	9,576.0	9,453.1	11,084.4	9,572.4	8,518.3	7,180.9	5,290.3	6,057.9	6,941.4	9,516.6	10,195.1	10,002.5
Exterior Wall Surfaces Heat Gain	4,971.8	5,407.6	6,376.6	5,701.0	4,648.9	3,217.4	2,017.0	2,351.3	3,463.4	5,663.6	5,984.2	5,455.3
Roof Surfaces Heat Gain	2,392.0	3,073.1	4,157.1	4,295.5	3,911.4	2,673.7	1,422.9	1,559.1	2,426.9	3,424.1	2,981.4	2,457.9
Ground Exposed Surfaces Heat Gain	20.7	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.3

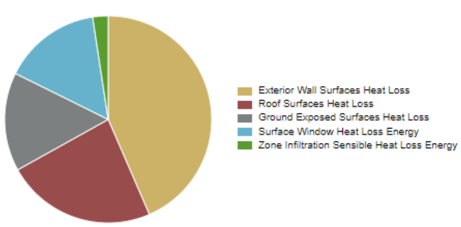
Heat Gains Monthly Breakdown (kBtu) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electric Equipment Total Heating Energy	485.5	438.5	485.5	469.9	485.5	469.9	485.5	485.5	469.9	485.5	469.9	485.5
Gas Equipment Total Heating Energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zone Lights Total Heating Energy	286.5	258.8	286.5	277.3	286.5	277.3	286.5	286.5	277.3	286.5	277.3	286.5
Zone People Sensible Heating Energy	4,327.7	3,786.6	3,793.3	3,559.6	3,605.5	3,318.7	3,446.8	3,510.9	3,430.1	3,547.5	3,855.7	4,231.3
Zone Infiltration Sensible Heat Gain Energy	0.0	2.4	8.3	34.4	57.9	53.2	45.8	43.4	28.2	15.2	4.3	0.0
Surface Window Heat Gain Energy	9,584.9	9,463.2	11,095.4	9,625.9	8,600.4	7,279.9	5,334.9	6,134.0	7,025.5	9,541.3	10,204.2	10,008.6
Exterior Wall Surfaces Heat Gain	5,389.2	5,846.3	6,869.0	6,179.0	5,066.9	3,527.1	2,205.2	2,580.5	3,768.0	6,094.7	6,440.4	5,889.3
Roof Surfaces Heat Gain	3,604.9	4,465.4	5,868.2	5,996.4	5,439.8	3,729.6	2,027.4	2,219.0	3,390.4	4,808.5	4,310.4	3,653.4
Ground Exposed Surfaces Heat Gain	24.9	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6

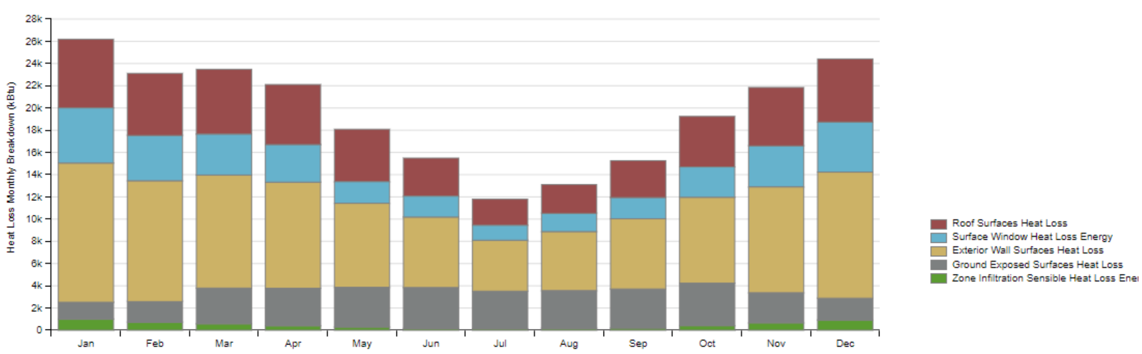
Heat loss of base, Case 1 and Case 7 respectively

Heat Loss Summary

Heat Loss Annual Breakdown (kBtu) - view table

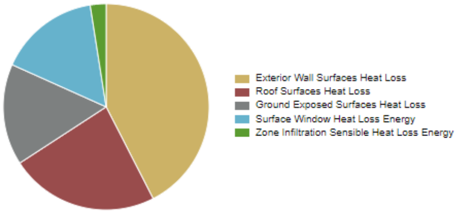


Heat Loss Monthly Breakdown (kBtu) - view table

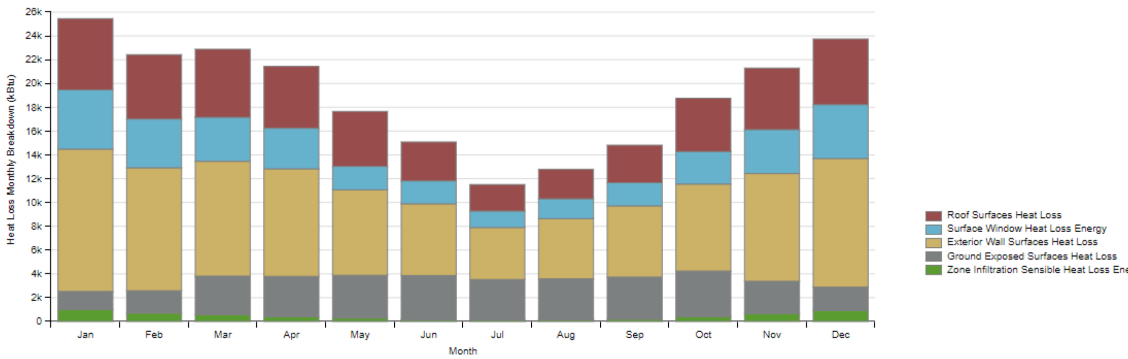


Heat Loss Summary

Heat Loss Annual Breakdown (kBtu) - view table

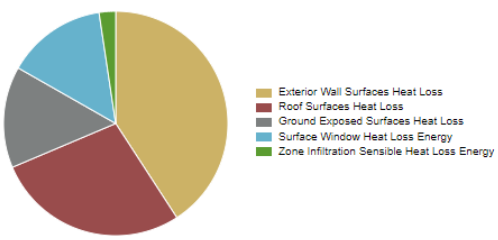


Heat Loss Monthly Breakdown (kBtu) - view table

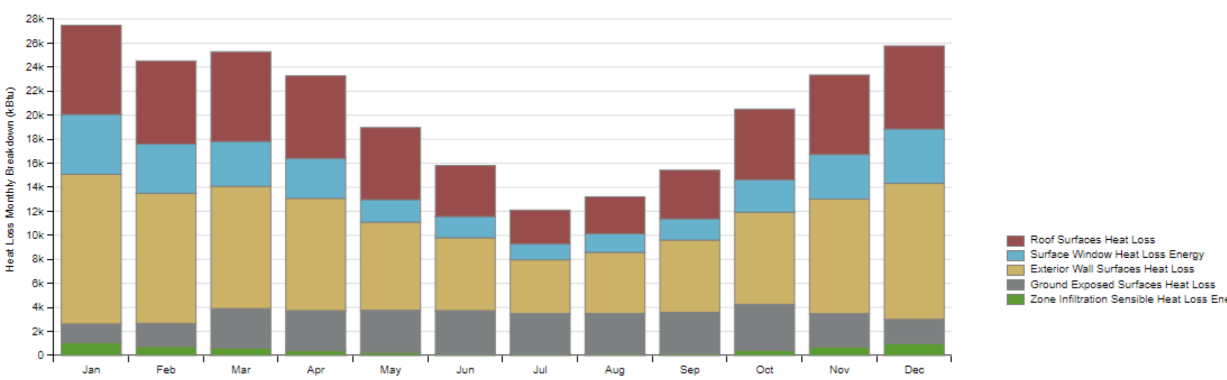


Heat Loss Summary

Heat Loss Annual Breakdown (kBtu) - view table



Heat Loss Monthly Breakdown (kBtu) - view table



Heat Loss Summary

Heat Loss Annual Breakdown (kBtu) - view table

Type	Quantity (kBtu)
Zone Infiltration Sensible Heat Loss Energy	5,613.5
Surface Window Heat Loss Energy	35,763.7
Exterior Wall Surfaces Heat Loss	101,830.1
Roof Surfaces Heat Loss	54,863.2
Ground Exposed Surfaces Heat Loss	36,075.6

Heat Loss Summary

Heat Loss Annual Breakdown (kBtu) - view table

Type	Quantity (kBtu)
Zone Infiltration Sensible Heat Loss Energy	5,651.4
Surface Window Heat Loss Energy	36,040.7
Exterior Wall Surfaces Heat Loss	96,750.7
Roof Surfaces Heat Loss	53,248.7
Ground Exposed Surfaces Heat Loss	36,164.9

Heat Loss Summary

Heat Loss Annual Breakdown (kBtu) - view table

Type	Quantity (kBtu)
Zone Infiltration Sensible Heat Loss Energy	5,837.0
Surface Window Heat Loss Energy	35,348.8
Exterior Wall Surfaces Heat Loss	100,322.3
Roof Surfaces Heat Loss	68,285.0
Ground Exposed Surfaces Heat Loss	35,910.7

Heat Loss Monthly Breakdown (kBtu) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zone Infiltration Sensible Heat Loss Energy	1,004.3	711.4	579.1	397.5	284.6	159.2	141.4	160.4	187.9	404.4	665.2	918.2
Surface Window Heat Loss Energy	4,961.6	4,077.2	3,684.8	3,382.0	1,950.1	1,887.1	1,352.0	1,640.5	1,910.8	2,729.1	3,682.0	4,506.6
Exterior Wall Surfaces Heat Loss	12,528.5	10,872.5	10,171.5	9,543.3	7,561.5	6,340.2	4,581.7	5,307.6	6,314.2	7,728.7	9,532.9	11,347.5
Roof Surfaces Heat Loss	6,179.9	5,588.7	5,831.5	5,402.8	4,709.1	3,419.0	2,344.6	2,588.5	3,316.7	4,548.6	5,255.3	5,678.5
Ground Exposed Surfaces Heat Loss	1,516.0	1,867.6	3,218.2	3,385.0	3,581.2	3,685.8	3,375.6	3,408.9	3,529.4	3,834.2	2,709.3	1,964.4

Heat Loss Monthly Breakdown (kBtu) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zone Infiltration Sensible Heat Loss Energy	1,004.8	712.9	582.7	401.4	289.0	163.7	145.0	164.6	192.6	408.3	667.4	919.2
Surface Window Heat Loss Energy	4,985.4	4,096.1	3,700.5	3,410.2	1,971.0	1,924.0	1,380.4	1,673.5	1,945.5	2,737.9	3,691.7	4,524.5
Exterior Wall Surfaces Heat Loss	11,953.6	10,332.8	9,648.8	9,034.3	7,181.2	6,026.2	4,365.8	5,057.4	5,982.5	7,304.2	9,053.2	10,810.8
Roof Surfaces Heat Loss	5,990.2	5,410.7	5,719.3	5,199.8	4,618.6	3,271.2	2,232.8	2,479.1	3,158.1	4,476.2	5,173.0	5,519.8
Ground Exposed Surfaces Heat Loss	1,520.9	1,872.5	3,229.0	3,393.4	3,592.5	3,698.5	3,385.9	3,418.7	3,538.4	3,833.7	2,713.1	1,968.3

Heat Loss Monthly Breakdown (kBtu) - view table

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Zone Infiltration Sensible Heat Loss Energy	1,070.0	759.9	625.0	404.2	272.7	136.8	138.6	146.8	163.7	427.2	712.2	979.9
Surface Window Heat Loss Energy	4,990.3	4,102.5	3,718.8	3,320.7	1,876.2	1,766.2	1,316.0	1,543.2	1,760.3	2,712.7	3,704.9	4,537.0
Exterior Wall Surfaces Heat Loss	12,449.5	10,830.6	10,185.9	9,354.5	7,334.5	6,069.6	4,470.6	5,089.3	6,019.8	7,666.3	9,538.2	11,313.6
Roof Surfaces Heat Loss	7,424.7	6,915.7	7,473.0	6,881.5	5,999.0	4,239.5	2,821.7	3,083.5	4,049.2	5,873.3	6,614.6	6,909.2
Ground Exposed Surfaces Heat Loss	1,553.5	1,910.0	3,279.8	3,327.1	3,487.0	3,595.0	3,354.8	3,346.7	3,431.0	3,828.7	2,771.6	2,025.4

APPENDIX 6: IOE Graduate Conference Acceptance Letter and Paper

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फोन: ०१-५३३९७६६

Date: April 21, 2025

To Whom It May Concern:

This is to certify that the paper titled **"Infrared Thermography for Assessing Thermal Bridges in Residential Buildings: Identification and Analysis of Critical Heat Loss Locations in a Temperate Climate"** (Submission# **499**) submitted by **Ritik Man Shrestha** as the first author, which had been accepted for presentation after the peer-review process, has successfully been presented at the 16th IOE Graduate Conference held during April 18 - 20, 2025. Kindly note that the final revision of the papers and publication process of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon timely response to further edits during the publication process.

16th IOE Graduate Conference, 2025
THAPATHALI CAMPUS

Dr. Raj Kumar Chaulagain,
Convener,
16th IOE Graduate Conference

IOE Graduate Conference
[Placeholder for Publication Information]

Infrared Thermography for Assessing Thermal Bridges in Residential Buildings: Identification and Analysis of Critical Heat Loss Locations in a Temperate Climate

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Abstract

Buildings are significant contributors to global energy consumption and greenhouse gas emissions, with thermal bridges playing a critical role in undermining the thermal performance of building envelopes. Thermal bridges which are areas of low thermal resistance in the building envelope, lead to increased heat transfer, higher energy consumption, and potential issues such as condensation and mold growth. This study focuses on identifying and analyzing thermal bridges in residential buildings in Kathmandu, Nepal, using infrared thermography and numerical simulation (THERM). The research examines key areas such as balcony-wall junctions, roof-wall junctions and window-frame junctions to assess their impact on energy efficiency. Through thermal imaging and 2D heat transfer analysis using THERM software, the study quantifies the linear thermal transmittance (psi value) of these thermal bridges. Thermal images of six RCC-framed structures were analyzed to identify key areas of heat loss across the building envelope. The findings reveal that roof-wall junctions are particularly prone to thermal bridging, with a calculated linear thermal transmittance of 0.5275 W/m-K, which is high compared to passivhaus standard (<0.01 W/m-K) and other thermal bridging guides (<0.3 W/m-K). This research highlights the importance of addressing thermal bridges in building design to improve energy efficiency, reduce heat loss, and enhance indoor comfort in the context of Nepal's rapidly urbanizing environment.

Keywords

Thermal bridge, overall heat transfer coefficient, linear thermal transmittance, infrared thermography

1. Introduction

Buildings account for 30% of the global final energy consumption and 26% of global energy related CO2 emissions. By 2030, it is estimated that the global building stock will increase by 15%[1]. Buildings currently contribute a significant portion to the global energy consumption and greenhouse gas emissions, highlighting the critical importance for energy conservation measures. Energy efficient buildings helps to curb not only the energy consumption but also fosters comfortable living spaces while also reducing carbon emissions and mitigating climate change. Energy efficient buildings are the first step toward achieving sustainability in buildings, to control rising energy costs, reduce environmental footprints and increase the value of buildings[2].

In the context of Nepal, rapid urbanization and increased economic activities have led to a surge in construction, driving up energy demand, especially for space heating, cooling, lighting and electrical appliances[2]. Nepal ranks among the top ten fastest urbanizing developing nations. But buildings designed recently have not taken into consideration the local climate and energy efficiency, resulting in uncomfortable indoor environments and led to high energy consumption to compensate for this discomfort. Many of these could be improved with improvements in building envelope design, including enhanced insulation of walls and roofs[3].

The building envelope has areas with low thermal resistance through which the heat can transfer easily (windows, doors, skylights and thermal bridges). Thermal bridges are defined as areas of building envelope with very low thermal resistance, usually as a result of a penetration through building insulation layers[4]. High heat flow takes place across the thermal bridges increasing the overall heat transfer coefficient (U-value) of components and creates condensation risks indoors, mould growth, heat loss, deterioration of indoor air quality as well as defects in the building itself[5]. The percentage impact of thermal bridges on the building's energy needs increases with the improvement of its thermal insulation[6].

Thermographic inspection allows instant location of thermal bridges (cold bridges) as well as specification of the range and surface temperature evaluation. Thermal inspection is not only aimed at answering the question whether cold bridges exist, but how significant they could be for the total thermal heat losses and if mold growth or surface condensation may appear[7]. Infrared (IR) thermography imaging technique is useful to conduct in situ analyses, since it allows a qualitative survey to evaluate the surface temperatures of the envelope surfaces. Through this investigation assessment of imperfections such as air infiltration, bad insulation and mold are easily recognized[8].

Given the lack of relevant studies of thermal bridging in the context of Nepal, studies are needed to analyze their influence on the energy needs of buildings. This work hopes to analyze the influence of thermal bridges in a residential building in Kathmandu using thermographic images. The main objectives of this research paper is to identify and analyze thermal bridges in key areas such as balcony wall junction, roof and wall connection and finally window frame junctions.

2. Literature Review

2.1 Heat Transfer Mechanism

Heat transfer is the transfer of energy because of temperature difference. Heat always flows from high temperature to low temperature. This is because materials seek to even out their temperature differences. In general, heat flows from here to there by three distinct mechanism[9]:

- By conduction (transfer of energy from matter to adjacent matter by direct contact, without intermixing or flow of any material)
- By convection (transfer of energy by the bulk mixing of clumps of material. In natural convection it is the difference in density of hot and cold fluid which causes the mixing. In forced convection a mechanical agitator or an externally imposed pressure difference causes the mixing)
- By radiation (such as light, infrared, ultraviolet and radio waves which emanate from a hot body and are absorbed by a cooler body)

2.2 Thermal bridge

Thermal bridge is an example of heat transfer through conduction. The rate of heat transfer depends on the thermal conductivity of the material and the temperature difference experienced on either side of the thermal bridge. When a temperature difference is present, heat flow will follow the path of least resistance through the material with the highest thermal conductivity. Thermal bridging describes a situation in a building where there is a direct connection between the outside and inside through one or more elements that possess a higher thermal conductivity than the rest of the envelope of the building. Thermal bridges can be classified into[10]:

- Geometrical thermal bridge (developed where the geometry or shape of the building structure changes)
- Material thermal bridge (where the material of a building structure changes but the geometry does not)
- Repeating thermal bridge (follow a pattern and are repeated over an entire area of the building's thermal envelope)
- Non-repeating thermal bridge (occur periodically and are found where there is a break in the continuity of the building's thermal envelope)
- Linear thermal bridge (disturbances in the continuity of the thermal envelope that can occur along a certain length of the envelope)
- Point thermal bridge (occur in one spot)

2.3 Thermal Transmittance

Thermal transmittance also known as U-value, is the rate of transfer of heat through matter. Construction elements with lower U-values are more effective to reduce the energy consumption in buildings due to its capacity to insulate from external weather conditions. The unit of thermal transmittance is W/m2k[9].

$LinearThermalTransmittance(y)$

Heat flow coefficient representing the added heat flow associated with linear thermal bridges that are not include in the clear field U-value. Linear thermal bridges typically occur at interface details[11].

$PointThermalTransmittance(x)$

Heat flow coefficient representing the added heat flow associated with a point thermal bridge that is not included in the clear field U-value. Point thermal bridges are countable points and are considered feasible to account for on an individual basis for U-value calculations[11].

The calculation of the transmission heat transfer coefficient includes the contribution due to thermal bridges according to the following equation from[12]:

$$H_D = \sum_i A_i U_i + \sum_k l_k y_k + \sum_j x_i$$

Where,

A_i is the area of element I of the building envelop, in m2

U_i is the thermal transmittance of element I of the building envelope, in W/(m2.K)

l_k is the length of linear thermal bridge l, in m

y_k is the linear thermal transmittance of linear thermal bridge k, in W/(m.K)

x_j is the point thermal transmittance of the point thermal bridge j, in W/K

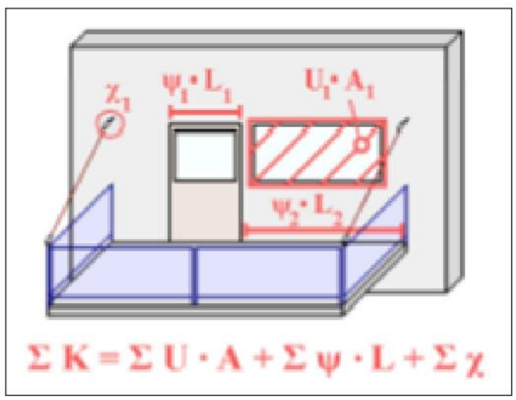

Figure 1: Example on where to use different thermal transmittance[13]

There are various methods for the determination of linear thermal transmittance, some of them are: numerical calculations (typical accuracy + 5%), thermal bridge catalogues (typical accuracy + 20%), manual calculations (typical accuracy + 20%) and default values (typical accuracy 0% to 50%)[12].

The linear thermal transmittance considered of the linear thermal bridge separating the two environments being, y, is given by following equation from[14]:

$$y = L_2D - \sum_j U_j l_j$$

Where,

L_2D is the thermal coupling coefficient obtained from a 2-D calculation of the component separating the two environments being considered

U_j is the thermal transmittance of the 1-D component, j, separating the two environments being considered

l_j is the length over which the value Uj applies

2.4 Infrared Thermography

Thermal infrared imaging is a valuable tool to perform non-destructive qualitative tests and to investigate buildings envelope behavior. Infrared thermography analysis represents one of the most reliable tools applied in existing buildings to investigate thermal bridges by finding out weak spots in the building envelope. Infrared thermography is a technique and method used to detect infrared energy emitted from an object, convert into temperature and display and image of temperature distribution. The temperature difference of the images obtained helps to identify different thermal anomalies[15]. Infrared thermography has been used in the monitoring of buildings both quantitatively and qualitatively in civil constructions. The qualitative analysis provides instantaneous reports as its focus is the profile and not the values. In quantitative analysis it is possible to define the severity of the situation for the studied object, this allows a precise determination of the temperature in a point of region[16].

2.5 Infrared Thermography in assessment of Thermal bridges

Researchers who have evaluated the heat loss caused by thermal bridging have used different approaches. Asdrubali, Baldinelli, & Bianchi[8] in their study carried out a quantitative analysis, using infrared thermography through thermographic surveys along with heat flow meters and then carry out analytical processing. They expressed the heat loss associated with thermal bridging as a ratio that reflects the increase of heat loss in the presence of a thermal bridge, this ratio the incidence factor was validated on a thermal bridge between window glazing and the window frame. FLUENT software was used for the Computational Fluid Dynamic analysis for finite volume analysis. The thermal field obtained with the three methods were very similar producing close values of the incidence factor of the thermal bridge. Through simulations it was found that thermal bridges caused an overall heat loss of 13.4% which reduced to 8.8% with a correction of the thermal bridge through insulation in winter time.

Bianchi, Pisello, Baldinelli, & Asdrubali[15] in their study used a quantitative analysis of the infrared thermography in the field measurement with the objective of evaluating the energy losses through a building. In this study, the external walls, ceiling and floor were evaluated. This study was a futher continuation of the study in 2012. This study concerend the application and an experimental validation in a full scale continuously monitored building. The thermography results were compared to the quantitative measured data.

O'Grady, Lechowska, & Harte[17] in their study presented a method to determine the actual heat flow rate caused by the thermal bridge in a building through the use of infrared thermography solely without using heat flow meters (HFM) and other calculation methods. This uses only the infrared thermography for full quantification of heat loss associated with thermal bridging. In this study the approach involves calculating hear flow rate for each pixel on an infrared line created from thermal images. Through this study it was found that linear thermal transmittance could be calculated which mirror the real thermal performance of the thermal bridge.

Carramiñana, Morena-Marqués, González-Avilés, Castilla, & Galiano-Garrigós[6] in their study conducted a detailed analysis of thermal bridges focusing on balconies and slab fronts in two buildings, located in Spain, qualitatively and quantitatively determining their influence on energy efficiency. Detailed thermographic photogrpahs were taken to qualitatively assess the thermal bridges, a thermal transmittance flowmeter was used to quantify thermal transmittances of thermal bridges and the totoal annula energy needs of the inspected buildings were evaluated through computer simulations (Líder-Calener Unified Tool, an official Spanish software). Through this study it was found that approximately 40% of the total annual energy needs of a resisdential building were caused due to thermal bridges, balcony façade and façade slab edge junctions are the most predominant thermal bridges analyzed in buildings.

Ramenah[18] in his study highlighted the assessment of balcony to wall thermal bridge using infrared thermography. The intent of the research was to illustrate that thermal imaging is a means of quality assurance for buildings by determining the position and magnitude of thermal bridges.

Smusz & Korzeniowski[19] in their study applied infrared thermography under real conditions of the building in winter season to study the effect of thermal bridges on heat losses through the building envelope. To verify and validate the results 2D numerical calculations were carried out with the use fo COMSOL Multiphysics commercial software. Through this study it was concluded that a quick and easy in situ infrared thermography measurements can be applied to evaluate the actual heat losses in a building.

Kaymaz[5] in her study used infrared thermography to visualize the thermal bridges and generate thermal patterns of exposed surfaces. An apartment block was considered for the study focusing on the external envelope components. External wall system componets with infill masonry walls and transparent sub components were examined from inside and outside of the building. Through this research she concluded that infrared thermography can be practically used on site for thermal bridge diagnostics.

2.6 THERM

THERM is a computer program developed at Lawrence Berkeley National Laboratory (LBNL) for the purpose of heat transfer in buildings. With THERM, we can model 2-dimensional heat-transfer effects in building components such as windows, walls, foundations, roofs and doors and other components where thermal bridges are a concern. THERM's heat transfer analysis allows us to evaluate the energy efficiency and local temperature patterns of building components which may relate directly to problems with condensation, moisture damage and structural integrity. THERM uses 2-dimensional conduction and radiation heat transfer analysis based on the finite element method to perform heat transfer analysis[20].

3. Methodology

This research uses both qualitative and quantitative research approaches. But primarily the study is quantitative as it involves collecting measurable data and analyzing numerical data from thermal imaging and simulations. It also involves qualitative aspects as we use the thermal imaging data to visually identify and understand thermal bridging patterns.

On external building elements, the surface temperature are uniform. The thermal bridge disturbs this uniformity by reducing the surface temperatures on the indoor surface and increasing the surface temperatures on the outdoor surfaces. Those temperature changes can be easily located and recorded on an infrared image. In this study, an infrared thermal imaging camera will be used to visualize the thermal bridges and generate thermal patterns of exposed surfaces. The indoor and outdoor ambient temperature and relative humidity are measured with a data logger. A residential building will be considered focusing on the external envelope components mainly the balcony slab and roof/wall junction. The external wall system components with infill masonry walls will be examined from inside and outside of the building. Thermal bridge is defined by linear thermal transmittance y.

$$y = L_2D - \sum_{j}^{k} U_j l_j \tag{1}$$

where: L_2D – thermal coupling coefficient of the component separating the two environments,

U_j – overall heat transfer coefficient

l_j – length over which the value U_j applies

K – number of 1D components

Overall heat transfer coefficient (U) is given by,

$$U = \frac{1}{\frac{1}{h_a} + \frac{l_1}{k_1} + \frac{l_2}{k_2} + \ldots + \frac{1}{h_b}} \tag{2}$$

Where, U = overall heat transfer coefficient (W/m2-K)

h_a, h_b = film coefficient (W/m2-K)

$l_1, l_2\ldots$ = thickness of material (m)

k_1, k_2 = thermal conductivity (W/m-K)

In order to verify and validate the results a 2D numerical calculations need to be carried out. THERM is such a software which can be used for this. The results from the infrared calculations and the simulations are compared to verify the results.

As the indoor environment can have a better controlled environment due to control over factors such as solar radiation and wind, the thermal imaging will be taken from the indoors maintaining the proper distance between object and camera as well as maintaining the emissivity settings

4. Material and Method

In this study, an infrared camera is used to visualize the thermal bridges and generate thermal patterns of various building envelope components. The thermal images are recorded using a Trotec EC060V model IR camera. This camera captures both thermal as well as digital images, so thermal and digital image of the same component is captured one after the other. Indoor and outdoor ambient temperature along with relative humidity are measured with data loggers. For the outdoor ambient temperature, a HOBO MX2300 series ext temp logger model was used whereas for the indoor ambient temperature a T&D TR-76Ui model was used. Relative humidity for indoor is only measured as the TR-76Ui model also measures the relative humidity whereas the MX2300 ext temp model only measures temperature.

Figure 2: HOBO, T&D data logger and TROTEC IR Camera

5. Case Study

A RC skeleton structural frame (column, beam and slab) with infill masonry walls (brick masonry, mortar and surface finishes) and transparent sub components (frame, glazing and window sill) form a considerable part of the typology in Kathmandu, Nepal which is in a temperate region. The RC framed structure is very widespread in this region which may be considered suitable to assess thermal bridge. According to National Population and Housing Census 2021 published by the National Statistics Office approximately 54.10% of buildings in Kathmandu are RCC framed structures, 92.09% have outer walls of cement bonded bricks or stones and 86.78% have RCC roofs.

For this case study, thermographic inspection with an IR camera is used to study 6 RCC framed structured buildings in different locations of Kathmandu for a general assessment to identify common areas where thermal bridging may be prominent. Thermographic inspection of the whole building focusing on wall/slab joints, roof/wall joints, window/door frame junctions and balcony slab junctions are carried out.

Data logging for indoor and outdoor ambient temperature and relative humidity are carried out only in one building, since the structures and the climate is similar. Similarly, the 2-dimensional heat transfer analysis using the software THERM will be used for a common general location of thermal bridge which can be further used similarly for other locations of thermal bridges.

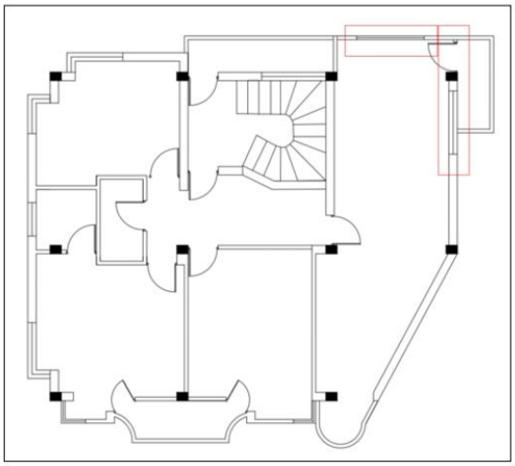

Figure 3: Floor plan showing area where IR images where captured as well as where indoor data was logged

6. Analysis and Findings

Thermal images where captured of various building envelope components to identify locations where thermal bridges were most prominent. The outdoor environment is affected by various environmental factors such as solar radiation, wind and other parameters, which severely affect the temperature and humidity data, hence the thermal imaging will only be taken from indoors as the environment can be better controlled.

Through the study of the thermal images captured of the 6 buildings, the roof wall junction was found to be one of the areas where thermal bridges could be prominent.

6.1 Thermal images

Thermal images of various building envelope locations were captured along with their digital image. As the roof wall junction was found to be one of the most prominent areas where the thermal bridges exist through the analysis of thermal images, this roof wall junction is considered for further analysis through the THERM software. Figure 4 shows the thermal and digital images of roof wall junction of some of the surveyed buildings.

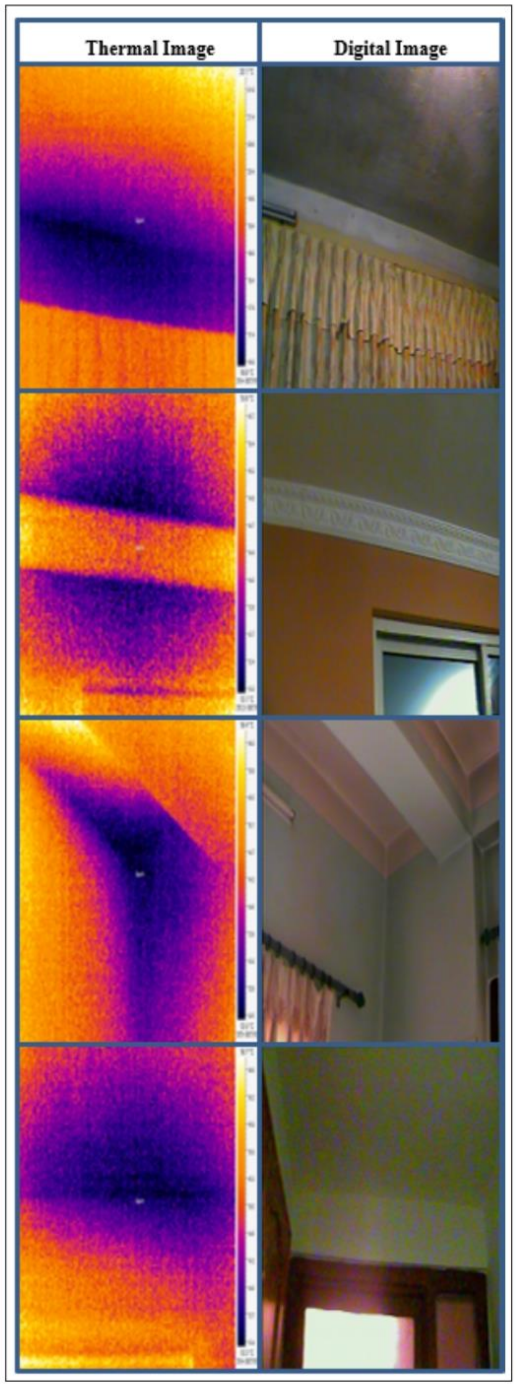

Figure 4: Thermal and digital images of roof wall junction

6.2 Temperature analysis

Ambient temperature was recorded for both outside and inside with data loggers for a period of 10 days, the temperature was logged at an interval of 1 hour. The outside and inside temperature is needed to simulate in the THERM software. Variation of indoor and outdoor temperature graph is shown in Figure 5.

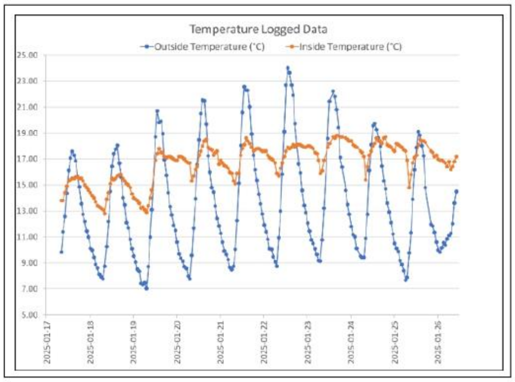

Figure 5: Indoor and outdoor temperature variation

6.3 THERM analysis

THERM software is used for the analysis of thermal bridge in the roof slab and wall junction. The different physical and thermal properties of the building envelope materials have been listed in the Figure 6 &7. The thermal properties namely the thermal conductivity, inner and outer film coefficient has been taken from the ASHRAE handbook fundamentals. The outside and inside ambient temperature are taken to be 10°C and 18°C respectively.

Component	Materials	Width (mm)	Thermal conductivity (W/m.K)
Wall	Brick	230	0.9
	Plaster	12	0.72
Roof	Concrete	150	0.5334
	Cement mortar	20	0.72
	Tile	12	0.6

Figure 6: Physical parameters considered in THERM

Position of Surface	Direction of Heat Flow	Film Coefficients (W/m^{2}K)
Indoor		
Vertical	Horizontal	8.29
Horizontal	Downward	6.13
Horizontal	Upward	9.26
Outdoor		
Winter	Any	34

Figure 7: Boundary parameters considered in THERM

Figure 8 shows the drawing of the roof slab and wall junction which is modelled in the THERM software for the 2-dimentional analysis. Figure 9 shows the heat flux distribution along the wall and roof slab gained from THERM.

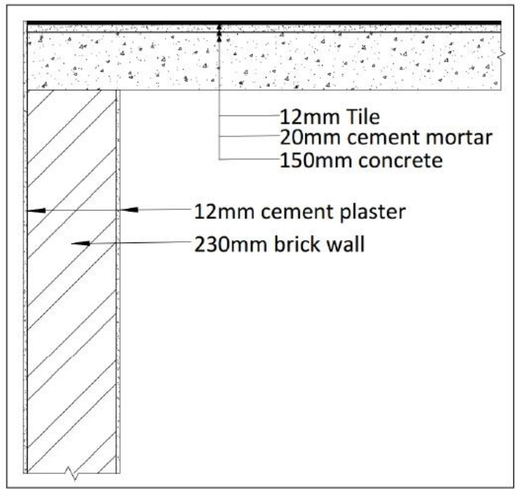

Figure 8: Drawing of roof slab wall junction

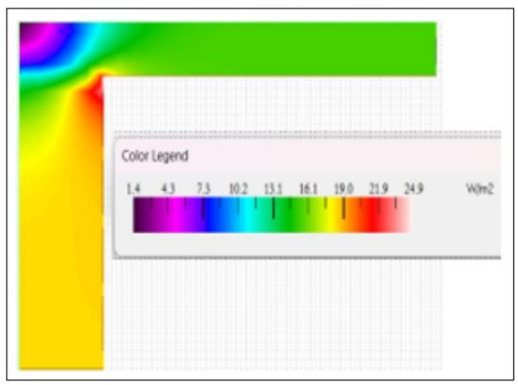

Figure 9: Analysis of roof slab wall junction from THERM

The THERM software gives the U-factor of the roof slab and wall section. This U-factor multiplied with the length of the specified section gives the thermal coupling coefficient (L_2D). The U-factor produced from the simulation is shown in Figure 10. The overall heat transfer coefficient (U value) of the same section of roof slab and wall is calculated based on the same material and boundary properties considering the whole section as the slab material, using equation (2) which was found to be 1.9289 W/m2-K. The linear thermal transmittance(y) was calculated from the equation (1), which comes out to be 0.5275 W/m-K. Multiplying this y value with the overall length of the junction of the roof slab and wall junction gives the additional heat loss through this thermal bridge.

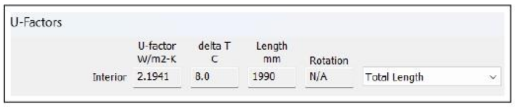

Figure 10: U factor from THERM

$$L_2D = Ufactor * L = 2.194 * 1.99 = 4.366W/m$$
$$U = \frac{1}{\frac{1}{ha}+\frac{l_1}{k_1}+\frac{l_2}{k_2}+\frac{1}{h_b}} = \frac{1}{\frac{1}{34}+\frac{0.02}{0.72}+\frac{0.012}{0.6}+\frac{0.15}{0.533}+\frac{1}{6.13}} = 1.9289W/m^2.K$$
$$y = L_2d - U * L = 4.366 - 1.9289 * 1.99 = 0.5275W/m.K$$

7. Conclusion

This study highlights the critical role of thermal bridges in the energy efficiency of residential buildings, particularly in the context of Nepal's temperate climate. By employing infrared thermography and numerical simulation (THERM), the research successfully identified and quantified thermal bridges in a key area such as a roof-wall junction, similarly this can be carried out for balcony slabs, and window frames. The analysis revealed that roof-wall junctions are particularly susceptible to thermal bridging, with a calculated linear thermal transmittance of 0.5275 W/m-K. For passivhaus standard the linear thermal transmittance should be below 0.01 W/m-K. From other thermal bridging guides like the Building Envelope Thermal bridging guide by BC Housing, linear thermal transmittance greater than 0.3 W/m-K is considered poor in terms of building performance. These findings emphasize the need for improved building envelope design, including enhanced insulation and careful consideration of thermal bridging in construction practices. Addressing thermal bridges can significantly reduce energy consumption, mitigate heat loss, and improve indoor comfort, contributing to more sustainable and energy-efficient buildings. Future research should expand on these findings by exploring additional building typologies and climates, as well as developing localized solutions to minimize thermal bridging in Nepal and similar regions. Also, the thermal properties of the building materials where taken from ASHRAE standard, future research may make use of instruments such as a heat flow meter to measure actual properties like thermal conductivity and resistances of various building materials.

8. Acknowledgment

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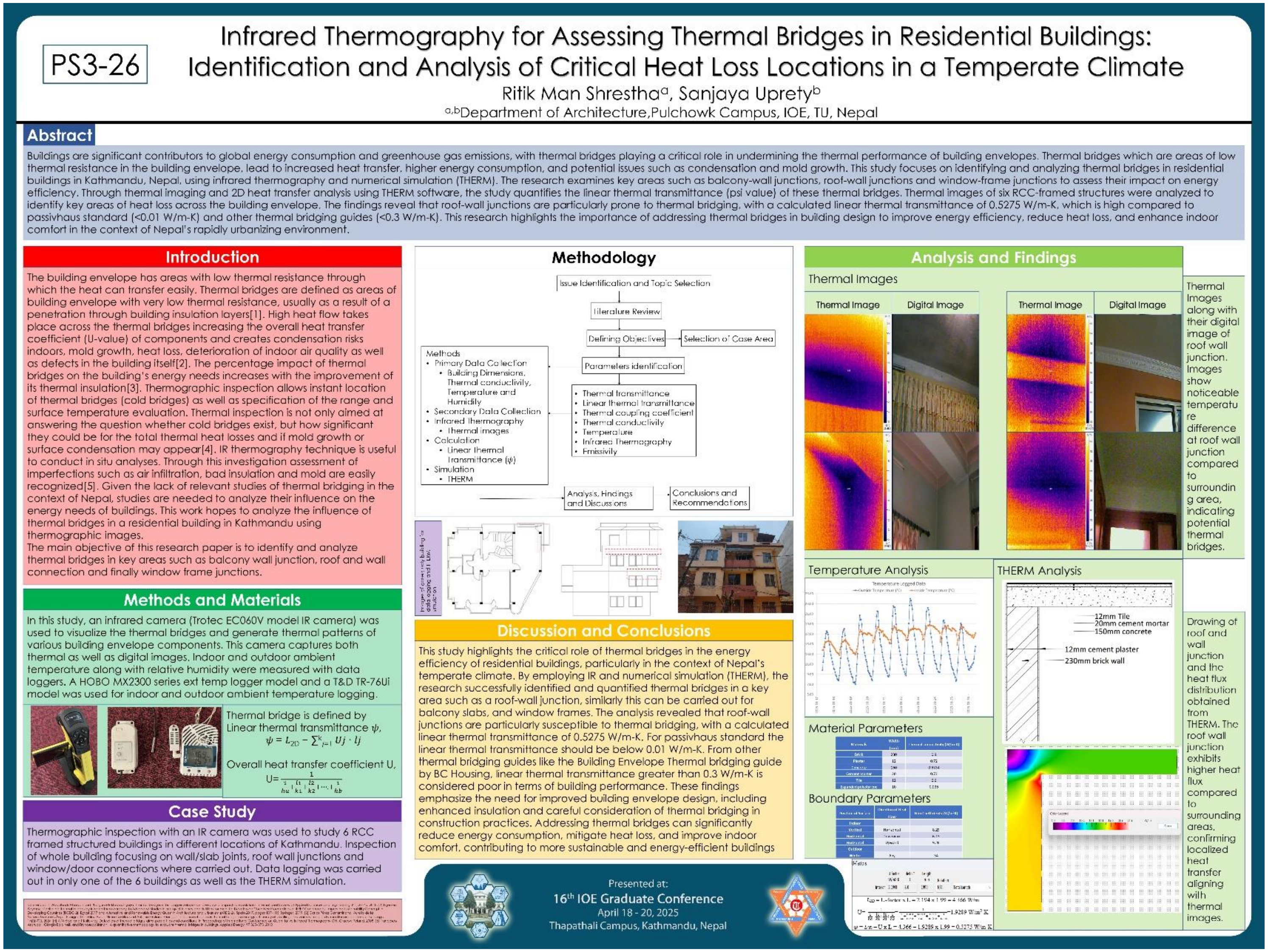

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