South African Building Envelope Thermal Performance Simulation: Parameters and the Role of Moisture Content

by

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Abstract

Literature tells of a connected, yet not well harmonised, narrative between building sustainability, building performance, building simulation and building regulations. Building simulation is actively used in industry to achieve targeted building ratings, but the targets do not always match reality due to the associated complexity and uncertainty associated with building simulation. This is further complicated by how the target is set for building performance, as many require an improvement over a benchmark value. For South Africa, the benchmark is provided by building standards.

The need to investigate hygrothermal analysis for South African buildings is based on three observations. First, there is a lack of hygrothermal studies in South Africa. Second, conclusions drawn in the literature that focus on the thermal performance of South African low-income housing are based on 'what' environmental conditions are experienced and not 'why' specific environmental conditions are experienced. Third, although climate may be similar when comparing studies that focus on building performance, differences in results exist due to differences in the assumptions used for building simulation. The purpose of this study is to establish the case for improved building simulation and the regulation thereof in South Africa. To do so, four building models were adapted or created and modelled under specific conditions.

The first two building models provide insight into how design choices influence the heating and cooling loads of two South African Green Star buildings when only considering heat-only analysis. Results indicate that providing high performance thermal insulation in combination with a large window-to-wall ratio will put additional strain on the air conditioning systems of the Green Star buildings. Furthermore, increasing the window-to-wall ratio of all glazed surfaces during analysis provides limited insight into the effect of the window-to-wall ratio of the Green Star buildings, unless considered alongside the changes to heat transfer through opaque building components, or considering specific surfaces.

The third building model highlights the influence of moisture buffering materials on the environmental conditions of the building environment for a typical summer and winter week in South Africa. Results indicate that hygric materials directly influence the building environment. Furthermore, the sorption isotherm and initial moisture content of the material appear to influence simulation results significantly. Results indicate that if sufficient hygroscopic building materials are exposed (in terms of surface area and volume) to the South African environmental conditions, expected simulated results will be different, depending on the inclusion of moisture in heat transfer through building materials.

The final building model serves as validation for the conclusions made regarding the importance of hygrothermal analysis. The model also highlights the need for improved modelling guidelines for South African buildings and additional requirements regarding buildings' material properties. The accuracy of the hygrothermal analysis, compared to heat-only analysis, confirms that hygrothermal analysis is required to accurately simulate the environmental conditions in South African buildings with moisture buffering components.

Although results show the influence of moisture buffering materials on simulated temperature and relative humidity, further research is still required in South Africa to allow for independent hygrothermal analysis, i.e. hygrothermal analysis using South Africa specific data. Future research towards improved building simulation in South Africa should focus on expanding simulation input data provided for South African building performance simulation, as well as when hygrothermal modelling is needed.

Opsomming

Literatuur vertel 'n samehangende, maar nie goed geharmoniseerde, verhaal oor volhoubare konstruksie van geboue, die gedrag en simulering van geboue, en bou-regulasies. Simulering van geboue word aktief in die industrie gebruik om geteikende gebou-graderings te behaal, maar die teikens pas nie altyd by die werklikheid nie as gevolg van die kompleksiteit en onsekerheid wat verband hou met die bousimulering. Dit word verder kompliseer deur die manier waarop die mikpunt vir gedrag van geboue gestel word, aangesien baie 'n verbetering verg ten opsigte van 'n bepaalde maatstaf. Vir Suid-Afrika word die maatstaf voorgeskryf in bou-standaarde.

Die behoefte om higrotermiese analise vir Suid-Afrikaanse geboue te ondersoek, is baseer op drie waarnemings. Eerstens, is daar 'n gebrek aan higrotermiese studies in Suid-Afrika. Tweedens, word gevolgtrekkings gemaak in die literatuur wat fokus op die termiese prestasie van Suid-Afrikaanse lae-inkomste-behuising, baseer op slegs die omgewingstoestande en nie waarom spesifieke omgewingstoestande ondervind word nie. Derdens; hoewel die klimaat soortgelyk kan wees by die vergelyking van studies wat fokus op gedrag van geboue, is daar verskille in resultate as gevolg van verskille in die aannames wat gemaak word vir die bou-simulering. Die doel van hierdie studie is om ‘n saak te maak vir beter gebou-simulering en die regulering daarvan in Suid-Afrika. Om dit te doen, word vier bou-modelle onder spesifieke omstandighede aangepas of geskep en gemodelleer.

Die eerste twee boumodelle bied insig in hoe ontwerpkeuses die verhitting- en verkoelingsladings van twee Suid-Afrikaanse Groen-Ster geboue beïnvloed wanneer slegs ontleding met warmte oorweeg word. Resultate dui aan dat die gebruik van hoë werkverrigting termiese isolasie in kombinasie met ‘n groot venster-tot-muur verhouding bykomende druk op die lugversorgingstelsels van die Groen-Ster geboue sal plaas. Verder bied die verhoging van die venster-tot-muur verhouding van alle geglasuurde oppervlaktes tydens ontleding beperkte insig in die effek van die venster-tot-muur verhouding van die Groen-Ster gebou, tensy dit saam met die veranderinge aan hitte-oordrag deur ondeursigtige geboukomponente oorweeg word, of spesifieke oppervlaktes oorweeg word.

Die derde boumodel bied insig in hoe vogbuffermateriale die omgewingstoestande van die gebou-omgewing beïnvloed vir ‘n tipiese somer- en winterweek in Suid Afrika. Resultate dui aan dat higroskopiese materiale die gebou-omgewing direk beïnvloed. Verder blyk dat die sorspsie isoterm en die aanvanklike voginhoud van die materiaal simulering-resultate noemenswaardig beïnvloed. Resultate dui aan dat indien voldoende vogbuffermateriale aan die omgewingstoestande van Suid Afrika blootgestel word (in terme van oppervlakte en volume), verwagte gesimuleerde resultate anders sal wees, afhangende van die insluiting van vog in hitte-oordrag deur boumateriale.

Die finale boumodel dien as bevestiging van die gevolgtrekkings rakende die belangrikheid van higrotermiese analise. Die model beklemtoon ook die behoefte aan verbeterde modelleringsriglyne vir Suid-Afrikaanse geboue en bykomende vereistes ten opsigte van geboue se materiaaleienskappe. Die akkuraatheid van die higrotermiese analise, in vergelyking met hitte-alleen-analise, bevestig dat higrotermiese analise nodig is om die omgewingstoestande in geboue in Suid Afrika met vogbuffer-komponente akkuraat te simuleer.

Alhoewel resultate die invloed van vogbuffermateriale op gesimuleerde temperatuur en relatiewe humiditeit toon, is verdere navorsing nodig in Suid-Afrika om onafhanklike higrotermiese analise moontlik te maak, dit wil sê higrotermiese analise met behulp van data spesifiek tot Suid-Afrika, insluitend data vir boumateriale, gebou ontwerp, weer, grond, besetting, skedules wat verband hou met boustelsels, asook hitte-wins data. Toekomstige navorsing vir verbeterde simulering van Suid-Afrikaanse geboue moet fokus op die uitbreiding van insetdata vir simulering, asook wanneer higrotermiese analise nodig is.

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List of Abbreviations

Abbreviation	Description
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BLAST	Building Loads Analysis and System Thermodynamics
BPS	Building Performance Simulation
BREEAM	Building Research Establishment - Environmental Assessment Method
CERL	Construction Engineering Research Laboratory
CIBSE	Chartered Institution of Building Services Engineers
CTF	Conduction Transfer Function
CVRMSE	Coefficient of Variation of the RMSE
DOE	Department of Energy
EDGE	Excellence in Design for Greater Efficiencies
EED	Energy Efficiency Directive
EMPD	Effective Moisture Penetration Depth
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EU	European Union
GBCSA	Green Building Council of South Africa
GBRT	Green Building Rating Tool
HAMT	Combined Heat and Moisture Transfer
HPLC	Heating Power Loss Coefficient
HTC	Heat Transfer Coefficient
HVAC	Heating, Ventilation, And Air Conditioning
IC	Inequality Coefficient
IPM	Integrated Performance Model
IR	Infrared
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCEA	Life Cycle Energy Analysis
LEED	Leadership in Energy and Environmental Design
MAE	Mean Absolute Error
MBE	Mean Bias Error
MCA	Multi-Criteria Analysis
NMBE	Normalised Mean Bias Error
NRMSE	Normalised RMSE
OSU	Oklahoma State University
PCM	Phase-Changing Material
PHPP	Passive House Planning Package
PMV	Predicted Mean Vote
r	Pearson Correlation Coefficient
R^2	Coefficient of Determination
RDP	Reconstruction and Development Programme
RMSE	Root Mean Square Error
SABS	South African Bureau of Standards
SANS	South African National Standard
SHGC	Solar Heat Gain Coefficient
SMART	Simple Multi-Attribute Rating Technique
TARP	Thermal Analysis Research Program

TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UIUC	University of Illinois-Urbana Champaign
WorldGBC	World Green Building Council
WWR	Window-To-Wall Ratio

Nomenclature

Symbol	Units	Description
[A], [B], [C], [D]	-	Coefficient matrices for the state space method
[u]	-	Vector of inputs for the state space method
[x]	-	Vector of state variables for the state space method
[y]	-	Output vector for the state space method
a	$W.s^b/(m^{2+b}.K)$	A constant used to calculate $h_{c,glass}$
A	m^2	The total area of a surface
A_{ij}	m^2	Contact surface area between cells
A_s	m^2	The area of a surface which is exposed to the sun's rays
b	-	A constant used to calculate $h_{c,glass}$
c	J/(kg.K)	Specific heat capacity of dry material
C^h	J/K	Heat Capacitance of a material
c^w	J/(kg.K)	Specific heat capacity of water (= 4 180 J/(kg.°C) at 20 °C)
C^w	kg	Moisture Capacitance of a cell
$\partial H/\partial T$	$J/(m^3.K)$	The moisture dependent heat storage capacity of a wall
D^w	m^2/s	Liquid Transport Coefficient of a material
$\partial w/\partial \phi$	kg/m^3	The moisture dependent moisture storage capacity of a wall
F_{air}	-	The view factor of wall surface to air
F_{ground}	-	The view factor of wall surface to ground surface
F_{sg}	-	The angle factor between the exterior surface and the ground
F_{sky}	-	The view factor of wall surface to sky
F_{ss}	-	The angle factor between the exterior surface and the sky
h_c	$W/(m^2.K)$	The convection coefficient of the surface of a wall
$h_{c,glass}$	$W/(m^2.K)$	The convective heat transfer coefficient for a very smooth surface (glass)
h_n	$W/(m^2.K)$	The natural convective heat transfer coefficient of a wall
h_v	J/kg	Evaporation enthalpy of water (= 2 489 000 J/kg)
i (as subscript)	-	Indicates inside surface of the building element
i,j (as subscript in HAMT equations)	-	Cell indices
I_b	W/m^2	The intensity of direct radiation which reaches a surface
I_g	W/m^2	The intensity of ground reflected diffuse radiation which reaches a surface
I_s	W/m^2	The intensity of sky diffuse radiation which reaches a surface
k	W/(m.K)	The dry thermal conductivity of a material
k^w	W/(m.K)	The thermal conductivity of a material adjusted based on moisture content
n	-	Number of nodes which makes up a wall in the Conduction Transfer Function equation
o (as subscript)	-	Indicates outside surface of the building element

P	Pa	Vapour pressure
p (as a superscript)	s	Present Time Step
$P_{ambient}$	Pa	Ambient air pressure
P^{sat}	Pa	Saturated vapour pressure of a cell
q^{adds}	W	Added heat from additional sources
q''_{air}	W/m^2	The net long wavelength (thermal) radiation flux exchange between the exterior surface and the air
$q''_{\alpha sol}$	W/m^2	The direct and diffuse solar (short wavelength) radiation flux which is absorbed by the exterior surface
Q_c	W	The total convective flux exchange with air and the surface of a wall
q''_{conv}	W/m^2	The convective flux exchange with air and the surface of a wall
q''_{gnd}	W/m^2	The net long wavelength (thermal) radiation flux exchange between the exterior surface and the ground
q''_{ko} q''_{ki}	W/m^2	The heat flux through a wall due to conduction
q''_{LWR}	W/m^2	The net long wavelength (thermal) radiation flux exchange between the exterior surface with the air and its surroundings
q''_{LWS}	W/m^2	The longwave radiation flux which is absorbed by the interior surface from equipment in a zone or group of zones
q''_{LWX}	W/m^2	The net long wavelength (thermal) radiation flux exchange between surfaces in a zone or group of zones
q''_{sky}	W/m^2	The net long wavelength (thermal) radiation flux exchange between the exterior surface and the sky
q''_{sol}	W/m^2	The transmitted solar radiation flux absorbed by the interior surface
q''_{SW}	W/m^2	The net short wavelength radiation flux which is absorbed by the interior surface from lighting in zone.
q^v	W	Heat generated due to vaporisation
R_f	-	The surface roughness multiplier used to adjust the convective heat transfer coefficient of a wall
R^h	K/W	Heat resistance between cells
R^v	s.Pa/kg	Vapour Resistance between cells
R^w	s/kg	Liquid Moisture Resistance between cells
t	s	Indicates the current time step
T	K	Temperature
$T_1, T_2, \ldots, T_{n-1}, T_n$	K	Finite difference nodal temperatures used for the Conduction Transfer Function
T_{air}	K	The temperature of air to which the wall is exposed to
T_{gnd}	K	The surface temperature of the exterior ground surface
T_i and T_o	K	Interior and exterior air temperature
T_{sky}	K	The effective temperature of the sky
T_{surf}	K	The temperature of the surface of a wall
V_z	m/s	The wind speed at an altitude of z metres

w	kg/m^3	Moisture Content
x	m	Distance between cell centres
X and Y	-	Response factors used for the calculation of the conduction heat transfer through a wall
X_j	-	Outside CTF coefficient, j = 0,1,…,nz
Y_j	-	Cross CTF coefficient, j = 0,1,…,nz
Z_j	-	Inside CTF coefficient, j = 0,1,…,nz
α	-	The fraction of short wavelength radiation flux which is absorbed by a surface
δ	kg/(m.s.Pa)	The vapour diffusion coefficient in air
ΔT	K	The difference between the temperature of a surface and temperature of air to which the surface is exposed to
$\Delta\tau$	s	Time step between calculations
ΔV	m^3	Cell Volume
ε	-	The surface long-wave emissivity property of a surface (longwave radiation emitted by a surface)
θ	radian	The angle of incidence of the sun's rays on a surface (the angle between the normal of a surface and the sun's rays)
μ	-	Moisture dependent vapour diffusion resistance factor of a cell
ρ	kg/m^3	Material Density
$\sum$	radian	Surface tilt angle (the angle between the normal of a surface and the vertical axis)
σ	W/(m^2.K^4)	Stefan-Boltzmann constant (= 5.67×10^{-8} W/(m^2.K^4))
ϕ	-	Relative humidity
Φ_j	-	Flux CTF coefficient, j = 1,2,…,nq

Chapter 1 Introduction

1.1 Introduction

The South African house market comprises of 18.7% low-income houses (Republic of South Africa, 2019). The number of low-income houses has led to research focusing on the air quality and living conditions in these homes, as living conditions can become uncomfortable. Additional studies have focused on improving living conditions and how building designs may be changed to improve comfort conditions with minimal investment. Although these studies capture the low-income housing's environmental conditions, the conclusions drawn are based on 'what' environmental conditions are experienced and not 'why' specific environmental conditions are experienced. Thus, conclusions are drawn without considering the environmental conditions in combination with the building makeup. Furthermore, when computer simulations are used in studies focusing on building performance in South Africa, heat balance is treated using a heat-only solution algorithm due to the associated complexity and increased computational time with coupled heat-and-moisture transfer solution algorithms.

Although not enjoying as much research as South-African low-income housing, green buildings in South Africa have seen a significant increase in uptake. This is due to the attached perceived benefits and the increase in building typology for which a green building rating can be awarded. The Green Star program in South Africa has also adopted a green building tool for residential buildings, known as the Excellence in Design for Greater Efficiencies (EDGE) rating tool. Green Star buildings are susceptible to performance gaps. As-designed and As-built Green Star ratings are rewarded by comparing simulated building performance to a base case simulated building performance. Thus, ratings are not based on measured building performance, even when the building rating is awarded for a building that has been occupied.

Both low-income housing and Green Star buildings must adhere to the building standards of South Africa, South African National Standard (SANS) 10400-XA:2011 (South African Bureau of Standards, 2011b), specifically with regard to building sustainability and energy efficiency. Compliance with SANS 10400-XA:2011 (South African Bureau of Standards, 2011b) can currently be achieved through three means. The first path towards compliance requires performing building simulation using modelling guidelines provided by SANS 10400-XA:2011 (South African Bureau of Standards, 2011b). If the simulated energy consumption is less than the energy consumption stipulated in Table 1.1, compliance is achieved. The second path towards compliance requires the building design to adhere to a set of requirements. The third path towards compliance requires the building to be simulated twice, the first model adhering to the requirements stipulated by the second method of compliance, and the second modelled using modelling inputs as expected after building occupation, also known as the rational design of the building. Thus, compliance is achieved through performance-based or prescriptive-based means. The performance-based approach requires a building model to be simulated which is shown to consume a limited amount of energy while still providing an environment which satisfies the needs of the occupants. The accuracy of the simulated model is a combination of the calculation methods used by the software, as well as the detail of inputs provided. Modelling guidelines are used to address both these aspects of modelling accuracy. Modelling guidelines allow the building design and analysis team to minimise the possible performance gap due to the influence of occupancy, material properties, boundary conditions from the weather file, and calculation methods. By inspection, it can be argued that SANS 10400-XA:2011 (South African Bureau of Standards, 2011b) provides too little information for performance-based compliance. Currently only five design assumptions are provided by SANS 10400-XA:2011 (South African Bureau of Standards, 2011b): design occupancy schedules, space temperature range, ventilation requirements, internal heat gains associated with occupants, hot food, lighting, and appliances and equipment, as well design requirements related to hot water. It however lacks guidance with regards to the calculation methods which should be used with software, as well as how occupancy should be modelled.

Table 1.1: Maximum Annual Building Energy Consumption in South Africa (recreated from SANS 10400-XA:2011 (South African Bureau of Standards, 2011b))

	Maximum energy consumption (kWh/m^2)					
	Climatic zone					
Description of building	1	2	3	4	5	6
Entertainment and public assembly	420	400	440	390	400	420
Theatrical and indoor sport	420	400	440	390	400	420
Places of instruction	420	400	440	390	400	420
Worship	120	115	125	110	115	120
Large shop	240	245	260	240	260	255
Offices	200	190	210	185	190	200
Hotel	650	600	585	600	620	630

The technical aspects of building simulation are related to the 'how' of building simulation. This includes the surface heat balance, which is a meaningful simulation input in structures with hygroscopic materials. Although building simulation results vary based on climate, results have provided different trends even when the climate is considered the same. Nevertheless, studies focusing on different surface heat-balance solution methods agree that heat-only solution algorithms are insufficient for building simulations, except for buildings in hot/dry climates.

1.2 Aims & Objectives

The study has four aims. To realise these aims, the objectives required to be completed for each aim are listed below.

Aim 1: "Assess the change in energy performance with changes to the thermal performance of the building envelope of South African Green Buildings"

Objective 1.1. Perform parametric analysis of building energy performance of South African Green Star buildings, using the thermal bulk properties and glazing properties of the building envelope as input parameters.

Objective 1.2. Evaluate the change in building energy performance of South African Green Star buildings due to changes in the thermal bulk properties and glazing properties of the building envelope.

Aim 2: " Establish a case for the building performance of a representative low-income house in South Africa to be influenced by moisture buffering materials"

Objective 2.1. Perform parametric analysis of the air temperature of a representative low-income house in South Africa, using different heat transfer solution methods and moisture transfer properties as input parameters.

Objective 2.2. Evaluate the change in air temperature of a representative low-income house in South Africa due to changes in the heat transfer solution method and moisture transfer properties.

Aim 3: "Evaluate the influence of moisture presence and changes in simulation assumptions regarding occupant behaviour and building design on the environmental parameters for a low-income house in South Africa"

Objective 3.1. Perform parametric analysis of the air temperature and relative humidity of a low-income house in South Africa, using different heat transfer solution methods as input parameters.

Objective 3.2. Evaluate the difference in simulated and captured environmental parameters of a low-income house in South Africa due to changes in the assumptions of occupant behaviour and building design.

Aim 4: "Assess the need for South African building simulation guidelines to include requirements for hygrothermal simulation"

Objective 4.1. Determine whether simulation results in South Africa, compared to captured environmental data, provide improved simulation results when performing hygrothermal analysis compared to thermal analysis.

1.3 Brief Chapter Overview

This study consists of six chapters and five appendices.

The first chapter of the study is the introduction. This chapter provides a brief background to the study, as well as the purpose of the study. Also, the aims and objectives of the study are presented. The chapter concludes with the chapter overview.

The second chapter of the study is the literature review, focussing on five themes: green buildings, building performance, the building envelope, building simulation, and thermal and building simulation studies in South Africa. The section on green buildings describes the principles and concepts of green buildings, as well as a discussion on the research trends of green buildings. Literature related to building performance is presented with a focus on how performance is described and influenced, the concept of prescriptive and performance-based design, how building standards are developed to ensure desired building performance, and how the building environment is conditioned. The third theme, the building envelope, is a discussion of how the building envelope and its components can be defined, how the performance of building envelope components is defined, as well as an overview of the functions of the building envelope and its components. A discussion on thermal performance of the building envelope is also presented under the theme of the building envelope, providing background to the heat transfer mechanics of the building envelope, and thermal properties and performance of the building envelope and its components. The theme of building simulation provides the background for building performance simulation, how it is defined, influenced, and validated. In addition, two methods of surface heat balance used for building performance simulation is addressed, discussing why different surface heat balance methods should be considered for building simulation, research which has been done to support the claim that different surface heat balance methods should be considered for building simulation, and a description of the two main methods of surface heat balance used for building performance simulation. The final theme, thermal and building simulation studies in South Africa, provides the background into thermal studies which have been done in South Africa, which resources are available to designers for the thermal design of building envelopes in South Africa, and how green buildings are being integrated into the South African building stock.

The third chapter of the study is a heat-only parametric analysis of two green buildings, as rated by the Green Building Council of South Africa (GBCSA). The chapter provides an overview of the chosen buildings, why the buildings were chosen, how it aligns with the aims and objectives of the study, how the buildings were analysed, and conclusions made by inspecting the building simulation results.

The fourth chapter provides an advancement of the building analysis presented in Chapter 3. A base case model for a South African low-income house is presented and analysed using parametric analysis. The parametric analysis is described, providing information related to the calculation methods and material inputs used for the parametric analysis. A building layout adhering to minimum requirements is selected for the building analysis.

The fifth chapter of the study is a heat-only and hygrothermal parametric analysis of a low-income house. The chapter provides an overview of the chosen building, why the building were chosen, how it aligns with the aims and objectives of the study, how the building was analysed, how the building model was validated, and conclusions made by inspecting the building simulation results and comparing it to measured data.

The final chapter of the study is the conclusion. This chapter provides observations and comments related to building simulation and a summary of the conclusions, which can be drawn from Chapters 3 to 5. The chapter concludes with a summary of the study's contributions and future research required to improve building simulation in South Africa.

The appendix contains data related to the input of the building simulation models. Appendix A includes a comparison between the results of building simulation software and a finite element analysis software for the sake of software validation. Appendix B provides insight into the modelling options used in Chapters 3 to 5. Appendices C to E presents data related to the weather, internal heat gains, occupancy, ventilation, heating/cooling, and parameters subject to parametric analysis used in the modelling of buildings in Chapters 3 to 5.

Chapter 2 Literature Review

Building simulation is often used to show targeted energy savings or to target comfortable living conditions. The complexity of building simulation is determined by multiple factors, including the choice to include the effects of moisture in heat transfer. The complexity associated with hygrothermal building simulation is better understood by examining the research areas contributing towards building simulation. A connecting narrative is presented in this chapter, coupling the fundamentals of green buildings to the complexities of building simulation. The chapter is divided into five sections, presented in Figure 2.1: green buildings, building performance, the building envelope, building simulation, and studies of the aforementioned in South Africa.

Green buildings are studied by examining how they are defined, both as a concept and metric, what determines success or failure, and how green buildings and building envelopes have advanced with time. Building performance is studied by examining the concept of building performance, how building design and occupancy influences building performance, and how building performance can be coupled to the interior conditioned environment. The building envelope is studied by examining how the building envelope and its components are defined, their functions, external factors that influence choice, and how performance is defined and measured. Building simulation is studied by examining the usage of building simulation software for building performance prediction, the associated accuracy of simulated building performance, the simulation mode parameters, and a comparison between heat-only and coupled heat-and-moisture transfer building performance simulation. Studies devoted to commercial and residential building performance in South Africa are reported. A summary of building energy standards and green building governance in South Africa is presented.

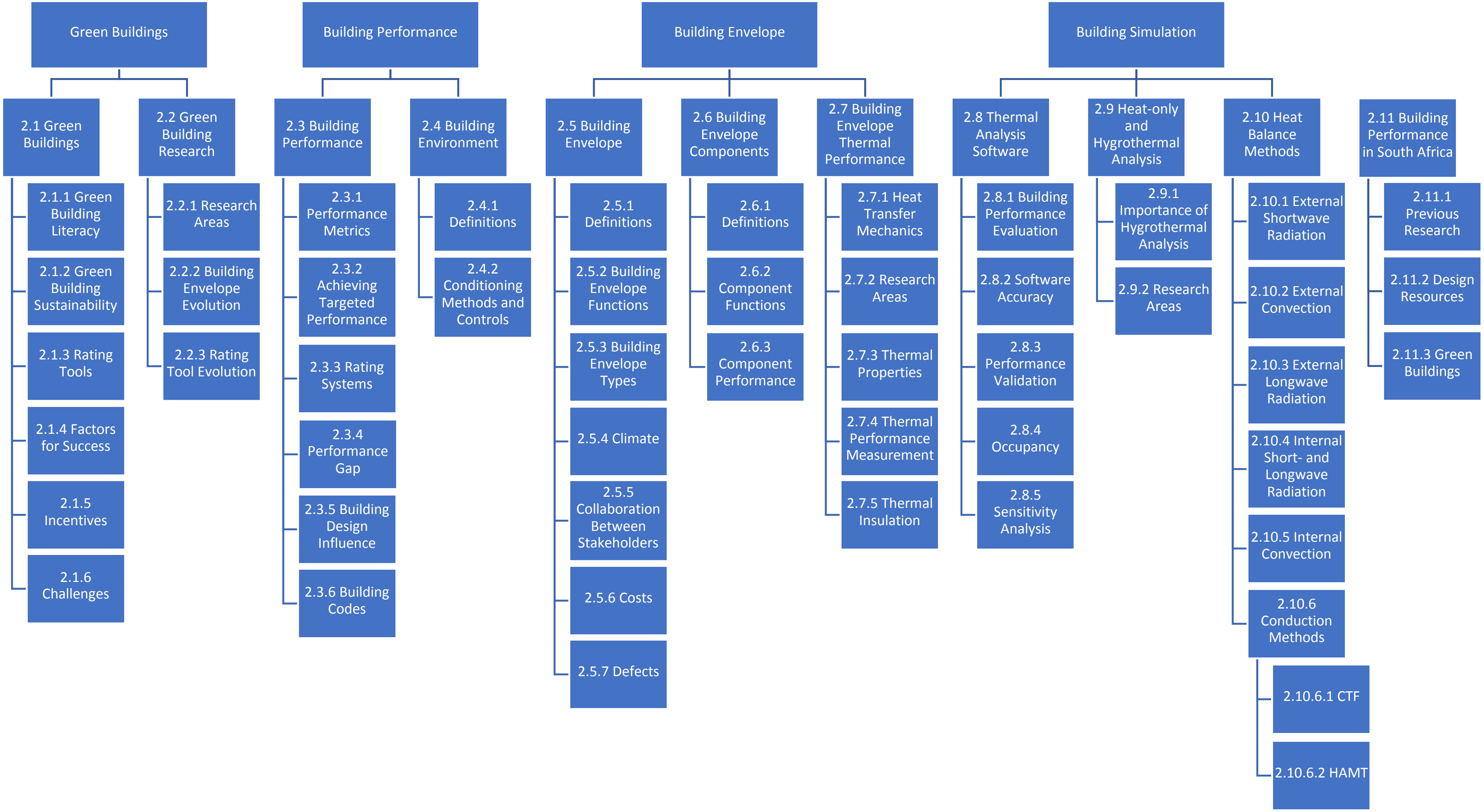


Figure 2.1: Hierarchy Map of the Structure of the Literature Review

2.1 Green Buildings

2.1.1 Defining Green Buildings and Green Literacy

2.1.1.1 Definition and traits of Green Buildings

The need for green buildings originates from the number of resources consumed by buildings (Huovila, 2007). Green buildings are defined as buildings exhibiting environmentally responsible and resource-efficient characteristics while maintaining a comfortable indoor environment (Alawneh *et al.*, 2019) (Wong and Zhou, 2015). The exact characterisation of green buildings does, however, vary between countries due to varying economies, available resources, and climate (Shi and Liu, 2019). Regardless of characterisation, all green buildings are built to reduce buildings' negative impact on the indoor and outdoor environment (US Green Building Council, 2003; Lee and Tiong, 2007; Pitts and Jackson, 2008).

Green buildings provide environmental, economic, and social benefits (Giduthur and Vanakuru, 2017). Environmental aspects are concerned with ecosystems, air and water quality, building waste, and resource usage (Giduthur and Vanakuru, 2017). Economic aspects are concerned with operational costs, occupant productivity, building value, and life-cycle economic performance. Social aspects concern themselves with the occupants' quality of life and the strain the building puts on national utility infrastructure.

Design decisions that impact buildings' environmental aspect are guided by analysis and reasoning (Mahdavi, 2020). These design decisions form part of green building design, integrating site planning, building envelope design, building system design, renewable energy, waste and water management, material selection, and indoor environmental quality (Giduthur and Vanakuru, 2017). Green building design reduces the environmental impact of a building through economic and energy efficiency (Burinskienė and Rudzkienė, 2007; Bojnec and Papler, 2011).

2.1.1.2 Net-Zero Buildings

When a building produces an amount of energy equal to or more than the energy it consumes, it is classified as a Net-Zero building (Lin and Li, 2011). A Net-Zero building is typically characterised by a reduction in resources across all the phases of its life cycle (Naess, 2001). A reduction of resources across all the phases of a building's life cycle is required because focusing on a single aspect of building design proves insufficient when designing a net-zero building (Perino and Serra, 2015).

Net-Zero building design consists of modifying the design of a notional building (Shehadi, 2020). Design changes are made regarding building envelope measures, energy efficiency measures, and renewable energy measures (Košir, 2016). Design changes are made considering building orientation, glazing area, solar exposure, shading, heat island presence, lighting system, lighting capacity, indoor temperature, humidity levels, relative humidity levels, landscaping, natural resource usage, and system efficiency variables. In addition to such passive design changes, energy efficient building systems are required to minimise resource usage (Košir, 2016).

2.1.1.3 Need for Green Literacy

Green building knowledge is seen as a skill for which experience can be acquired (Cole, 2019). It requires an understanding of the building environment, its complexity, and the impact that decisions may have on the building environment (Stables and Bishop, 2001; McBride *et al.*, 2013). This understanding is developed through green building education, allowing individuals to critically evaluate cultural, social, and political influence (Cole, 2019).

When building professionals are green literate, they can design buildings with a minimal performance gap (Zero Carbon Hub, 2014a; Alencastro, Fuertes and de Wilde, 2018). However, the capacity to become green building literate is restricted by an individual's sensitivity and concern towards the environment, self-efficacy, sense of self-responsibility, and inclination to influence the environment (Cole, 2019).

2.1.2 Defining Green Building Sustainability

The concept of sustainable development was first conceived in 1987 by the Brundtland Commission (World Commission on Environment and Development, 1987). They defined sustainable development as "development that meets the need of present generations without compromising the ability of future generations to meet their needs and aspirations" (World Commission on Environment and Development, 1987; United Nations Conference on Environment and Development (UNCED), 1992).

Sustainable development requires sustainability in an environmental, social, and economic sense (Khan, 1995; Salgın *et al.*, 2017; Shehadi, 2020). This is possible by designing a building that efficiently uses resources to maximise building performance (Raman, 2005; Lee and Tiong, 2007). The resources consumed by the building include energy, water, land, and materials (Sadineni, Madala and Boehm, 2011).

The resources consumed by a building serves as a measurement for the environmental impact of a building (Santamouris, 2006). The environmental impact is assessed using Life Cycle Assessment (LCA) (Gan *et al.*, 2020). Two main types of LCA exist. The first is process-based LCA which quantifies the carbon emissions for each stage in a building's life (van Ooteghem and Xu, 2012). The second is the hybrid economic input-output LCA, in which the pre-operational and operational phases of a building are analysed separately (Guggemos and Horvath, 2005). When improving building sustainability through LCA, it requires optimising: the structural systems or building materials used in a building, the passive design of a building, and the efficiency and control method of building service systems (Gan *et al.*, 2020)

2.1.3 Green Building Rating Tools for Building Assessment

International green building councils were created to establish sustainable building practices (Bahaudin, Elias and Saifudin, 2014). The World Green Building Council (WorldGBC) is responsible for establishing these green building councils and associated initiatives (Sadineni, Madala and Boehm, 2011). To evaluate building sustainability, green building councils employ Green Building Rating Tools (GBRTs) for assessment (Du Plessis and Cole, 2011; Nag, 2019). Evaluation can be performed for a proposed design based on potential performance, or a rating can be given for a built building using measured performance (Gabe and Christensen, 2019).

Due to the amount of GBRTs established, the classification of evaluation criteria used by GBRTs may vary (Wen *et al.*, 2020). This is observed when comparing GBRTs and observed when comparing versions of the same GBRT. Also, GBRTs vary based on their credit weighting. Although the classification of evaluation criteria may vary between GBRTs, they can be categorised as focusing on either environmental, social, or economic sustainability (Elkington, 1998; Sjostrom and Bakens, 2010; Bernardi *et al.*, 2017)

GBRTs consist of an indicator system, scoring system, and rating system (Ali and Al Nsairat, 2009; Usman and Abdullah, 2018; Zhang *et al.*, 2019; Wen *et al.*, 2020). The indicator system categorises performance criteria, the scoring system ranks the different indicators, and the rating systems provide an overall building performance score. The indicator system itself is composed of 4 levels: categories, subcategories, criteria, and indicators (Zhang *et al.*, 2019; Wen *et al.*, 2020). The category level is an indicator of sustainability for an identified aspect of sustainability. The subcategory level consists of the aspects of the category. The criteria level consists of performance metrics of the aspects of the category level. The indicator level quantifies the performance metrics of the criteria level.

Although multiple rating systems can co-exist in the same region, some rating systems will experience a more significant uptake (Bahaudin, Elias and Saifudin, 2014). Due to the maturity of GBRTs, international leaders have been established which are considered the best (Schwartz and Raslan, 2013). The two GBRTs considered international leaders are the Building Research Establishment - Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) rating systems (Roderick *et al.*, 2009). Both GBRTs asses building performance by comparing the simulated performance of the actual building design, existing or conceptual (Hamza, 2004), to a notional design (Schwartz and Raslan, 2013).

2.1.4 Factors for Success for Green Buildings

A green building's success depends on its project delivery attributes, critical success factors, benefits, drivers, barriers, and risks (Ahmad, Aibinu and Stephan, 2019). In addition, the success of green buildings within the construction industry is dependent on the knowledge of the personnel within the construction industry (Clarke *et al.*, 2019). Because smaller companies have such a large presence in the construction industry, the knowledge of the personnel within the construction industry is influenced by the investment of smaller companies in improving the knowledge of their employees.

Regarding the drivers for success, energy-efficiency, reduced environmental impact, water efficiency, occupants' health, comfort and satisfaction, company image, and government regulations and policies are considered the drivers for successful green building implementation (Darko *et al.*, 2017; Darko, Zhang and Chan, 2017).

The success of green buildings is also determined by the collaboration between building stakeholders (Clarke *et al.*, 2019). Collaboration is required for innovation, both of which are required to construct energy-efficient buildings. Collaboration, however, is challenged by human- and commercial-related barriers (Eriksson and Westerberg, 2011). Human related barriers include trust, communication, and understanding of collaborators, cultural differences, and relationships (Clarke *et al.*, 2019). Commercial-related barriers are the complexity of commercial and contractual frameworks (Ey, Zuo and Han, 2014).

2.1.5 Incentives Offered by Green Building Development

Green buildings incentives can be studied through four areas (Olubunmi, Xia and Skitmore, 2016). These are the categorisation of green building incentives, the effectiveness of green building incentives, criticisms of green building incentives, and strategies for improving green incentives to promote higher adoption rates of green building.

Green building incentives can be categorised as either external or internal incentives (Olubunmi, Xia and Skitmore, 2016). External and internal incentives can further be categorised by incentive type: financial or non-financial. Internal green building incentives are referred to as incentives that result from stakeholder interest in sustainability (Abidin, 2009). External green building incentive is referred to incentives that result from complying with a set of requirements, typically incentives provided by governments (Olubunmi, Xia and Skitmore, 2016).

Internal incentives include improved resource efficiency, increased building marketability, increased occupant comfort and health, increased productivity, decrease in tenant turnover and interruptions in return on investment, increased rental prices, recognition of achievement, satisfying the philanthropic beliefs of stakeholders, and the opportunity to be recognised as a flagship project (Kats *et al.*, 2003; Swett, Wein and Martin, 2007; Kimmet, 2008; Ashuri and Durmus-Pedini, 2010; Antoniades, 2011; Robichaud and Anantatmula, 2011; Sundbom, 2011; Harrison and Seiler, 2011;

Cotten, 2012; World Green Building Council, 2013; Azis, Sipan and Sapri, 2013; Diyana and Abidin, 2013; Gou, Lau and Prasad, 2013; Giduthur and Vanakuru, 2017; Ade and Rehm, 2020).

Incentives provided by governments include subsidies, mandatory regulations, tax reductions, rebates, discounts in building-related admin processes, increased floor usage allowance, technical assistance, expedited building admin processes, and business planning and marketing assistance (Yudelson Associates, 2007; Sentman, Del Percio and Koerner, 2008; Choi, 2009; Deng and Eigerman, 2010; Karkanias *et al.*, 2010; Shapiro, 2011; Diyana and Abidin, 2013; Wang *et al.*, 2014)

Improvements with regards to external incentives are still required (Eon *et al.*, 2020). Methods to incentivise green building development should include the cooperation from private institutions and governments (Olubunmi, Xia and Skitmore, 2016). Private institutions should provide improved lending rates and rebates on payments for green buildings (Roodman, Lenssen and Peterson, 1995). Incentives provided by the government should account for the social, financial, and political situation for the building's region (Pippin, 2009; Ghodrati, Samari and Shafiei, 2012).

The issues faced by governments with regards to providing adequate incentives stems from their inability to determine the level of incentive required to promote green building development (Fletcher, 2009). Criticisms regarding the incentives offered by governments include the inability to recover the costs associated with attempting to fulfil the requirements of a green building, not being able to factor in financial incentives due to ratings not being guaranteed, and the high costs associated with green building development which nullify the Incentives that are attached to certification (Shapiro, 2011; Qian, Chan and Choy, 2012).

2.1.6 Issues Faced by Green Building and Green Building Rating Tool Adoption

2.1.6.1 Challenges Encountered for Green Building Adoption

Green Building adoption is mainly challenged by aspects of building assessment and building design (Iwaro and Mwasha, 2013; Crawley *et al.*, 2020). Additional barriers towards green building adoption include uncertainty regarding the payback period of green building measures, lack of government regulations and policies, lack of information, cost, lack of incentives, and lack of interest and demand from industry (Achtnicht and Madlener, 2014; Darko *et al.*, 2017; Hu and Milner, 2020).

Regarding building assessment, a lack of reliability in energy ratings is considered an issue (Crawley *et al.*, 2019; Hardy and Glew, 2019). This can result from buildings not performing as designed (Ade and Rehm, 2020) or specific stakeholders being misinformed due to expecting certain levels of resource efficiency (Ade and Rehm, 2020). Although performing performance verification throughout a building's life-cycle is required for complete verification, it is limited by time and financial constraints (Gram-Hanssen *et al.*, 2018; Zou *et al.*, 2018).

Regarding building design, the complexity of sustainable building design is attributed to the multi-dimensionality of sustainable building design (Lombardi, 1999; Ding, 2005). Because sustainable design requires the demands of the different aspects of building sustainability to be met (Shehadi, 2020), investigating one aspect of sustainability requires all aspects to be studied (Iwaro and Mwasha, 2013). These requirements are in addition to the building's structural requirements, which can influence thermal performance (Sadineni, Madala and Boehm, 2011).

2.1.6.2 What are the Challenges Encountered by Green Building Rating Tool Adoption

The adoption of GBRTs is still met with resistance in the industry due to a lack of cultural change within the industry (Kotter, 2012; Matinaro and Liu, 2017). It finds success when it is easy to implement, is limited to a few categories, is cost-effective for building owners, and will provide a return on investment (Yudelson, 2016; Ade and Rehm, 2020).

Considering the factors towards successful GBRT adoption, the challenges towards GBRT adoption are the costs associated with obtaining a rating, the complexity associated with energy modelling, and lacking knowledge of the benefits associated with achieving GBRT credits (Kats *et al.*, 2003; Lockwood, 2008; Zhang, Platten and Shen, 2011; Hwang *et al.*, 2017; Zhang, Wu and Liu, 2018; Ade and Rehm, 2020; Illankoon and Lu, 2020). The complexity associated with energy modelling requires design teams to have an adequate technical background and understand up-to-date green building practices concerning their field of expertise (Giduthur and Vanakuru, 2017).

2.2 Green Buildings Research

2.2.1 Identifying the Areas of Research of Green Buildings

Because of the increasing amount of green building research (Ulubeyli and Kazanci, 2018; Venkataraman and Cheng, 2018), seen in Figure 2.2, scientometric analysis studies have been used to capture the status quo and trends of green building research (Darko *et al.*, 2019). Scientometric software allows the essential parts of large amounts of research to be identified (Chen, 2006). In addition, scientometric analysis allows for the strength and weaknesses of previous research to be identified, providing a means to identify improvements towards research (Ahmad, Aibinu and Stephan, 2019).

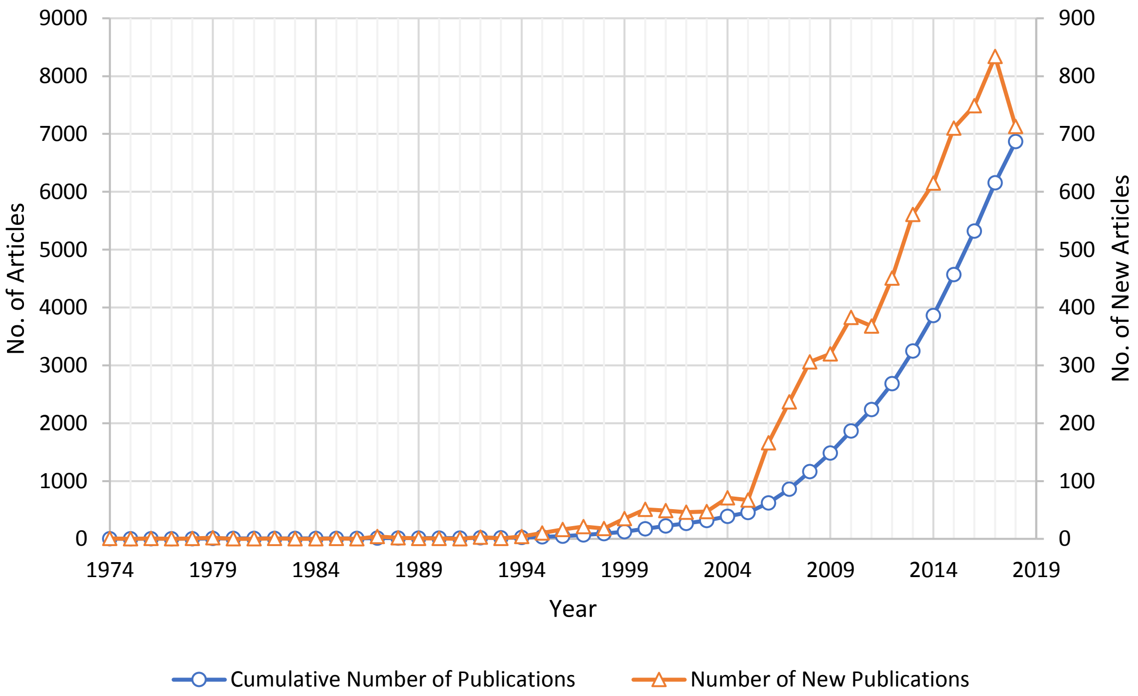


Figure 2.2: Articles Released between 1974 and 2018 related to Green Buildings (Recreated from (Darko et al., 2019))

Using scientometric analysis, (Darko *et al.*, 2019) shows that green building research started as early as 1974, with an upswing starting in 1999. Their work also shows that specific keywords have been associated with citation bursts, presented in Figure 2.3. From their scientometric analysis, (Shi and Liu, 2019) identified citation bursts according to references with the strongest citation burst strength. In total, green building research citation bursts have focused around nine themes between 2002 and 2018, presented in Figure 2.4. The first research burst for green buildings, which focused on the cost-effectiveness of green buildings, can be observed for 2005. Research bursts stemming from 2009 focused on methods to address the environmental issues associated with buildings. Citation bursts in 2011 found no general theme but branched into the topics previously focused on. Citation bursts in

2012 and 2013 focused on energy efficiency, energy reduction, and modern technologies integration. Publication trends show that green building research has entered a steady-growth stage in which the number of publications a year remains within an upper and lower limit (Shi and Liu, 2019). Despite the steady-growth stage, research is still required for closing the building performance gap, the collaboration between building stakeholders, improving professionals' training, using post-occupancy data to build simulation verification, building standards, life-cycle thinking, the impact of the construction and commissioning phase, integration of AI, and sustainable use of concrete (Zou *et al.*, 2018; Darko *et al.*, 2019; Eon *et al.*, 2020). Despite its success, green building research is challenged by a lack of collaboration between researchers, by research that does not display similar quality, and a lack of equal priority between the phases of a building's life-cycle (Ahmad, Aibinu and Stephan, 2019; Darko *et al.*, 2019; Eon *et al.*, 2020).

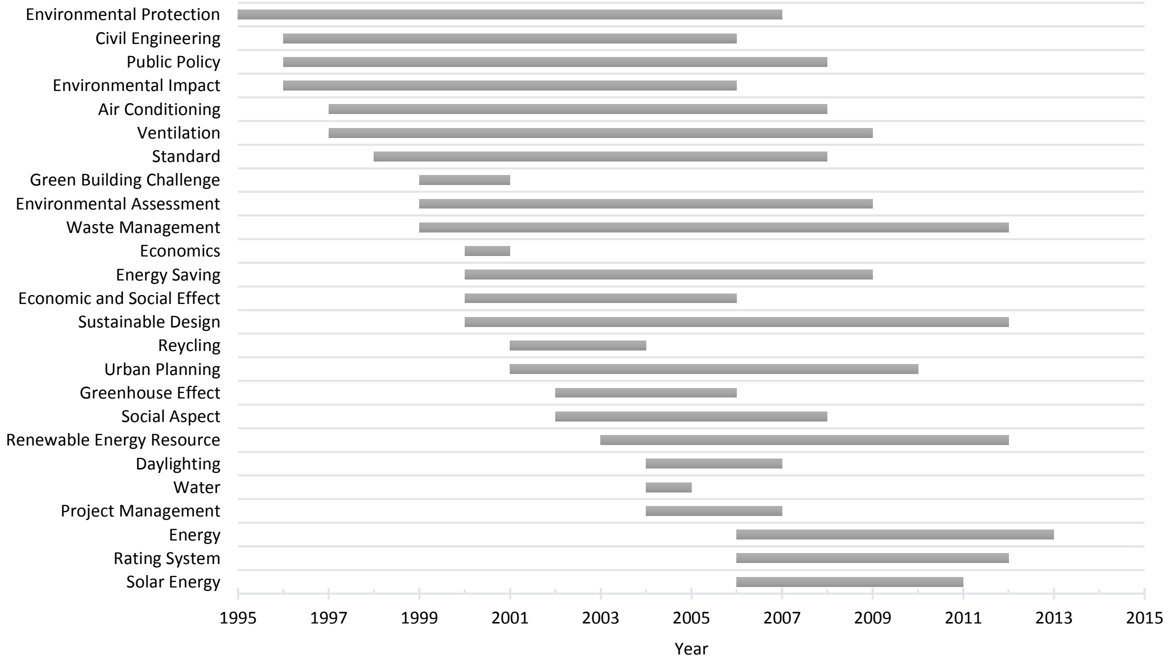


Figure 2.3: Keywords Appearing in Citation Bursts Related to Green Buildings (1978 – 2018) (Recreated from (Darko et al., 2019))

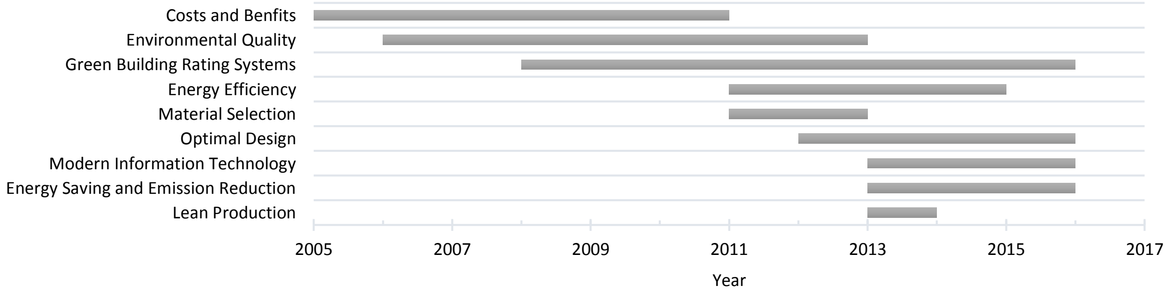


Figure 2.4: Citation Burst Themes (2002 – 2018) (Recreated from (Shi and Liu, 2019))

Green building research ultimately improves the knowledge graph of green buildings (Shi and Liu, 2019). The knowledge graph is made of a knowledge base, knowledge domain, and knowledge evolution, presented in Figure 2.5. The knowledge base presents the keywords most often used in green building research, i.e. the topics which are addressed by green building research. Using keyword co-occurrence, (Shi and Liu, 2019) shows that energy performance, energy type, and GBRTs are the core of green building knowledge. The knowledge domain presents the research clusters of green building research. It groups green building research based on the similarity of its focus area and identifies the trends and critical parts of green building research. Five research clusters can be developed from green building research: green building technologies adoption, materials selection, panel data, green building project management, and green building assessment system. These research clusters can be divided into a management system, a technology system, and an evaluation system. The management system is the aspects of green buildings related to choices made to ensure project success. The technology system comprises the technical aspects contributing to green building performance. The evaluation system comprises the aspects related to green building assessment. The knowledge evolution provides the information related to the central themes of citation bursts in green building research.

Knowledge Evolution	• Cost and Benefits • Environmental Quality • Materials Selection • Energy Efficiency • Lean Production • Energy Saving and Emission Reduction	• Optimal Design • Modern Information Technology • Green Building Rating System	
Knowledge Domain	Management System Clusters: • Materials Selection • Green Building Project Management	Technology System Clusters: • Green Building Technology Adoption	Evaluation System Clusters: • Green Building Assessment System and Building Assessment Tool • Panel Data Approach
Knowledge Base	• Architecture • Barrier/Challenge • Behavior • BIM • China/Hong Kong • Climate Change/Climate • Concrete/Cement • Construction Industry • Construction/Building • Consumption • Cost • Design/Sustainable Design • Driver • Education • Efficiency/Productivity • Embodied Energy • Emission • Energy Consumption/Consumption • Energy Efficiency • Energy Saving/Energy Conservation • Energy/Renewable Energy/Solar Energy	• Environment/Built Environment • Environmental Assessment Method • Environmental Performance • Fly Ash • Framework • Genetic Algorithm • Green Building Design • Green Building Material • Green Building Project • Green Building/Sustainable Building/Sustainable/Construction • Health • Impact/Environmental Impact • Indoor Environmental Quality • Industry • Innovation • LEED/BREEAM/Assessment Tool • Life Cycle • Life Cycle Assessment/LCA • Management • Mechanical Property	• Model/Simulation • Natural Ventilation • Optimization • Performance/Energy Performance • Perspective • Policy • Project • Quality • Recycling • Residential Building/Office Building • Risk • Selection • Strategy • Sustainability/ Sustainble Development/Green • System • Technology • Thermal Comfort/Comfort • Thermal Performance • Waste

Figure 2.5: Green Building Knowledge Graph (Recreated from (Shi and Liu, 2019))

2.2.2 The Development of Building Envelopes with Time

The building envelope is researched at three levels: concept, system, and material level (Goia, 2013). The concept level is associated with methods for improving building performance (Perino and Serra, 2015). The system level is associated with the development of multi-functional building envelopes. The material level is associated with the usage of materials and building components in multi-functional building envelopes.

The development of building envelope systems can be predicted by reviewing historical systems and factors (Heidari Matin and Eydgahi, 2019). This is achieved by investigating façade development through literature and depicting development through a timeline, coupling events and milestones in adaptive envelope evolution. Combining historical research allows for research areas lacking in information to be identified, how the field is currently being developed, and how direction research is being undertaken (Zuo and Zhao, 2014).

Historical evidence suggests advancement of building envelopes does not come from within the industry itself but rather from other disciplines and technologies (Knaack *et al.*, 2014; Heidari Matin and Eydgahi, 2019). Regarding the direction of building envelope development, the building envelope was initially advanced with the philosophy of design with an "energy conservative approach" (Goia, 2013). This design philosophy requires buildings' energy efficiency to be improved by minimising loss and maximising heat gains during winter (Perino and Serra, 2015). This also resulted in thermo-physical requirements for building envelope components, which led to advances in insulation, thermal transmittance properties of glazing, improving air-tightness, and harvesting and recovering heat.

However, the advancement of building envelopes is challenged by industry complexity and reliance on manual labour and socio-cultural, eco-political, environmental, and technological factors (Oyedele *et al.*, 2016; Heidari Matin and Eydgahi, 2019). Also, advances in building envelope systems can be slow due to either the outcome being secondary or research being kept confidential (Loonen *et al.*, 2013). Specific building envelopes also enjoy more attention than others, as observed with transparent building envelopes, which has been the more significant focus of adaptive building envelopes (Košir, 2016). Advancing building envelope systems also require performance and occupant satisfaction to be monitored (Loonen *et al.*, 2013). Similarly, the design philosophy of energy conservation has also been met by setbacks (Perino and Serra, 2015). Restrictions placed by the design philosophy of energy conservation can result in overheating of the building environment, change of energy demand balance, and lower return from building improvements.

2.2.3 The Development of Green Building Rating Tools with Time

The development of GBRTs is researched through the comparison of GBRTs and implementation of literature reviews (Wen *et al.*, 2020). Comparisons are made by studying the weighting current GBRTs and historical trends of sustainability criteria, allowing current green building trends and the direction of green building development to be identified (Zuo *et al.*, 2017). Studies are, however, limited by the amount of material studied, timeframe of material studied, research depth, latest GBRT version studied (Wen *et al.*, 2020). Typical limitations of GBRT development or comparison studies can be overcome by including many GBRTs, ensuring the time frame captures the entire history to present, and compares equally.

Screening GBRTs for research analysis is a two-step process (Wen *et al.*, 2020). The first step ranks various GBRTs based on a score rewarded for relevant performance. The second step requires identifying the non-residential GBRTs of each selected GBRTs in the first step. Once GBRT indicators are reclassified, it is possible to compare the development of the GBRTs to each other.

Literature reviewing the development of GBRTs shows its development can be divided into three phases (Wen *et al.*, 2020). The first phase of GBRT development contained a few GBRTs, making overall changes to sustainability weightings easy to identify. The first phase was followed by the introduction of a large amount of GBRTs, which resulted in fluctuations in sustainability weightings. The third and current phase is considered the stabilised phase, in which fluctuations of sustainability weightings have been reduced and stabilised.

Regarding observations made with GBRT development, the literature shows that trends can be observed for all the aspects of building sustainability (Wen *et al.*, 2020). Changes to the weighting of the environmental category in GBRTs has experienced three trends: continuous decline, decline in fluctuations, stable and slight increase. The weighting of the social category in GBRTs is increasing in eight of the ten highest-ranked GBRTs. Although the weighting of environmental and social sustainability has become more balanced in GBRTs, the weighting of economic sustainability remains unbalanced with a low weighting. This is because trends regarding economic sustainability are not yet established, as some GBRTs have only recently included economic sustainability as a category. Regarding the weighting of individual credits within the three aspects of building sustainability, resources are the highest weighted aspect of environmental sustainability. Well-being is the highest weighed aspect of social sustainability, and value stability is the highest weighed aspect of economic sustainability in GBRTs.

The weighting of the aspects of building sustainability is also reflected by the amount of research these aspects obtain. Scientometric analysis reveals that environmental sustainability has enjoyed a large amount of green building research (Darko *et al.*, 2019). In contrast, social and economic sustainability has received much less attention.

2.3 Connecting the Building Performance to the Building Design

2.3.1 Defining Building Performance

Building performance can take on many forms, including acoustic performance, thermal performance, visual performance, air quality, sustainability, building integrity, and spatial performance (Rush, 1986). Indicators for building performance include primary or secondary energy usage, heating and cooling demand, carbon emission rate, a limit on operative temperature, water usage, and performance gap after a certain amount of time (O'Brien *et al.*, 2020).

Building performance can also be expressed by the performance of the building envelope (Elder, 2005). The performance of the building envelope is measured by its ability to control solar, moisture, thermal, air, and acoustics and provide fire protection (Brock, 2005; Leung *et al.*, 2005; Lee and Tiong, 2007). Building performance is deemed acceptable when building occupants are protected, their psychological needs are fulfilled, and the building is aesthetically pleasing, cost-effective, and environmentally sustainable (Brock, 2005; Leung *et al.*, 2005).

Building performance is evaluated using advanced building software or non-numerical methods (Enker and Morrison, 2020; Gan *et al.*, 2020). A combination of the two can be used to measure building performance for certain aspects of the building while estimating building performance for other aspects (Gan *et al.*, 2020). The advantage of measuring building performance is that it provides the required information to improve future building design projects and reduce the performance gap of future building simulations (Van Dronkelaar *et al.*, 2016; McElroy and Rosenow, 2019; Shi *et al.*, 2019). Improving building performance requires improving building design, materials, and construction techniques (Yao *et al.*, 2018; Lotfabadi and Hançer, 2019).

Comparing building performance is challenged by the lack of normalisation in building performance evaluation (Crawley *et al.*, 2020). When evaluating building energy performance, energy data and floor area are used as metrics (Republique Française, 2012). Although a common practice, it omits recognition of building location and occupancy (Crawley *et al.*, 2020). Normalisation is also absent for the time-resolution used during energy reporting (Loonen *et al.*, 2013). The lack of normalisation regarding time-resolution results from technologies operating at different times and performance metrics being expressed at different time intervals. A lack of normalising building performance has also been identified as an issue for performance gap reporting methods (Shi *et al.*, 2019).

Smart meters have been proposed as a solution for building performance normalisation (Crawley *et al.*, 2020). Smart meters can capture the thermal performance of buildings through two metrics:

Heating Power Loss Coefficient (HPLC) and Heat Transfer Coefficient (HTC) (Chambers and Oreszczyn, 2019). The HPLC expresses the energy required to maintain a temperature difference between the building exterior and interior. The HTC is simply the heat flow rate divided by the temperature difference between two environments. The success of smart meter adoption is determined by its availability in an industry, the amount of data it provides, and its accessibility to assessors (Crawley *et al.*, 2020). Adoption is, however, challenged by cost investment and the additional complexity it introduces to rating systems.

2.3.2 Achieving Prescriptive or Performance-Based Building Performance

When building standards require a building to achieve a specific level of building performance, compliance can be achieved through either prescriptive or performance-based design (GBRS, 2010; Halawa *et al.*, 2018). A prescriptive-based approach requires a building to be designed according to a set of restrictions (Halawa *et al.*, 2018). A performance-based approach requires improved building performance compared to an equivalent building designed according to the prescriptive-based approach (O'Brien *et al.*, 2020). Although both paths to compliance exist for many building codes, performance-based compliance is preferred (Evans, Roshchanka and Graham, 2017).

2.3.3 Building Performance Ratings

In addition to adhering to building codes, building performance can also be evaluated for Energy Performance Certificates (EPCs) (Crawley *et al.*, 2020). The awarded rating ranges from fully calculated to fully measured. Calculated building performance is typically used for a design rating, whereas measured building performance is used for a constructed rating. The rating awarded for calculated building performance is determined by comparing it to a national average or an expected value based on theory (SMHI, 2018; Lomas *et al.*, 2019).

Calculated building performance can be obtained using either a simplified approach using analytical methods or a detailed simulation approach, offering higher accuracy, using numerical methods (Shi *et al.*, 2019). Numerical approaches are provided by advanced building software (Schwartz and Raslan, 2013). The literature recommends EPCs are awarded for measured building performance (Van Dronkelaar *et al.*, 2016; Gram-Hanssen *et al.*, 2018; Zou *et al.*, 2018; McElroy and Rosenow, 2019). It considers evaluating calculated building performance against an industry or building code benchmark a fundamental failing of performance-based design (Yudelson and Meyer, 2013). Despite these concerns, EPCs awarded for green buildings are typically performance-based (Shi *et al.*, 2019).

2.3.4 Closing the Performance Gap Between As-Designed and As-Built

The objective of EPCs is to provide information regarding policy-making information and provide building energy performance data to buyers/tenants (European Parliament, 2010; Crawley *et al.*, 2020). These objectives are currently not being met (Crawley *et al.*, 2020). Because building performance is typically not measured after construction, it is impossible to compare the calculated building performance used for the EPC to actual building performance (Eon *et al.*, 2020).

The failure to achieve energy certificate targets has led to the formation of building performance gaps, i.e. the difference between a measured and predicted building performance (Demanuele, Tweddell and Davies, 2010; Zero Carbon Hub, 2010; Fokaides *et al.*, 2011; Menezes *et al.*, 2012; Petersen and Hviid, 2012; De Wilde, 2014; Rafols, 2015; Calì *et al.*, 2016; Herrando *et al.*, 2016). Building performance can be associated with energy, thermal, air quality, acoustic, or lighting variables (Shi *et al.*, 2019). The performance gap is evaluated by how they are defined, measured, the size of the performance gap, causes, and reduction measures.

Two types of performance gaps exist: a static performance gap and a dynamic performance gap (Eon *et al.*, 2020). The static performance gap is a comparison between predicted performance and measured performance. The dynamic performance gap is a comparison between the predicted performance of calibrated building models and measured performance.

The gap between current and demanded building performance can be assessed using an Integrated Performance Model (IPM) (Iwaro and Mwasha, 2011; Mwasha, Williams and Iwaro, 2012; Iwaro, Mwasha and Williams, 2013). The IPM is constructed around four frameworks: Life Cycle Cost (LCC), LCA, Life Cycle Energy Analysis (LCEA), and Multi-Criteria Analysis (MCA) (Iwaro and Mwasha, 2013). These frameworks assess building performance based on: energy efficiency, economic efficiency, environmental impact, regulation efficiency, material efficiency, and external benefit.

The exact cause of the performance gap is difficult to establish due to the number of possible error sources (Shi *et al.*, 2019). Although studies on the building's performance gap are different based on location, the performance gap's leading identified causes are similar (Eon *et al.*, 2020). It is created during all the stages in a building's life-cycle, where design decisions are made and implemented (Eon *et al.*, 2020). Factors leading to the building performance gap is summarised in Table 2.1. The factors considered the leading causes of the performance gap are occupant behaviour, climate, and building defects (Shi *et al.*, 2019).

Table 2.1: Factors contributing to the building performance gap.

Building Life Cycle Stage	Factors contributing to the building performance gap	Sources
Planning and Design	• Lack of communication between stakeholders • Incorrect assumptions made regarding occupant behaviour • Incorrect assumptions made regarding building design and material requirements • Lack of detailing on drawings • Building design complexity • Stakeholders not understanding design performance targets • Incorrect building simulation inputs • Advanced building software reporting incorrect results • Lack of modelling knowledge and experience • Assessment dishonesty	(Zero Carbon Hub, 2014a, 2014b; Imam, Coley and Walker, 2017; Alencastro, Fuertes and de Wilde, 2018; Zou *et al.*, 2018; Enker and Morrison, 2020; Eon *et al.*, 2020)
Procurement	• Changes to orders related to the construction of the building • Poor quality equipment or materials • Design changes made to initial building design	(Zero Carbon Hub, 2014a; Gram-Hanssen *et al.*, 2018; Zou *et al.*, 2018)
Construction	• Building defects • Site management • Workmanship • A mismatch between designed building elements and used building elements • Lack of documentation details	(AECOM, 2012; Tofield, 2012; Zero Carbon Hub, 2014a; Aïssani *et al.*, 2016; Chartered Institute of Building, 2016; Palmer *et al.*, 2016; Alencastro, Fuertes and de Wilde,

		2018; Enker and Morrison, 2020)
Commissioning	• Incorrect sizing of building systems • incorrect installation of building systems • Inefficient use of building energy management systems • Incorrect setting parameters for the building system	(Van Dronkelaar *et al.*, 2016; Eon *et al.*, 2020)
Occupancy	• Occupant behaviour • Poor use of technological systems • Lack of building maintenance • Weather variation	(Carbon Trust, 2011; AECOM, 2012; Zero Carbon Hub, 2014a; Jones, Fuertes and Lomas, 2015; Gupta and Kapsali, 2016; Alencastro, Fuertes and de Wilde, 2018)

Reducing the performance gap is done by implementing reduction measures (Shi *et al.*, 2019). These recommendations aim to improve building professionals' knowledge, verify predicted building performance, improve collaboration and management, ensure public access to building performance data, and develop new building codes and standards to make proper building design, construction, and commissioning easier to achieve (Eon *et al.*, 2020).

Reduction measures can be grouped into non-technical measures, technical measures, and hybrid measures (Shi *et al.*, 2019). Non-technical measures consist of improving management at all stages of a building's life-cycle. Technical measures consist of improving the assumption and inputs used for building simulation. Hybrid measures consist of improving management to improve the assumption and inputs used for building simulation, improving construction practices, and improving the building user's knowledge to enable efficient behaviour. Reduction measures can further be divided into four themes (Eon *et al.*, 2020): training, collaboration, performance accountability, and standards.

Reducing the performance gap requires building model validation through data collection and comparison, better model forecasting, and industry practice improvements across all the stages of a building's life-cycle (De Wilde, 2014). Improved communication protocols, communication guidelines, and better management are needed where a lack of communication and collaboration is identified to be a cause for the performance gap (IPECC, 2019; Shi *et al.*, 2019). Improving the building knowledge of building contractors and modellers through certification and qualification schemes have also been touted to reduce the performance gap (Zero Carbon Hub, 2014a; McElroy and Rosenow, 2019).

2.3.5 The Role of Building Design on Building Performance

Due to the amount of energy consumed by buildings (Sadineni, Madala and Boehm, 2011), a large amount of research has been carried out to improve building performance (Halawa *et al.*, 2018). The focus areas of these studies are either building control systems or building design (Halawa *et al.*, 2018; Gan *et al.*, 2020), a large part of which is focused on building envelope design (Iwaro and Mwasha, 2013; Pučko, Maučec and Šuman, 2020).

Improving building energy efficiency requires a holistic approach instead of improvement in the individual aspects of building design (Gan *et al.*, 2020). When only a single aspect is improved, energy losses are moved from one source to another (Perino and Serra, 2015). This is aggravated by the enforcement of minimum requirements for fresh air. Because building design requires a holistic approach while maintaining adequate air quality, the philosophy of 'energy conservation' must adapt to a philosophy that accounts for heating, cooling, lighting, and plug loads. Thus, building performance should not only target a single parameter but multiple parameters. In addition to designing for energy efficiency, designers should also design for safety (Gunasekaran, Emani and Malini, 2010).

Strategies to improve building performance are classified as active or passive strategies (Loonen *et al.*, 2013). Active strategies are associated with the building's mechanical systems (Sadineni, Madala and Boehm, 2011). In addition to improving building performance, active strategies also focus on minimising building performance degradation (Crawford, 2010). Passive strategies are associated with the building's design (Kaur, Kaur and Aggarwal, 2017). The focus of building design is often building envelope design (Ünver *et al.*, 2003). This is because building envelope design establishes building performance while the operation and maintenance stage maintains building performance (Ünver *et al.*, 2003; Aksamija, 2016).

Passive design strategies require logical choices to be made regarding building design (Sandak *et al.*, 2019). These strategies are governed by six design principles: biomimicry principle, human vitality principle, ecosystem principle, seven generations principle, conservation principle, and holistic principle (Iwaro and Mwasha, 2013). It focuses on changing the design characteristics of the building envelope, including the window-to-wall ratio, glazing properties, presence of external shading, building geometry, building location, and insulation (Mirrahimi *et al.*, 2016; Heidari Matin and Eydgahi, 2019). Changes made to the design characteristics are investigated with field and simulation studies (Price and Smith, 1995; Chan and Chow, 1998; Balaras *et al.*, 2000; Cheung, Fuller and Luther, 2005).

The success of building passive design is influenced by building function, building systems, climate, and occupancy (Cena and De Dear, 2001; DeKay and Brown, 2013). Climate influences applicable passive design strategies, as not all solutions are appropriate for all climate regions (Halawa *et al.*, 2018). Although the internal heat sources of a building can contribute additional thermal loads, the building's indoor environment is largely dependent on climate (Krainer, 2008; Haggard *et al.*, 2009; Szokolay, 2014).

2.3.6 The Importance of Building Codes to Achieve Targeted Building Performance

Building energy codes are guidelines and regulations which a government mandates to achieve a certain degree of building performance, and shape building rating methodologies (Bartlett, Halverson and Shankle, 2003; Evans, Roshchanka and Graham, 2017; Crawley *et al.*, 2020; Eon *et al.*, 2020). The quality of building energy codes is dependent on the extent of regulation and how it compares to 'green building codes' (Meir *et al.*, 2012; Boostani and Hancer, 2018). As with EPCs, compliance with building energy codes can be achieved through either a prescriptive-based or performance-based approach (O'Brien *et al.*, 2020). Another similarity is that building codes measure building performance in different ways.

The success of the adoption of building energy codes depends on its enforcement and promotion through market and social campaigns (Sadineni, Madala and Boehm, 2011; Ade and Rehm, 2020). Enforcement is typically prescribed through energy directives (e.g. the European Union (EU) regulates building energy performance through the Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive (EED)) (European Parliament, 2010, 2012; Košir, 2016). Although building energy codes are mandated by governments, enforcement is often lacking (Lucon *et al.*, 2014). The lack of enforcement contributes to buildings displaying performance gaps (Eon *et al.*, 2020). Enforcement should require prescribing and monitoring energy performance (Košir, 2016). This requires building energy codes to prescribe and monitor construction processes, building equipment, commissioning and installing building systems, building performance, and quality assurance during building construction (Zero Carbon Hub, 2014a; McElroy and Rosenow, 2019; Eon *et al.*, 2020)

Building energy codes are typically developed around the climate and regional requirements for the regions developed (Safarova *et al.*, 2018; Shi and Liu, 2019). This approach is similar to EPCs which are region-specific (Sev, 2011; Berardi, 2012). Other regions' building energy codes are adopted if climate and regional requirements are considered similar (Sadineni, Madala and Boehm, 2011). Also, when regional building energy codes do not address all the required guidelines for building design, alternative building energy codes are adopted (Gunasekaran, Emani and T.P, 2010).

When the focus of studies is to improve building energy codes, improvements must consider several requirements (O'Brien *et al.*, 2020). First, additions and modifications to prescriptive requirements must be made based on suggestions and observations made in the literature. Second, prescriptive requirements should be added based on the outcomes of published simulation studies. Additional requirements are associated with occupant behaviour. To update occupancy schedules, field studies must be conducted, accounting for building typology and climate. Due to the simplicity of occupancy schedules currently contained within building energy codes, occupancy schedules should incorporate concepts from occupant models to increase complexity. Building energy codes should also require multiple occupancy schedules to minimise uncertainty and specify which modelling approach should be used for building simulation. Updating building codes is essential to improve existing building codes and contribute to green building development (Reed *et al.*, 2009).

2.4 Creating the Building's Artificial Interior Environment

2.4.1 Defining the Building's Interior Environment

The building environment can be divided into two levels (Košir, 2016). The first level addresses cultural and social perceptions, i.e. what building occupants expect from the environment they inhabit. The second level addresses occupants' psychological and physiological response, i.e. how does the human body react to changes in the environment they inhabit. The physiological of the building environment is investigated through five sub-environment: thermal, visual, olfactory, sonic, and ergonomic (Košir, 2016). Regarding the thermal sub-environment, occupancy satisfaction with regards to this sub-environment can be measured using index tools (e.g. Predicted Mean Vote (PMV) index) or thermal comfort models adapted by building standards (Fanger, 1984; ASHRAE, 2004; International Organization for Standardization, 2005; Al-ajmi, 2010; Andreasi, Lamberts and Cândido, 2010; Pohl, 2011; Rasooli and Itard, 2018; Cheung *et al.*, 2019). The importance of ensuring comfortable thermal conditions is coupled to the impact of the thermal sub-environment on occupant health and productivity (Heschong and Mahone, 2003a, 2003b; Sobocki *et al.*, 2006; Day and Gunderson, 2015).

Thermal comfort models require additional data capture as the parameters used to define building performance are different from those of thermal comfort parameters (Lotfabadi and Hançer, 2019). Data used for thermal comfort models include air temperature, relative humidity, mean radiant temperature, metabolic rate, clothing insulation level, and air temperature (Djongyang, Tchinda and Njomo, 2010; Cui *et al.*, 2013; Koranteng, Essel and Amos-abanyie, 2015). Due to the associated complexity of thermal comfort, the data required for thermal comfort models require dynamic thermal analysis (Barrios *et al.*, 2012).

2.4.2 Building Interior Environment Conditioning and Control

The building environment can be conditioned using natural ventilation, Heating, Ventilation, And Air Conditioning (HVAC) systems, or a mixture of both (Sandak *et al.*, 2019). Due to the relationship between the building environment and the building envelope, the building envelope is adjusted to change building environmental conditions (Košir, 2016). The building environment is controlled using extrinsic or intrinsic control measures (Loonen *et al.*, 2013; Sandak *et al.*, 2019). Extrinsic control measures rely on user input and feedback to adjust the building envelope (Teuffel, 2004). This requires collecting environmental information, processing the collected data, and adjusting the building envelope using the collected data (Sandak *et al.*, 2019). In contrast, intrinsic control measures rely on environmental triggers to self-adjust building envelope shape, volume, material phase, and colour (Teuffel, 2004; Sandak *et al.*, 2019). The success of these control measures is measured with user satisfaction (Loonen *et al.*, 2013).

When extrinsic control measures are automated, building automation systems monitor and control building envelope systems (European Parliament, 2010; Ippolito, Sanseverino and Zizzo, 2014). The objective of these automation systems is to control energy consumption and indoor temperatures, allowing for improved energy efficiency (Masoso and Grobler, 2010; Day and Gunderson, 2015; Košir, 2016).

The efficiency of non-automated extrinsic building control systems is determined by the usability of the control system (O'Brien *et al.*, 2020). Thus, when non-automated extrinsic building control systems are designed using building codes, the building code must provide requirements regarding how it is used, the interface, and feedback that should be provided to occupants.

2.5 Importance of the Building Envelope

2.5.1 Defining the Building Envelope

The building envelope can be defined as the façade of the building, the external surface, or the front surface of the building (Sandak *et al.*, 2019). It is the product of architectural ideas, economic considerations, and environmental conditions (Hegger *et al.*, 2008). Its design is divided into building design parameters and engineering parameters (Ghabra, Rodrigues and Oldfield, 2017). Building design parameters concern the building envelope's design and components, whereas engineering parameters concern the building envelope's properties and components (Baker and Steemers, 1996).

The building envelope acts as both a separation element and connector between the building interior and exterior (Bixby, 2009; Loonen *et al.*, 2013). When acting as a separator, the building envelope is designed to protect, control, and regulate the building environment (Institution of Structural Engineers (Great Britain), 1999; Herzog, Krippner and Lang, 2004) to create an artificial environment (Košir, 2016). Separation is achieved by focusing on the building's visual and building performance aspects (Heusler and Kadija, 2018). When mechanical systems work alongside the building envelope to regulate the artificial environment, a microclimate is created (Sandak *et al.*, 2019).

2.5.2 Functions of the Building Envelope

Although the primary goal of the building envelope is to maximise performance and minimise resource consumption (Aksamija, 2009), the functions of the building envelope can be viewed as subjective due to its function being based on the views of the building stakeholders (Halawa *et al.*, 2018). Whereas aesthetics are of more concern for architects, the functional performance can be of more concern for engineers (Zemella and Faraguna, 2014). The subjective view of building function is further influenced by the cultural influence, which can determine building envelope materials, construction techniques, building form, and building typology (Okafor *et al.*, 2017). Although subjective, the importance of building functions can be assessed using ranking techniques, (e.g. the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) technique (Akbari *et al.*, 2020)), which ranks the importance of building functions based on a set of criteria (Chen, 2000; Yang and Hung, 2007). High performing building envelopes should show high acoustical, thermal, visual, indoor air quality, building integrity, and special performance (Akbari *et al.*, 2020).

Considering the building envelope's definition, the building envelope's functions are seen as either separating or connecting the external and interior environment (Akbari *et al.*, 2020). When the building envelope functions as a separator, it should ensure occupant safety and privacy (Akbari *et al.*, 2020), prevent excessive noise levels, monitor climate and environmental impact, and regulate the internal environment to ensure the needs of the building occupants are satisfied (Loonen *et al.*, 2013). When the building envelope functions as a connector, it should satisfy visual needs, provide adequate air quality, and allow sufficient daylight (Akbari *et al.*, 2020). For the building envelope to act as a separator or connector, it must have structural integrity. Structural integrity is maintained by maintaining the building insulation, tightness, and waterproofing (Perino and Serra, 2015).

To perform the functions of the building envelope, passive strategies are often employed to satisfy the needs of the building occupants (Santamouris, 2006). Passive strategies allow the building envelope to perform the functions required to harvest air, light, and solar radiation from the environment (Kishnani, 2002; Santamouris, 2006).

When the building envelope is designed to ensure occupant comfort, it must regulate heat, light, and acoustics transfer with minimal energy consumption (Ünver *et al.*, 2003; Oral, Yener and Bayazit, 2004; Wong *et al.*, 2004). This requires maintaining adequate daylight levels, thermal comfort conditions, and minimising visual glare and building energy consumption resulting from lighting, heating, and cooling (Loonen *et al.*, 2014). Because thermal comfort conditions comprise multiple parameters, the building design must account for all thermal comfort parameters and the other occupant comfort factors (Lechner, 2008).

2.5.3 Classifying the Different Building Envelope Types

Building envelopes can be classified based on their design or functions (Halawa *et al.*, 2018). When defining a building envelope based on its functions, two types of building envelopes can be classified: a static building envelope and an adaptive building envelope (Loonen *et al.*, 2013; Heidari Matin and Eydgahi, 2019). Static building envelopes are associated with building envelopes that cannot adjust their performance as a function of time. Although specific building envelopes can be considered a high-performance building envelope, they are not adaptive, as exemplified by the buildings displayed in Figure 2.6. This is due to static building envelopes being designed with a pre-defined set of parameters (Sandak *et al.*, 2019). Adaptive building envelopes are used when static building envelopes are not flexible enough to meet the demands of high-performance buildings (Deplazes, 2013).

(a) (b)

Figure 2.6: (a) Waha Office Building (Riyadh, Saudi Arabia) (Al-Shehri and Omrania, no date) *(b) Department of Environmental Affairs (Pretoria, South Africa)* (Mott MacDonald, no date)

Adaptive building envelopes refer to building envelopes capable of adapting to changing conditions and requirements (Loonen *et al.*, 2013). Adaption is done through extrinsic or intrinsic means (Kroner, 1997). The building envelope must have the ability to record information, process data, and exercise control over the building envelope (Macías-Escrivá *et al.*, 2013). Adaption is possible by coupling the changes made to the building envelope to building performance (Crawford, 2010). Such behaviour can be observed for the building envelope of the Al Bahr Towers (see Figure 2.7 (a)) and 90 Rivonia office building (see Figure 2.7 (b)), which reacts to the sun. Changes made to the building envelope is done at the macro and micro scale (Loonen *et al.*, 2013). Macroscale refers to the building envelope configuration and design, whereas microscale refers to building envelope material properties (Horn *et al.*, 2000; Kurnitski *et al.*, 2004; Xu and Van Dessel, 2008; Kuznik *et al.*, 2011).

(a) (b)

Figure 2.7: (a) Al Bahr Towers (Abu Dhabi, United Arab Emirates) (ARUP, no date)*(b) 90 Rivonia Office Building (Sandton, South Africa)* (Redefine Properties, no date)

When adaption of the building envelope is performed using a technical system, the adaption of the building envelope is done through several technical system subsets (Böke, Knaack and Hemmerling, 2019). The technical system of the building envelope is responsible for transforming, storing, or transporting materials, energy, or information. Each technical system is made up of a cybernetic system, mechatronic system, and embedded system. The cybernetic system is representative of a closed-feedback circuit, which the system architect provides. The mechatronic system couples the building's mechanical and electronic systems, allowing the building envelope to respond to processed data. The embedded system is representative of the microcomputer, which controls the system.

The challenge of designing high performing adaptive building envelopes is designing for multi-functionality (Knaack *et al.*, 2015; Perino and Serra, 2015). Due to the number of parameters associated with the building envelope, many technical and practical problems still exist for adaptive building envelopes (Sandak *et al.*, 2019). As a result, regulations for adaptive building envelopes are non-existent.

2.5.4 The Importance of Local Climate in Building Envelope Design

As the building environment can depend on the local climate, continuous adaption must regulate heat, light, moisture, and dirt to the building (Sandak *et al.*, 2019). When a building envelope addresses a specific climate, a climate-based design is employed (Halawa *et al.*, 2018). Designing for a specific climate makes it possible to identify shortcomings with prescriptive designs of building envelopes (Ghabra, Rodrigues and Oldfield, 2017). The need for climate-based design is also highlighted by design techniques that were successful in past climate conditions, not replicating success for present climate conditions and occupancy comfort requirements (e.g. vernacular architecture) (Lotfabadi and Hançer, 2019).

Climate-based design requires the building envelope to be aesthetically pleasing, minimise the thermal exchange between adjacent environments, and reduce building energy consumption (Halawa *et al.*, 2018). In addition, climate-based design requires the building envelope to be robust and flexible (Loonen *et al.*, 2013). A robust design requires the building envelope to mitigate the impact of unwanted boundary conditions (Fricke and Schulz, 2005). In contrast, a flexible design requires the building envelope to adapt to future changes in boundary conditions (Olewnik *et al.*, 2004; Crawford, 2010).

Each climate can be designed for by optimising building orientation, surface area to volume ratio, shading, thermal insulation, glazing shape, glazing configuration, and temperature control strategies (Sandak *et al.*, 2019). The importance of glazing design is attributed to the importance of maximising solar heat gain during winter and limiting solar heat gain during summer (Perino and Serra, 2015).

2.5.5 Need for Collaboration During Building Design

Due to the interdisciplinary approach of building envelope design (Aksamija, 2013), collaboration is needed to ensure all the factors are considered and addressed during the building envelope design stage (Halawa *et al.*, 2018). Collaboration with building project owners is essential due to their influence on the construction of buildings (Diyana and Abidin, 2013). Successful collaboration ensures a smooth transition between building design and construction, and that buildings are energy efficient and sustainable (Kelly, 2009; Iwaro and Mwasha, 2013; Eriksson, 2017). It improves project costs, time management, project quality, environmental impact, the work environment, and innovation (Egan, 1998; Oyedele *et al.*, 2016; Matinaro and Liu, 2017).

2.5.6 Costs Associated With the Building Envelope

The costs associated with the building envelope comprises of initial, repair and maintenance, and operational costs (Stansfield, 2001; Ünver *et al.*, 2004; Brock, 2005). Although quality defects result in repair and maintenance costs, they also contribute to initial project costs (Alencastro, Fuertes and de Wilde, 2018). The costs associated with quality defects can be direct or indirect. Direct costs are costs related to rectification. Indirect costs are costs related to labour overhead costs.

Building costs during building design are estimated by performing an economic assessment of buildings using LCC analysis (Pučko, Maučec and Šuman, 2020). LCC estimates the cost of a building over its lifetime by estimating initial capital costs, operation and maintenance costs, and the building's residual value and its assets at the end of its life. By estimating the cost savings possible with different construction configurations, it is possible to determine an optimal design considering the main construction material, and the thickness and material of intended insulation (Kumar *et al.*, 2020). This is not restricted to a specific building typology but is used for residential and non-residential building design to develop cost-optimal thermal strategies. It can also be used to analyse the expected lifetime cost of constructed buildings, e.g. LCC was performed in low-income housing (Udawattha and Halwatura, 2017) (see Figure 2.8 (a)) and an office building (Elkhayat *et al.*, 2020) (see Figure 2.8 (b)) to compare the lifetime cost when adjusting building materials.

(a) (b)

Figure 2.8: (a) Residential buildings subjected to LCC in Sri Lanka (Udawattha and Halwatura, 2017) *(b) Office building subjected to LCC in Egypt* (Elkhayat *et al.*, 2020)

2.5.7 Defects in the Building Envelope

Defects in the building envelope account for most building defects (Lee and Tiong, 2007). To classify a part of the building as a defect, it must not achieve or perform to the level of performance it was designed for, and it must be located within the building structure or systems (Watt, 2009). If a defect is identified, it can be classified as either a design defect, quality defect, or lifetime defect (Alencastro, Fuertes and de Wilde, 2018). Consequences of these defects include the formation of heat bridges and passageways for air leakage and infiltration (Van Dronkelaar *et al.*, 2016; Alencastro, Fuertes and de Wilde, 2018; McElroy and Rosenow, 2019). In addition to its impact on building performance, defects can influence project costs, project delivery time, client satisfaction, industry reputation, and health and safety.

Defects result from an external party's action (Alencastro, Fuertes and de Wilde, 2018). The defects originate from change, error, omission, or damage (Barber *et al.*, 2000; Love and Li, 2000; Forcada *et al.*, 2013; Love and Edwards, 2013). Changing the established design requirements results in building defects due to change (Alencastro, Fuertes and de Wilde, 2018). Building defects that originate from an error refers to a defect due to a mismatch between performance and requirements. Omission refers to elements that are missing at any stage during the life cycle of a building. Damage refers to the physical modification of building elements that impact performance. The actions which result in defects can be attributed to human error, improper management, lack of planning, and poor inspection processes (Alencastro, Fuertes and de Wilde, 2018; Zou *et al.*, 2018).

Apart from identifying building defects, it is essential to understand the impact of the defect on the building (Alencastro, Fuertes and de Wilde, 2018). This is necessary to develop a prioritisation system for building defect repair. The level of detail which can be understood regarding building defects is dependent on the level of knowledge of the individual inspecting for defects (Sommerville, Craig and Bowden, 2004; Sommerville and McCosh, 2006; Auchterlounie, 2009). Investigations can focus on either specific parts of the building or the collective of a building's defects (Alencastro, Fuertes and de Wilde, 2018). Defects are defined by their attributes, causes, and impact on the building structure or system (Watt, 2009). Attributes of building defects include defect type, affected building element, defect origin, and the defect's responsible party (Alencastro, Fuertes and de Wilde, 2018). By isolating building elements, it is possible to associate common defect types with specific building elements. Although specific defects, such as cracks and gaps in the building fabric, are a common defect regardless of building element (see Figure 2.9 (a)), others are unique to specific building elements (Chong and Low, 2006). This is the case of delamination of flooring (see Figure 2.9 (b)), weathering of windows and doors, and poor (or lack of) thermal insulation in the roof.

(a) (b)

Figure 2.9: (a) Corner cracks in at the window of a residential home (Kasi, Mahar and Khan, 2018) (b) Delamination of a concrete floor (Eschenasy, 2014)

2.6 Components of the Building Envelope

2.6.1 Defining the Components of the Building Envelope

The building envelope does not refer to a single part of the building surface but is an umbrella term for the system of components and sub-systems, which makes up the building envelope (Perino and Serra, 2015; Böke, Knaack and Hemmerling, 2019). The building envelope is comprised of opaque or transparent components (Aksamija, 2013). Opaque building components refer to non-transparent building components (e.g. concrete and masonry). Transparent building components typically refers to glazing. However, the building components that may be integrated into a building are restricted by construction limits and material availability (Boostani and Hancer, 2018).

The walls and roof system of a building make up the building envelope. The walls of the building envelope can be categorised as wood-based, masonry-based, metal-based, or advanced (Sadineni, Madala and Boehm, 2011). In addition to construction limits and material availability, the choice of building wall depends on the functionality of the wall. This function can require building walls to restrict heat (e.g. lightweight concrete walls and ventilated walls) (Ciampi, Leccese and Tuoni, 2003; Al-Jabri *et al.*, 2005), or store heat for delayed-release (e.g. vegetative walls, Trombe walls, and Phase-Changing Material (PCMs)) (Sadineni, Madala and Boehm, 2011; Halawa *et al.*, 2018).

Roof systems can be categorised based on design style or material composition (Sadineni, Madala and Boehm, 2011). Roof systems can be categorised as masonry roofs, lightweight roofs, ventilated roofs, vaulted roof, solar-reflective roofs, green roofs, photovoltaic roofs, and thermally insulated roofs. Improvements towards thermal performance are targeted by applying passive cooling techniques (e.g. evapotranspiration), applying different coatings, planting a vegetation layer on top of a roof system, and designing roofs with a large thermal heat capacity (Lazzarin, Castellotti and Busato, 2005; Sadineni, Madala and Boehm, 2011). Although design techniques have been developed to improve the thermal performance of roof systems, its design philosophy remains focused on climate (Akbari, Levinson and Rainer, 2005; Sandak *et al.*, 2019). The choice of roof system is climate dependent, as well as design measures aimed towards improving the thermal performance of roof systems.

Although glazing was mainly used for aesthetic reasons in the past, it has transitioned into a structural building component (Gunasekaran, Emani and Malini, 2010). The thermal and solar performance of glazing is dependent on the type of glazing used (Ledbetter, Walker and Keiller, 2006). The structural and optical properties of the glazing are obtained from the creation and coating process of the glazing (Gunasekaran, Emani and Malini, 2010). In addition to the material properties, the level of performance provided by glazing is dependent on geometry, placement, and climate (Singh and Garg, 2009). Improvements towards thermal performance are targeted through advancements with the glazing and the structural glazing frame (Sadineni, Madala and Boehm, 2011). Advancements in glazing focus on improving the structural, thermal, and light transmission performance, whereas advancements in the structural glazing frame focus on minimising thermal bridges.

2.6.2 Functions of the Components of the Building Envelope

The functions of the building components serve as a measurement of performance for specific building components (Gunasekaran, Emani and Malini, 2010). Building components are designed to either perform one or more of the following functions (Brown and Ruberg, 2005): transmit and reflect solar radiation, transmit light, regulate thermal heat transfer, transmit sound, and withstand structural and thermal stress. Multifunctionality can require building components to limit their functionality (e.g.

glazing, which must provide sufficient daylight while simultaneously preventing glare and unwanted levels of solar heat gain) (Boubekri, 2008; Pohl, 2011).

2.6.3 Performance of the Components of the Building Envelope

Each component of the building envelope has its performance measured against a specific set of parameters. The thermal performance of opaque components is characterised by its U-value (Kaur, Kaur and Aggarwal, 2017). The thermal performance of glazing is characterised by its solar heat gain coefficient and U-value (Sadineni, Madala and Boehm, 2011; Kaur, Kaur and Aggarwal, 2017). The daylight performance of glazing is characterised by visible light transmittance. When looking at the collective, building thermal performance is expressed by the thermal transmittance, thermal resistance, thermal conductivity, and diffusivity of its materials (Derbal *et al.*, 2014)

Because building performance is coupled to the performance of its components, improving one results in improving the other (Iwaro and Mwasha, 2013). Maximising the performance of the building components is the result of parametric analysis (Manioğlu and Yılmaz, 2006), assessment methods (e.g. Simple Multi-Attribute Rating Technique (SMART) assessment method) (Boostani and Hancer, 2018), and technological improvements (Perino and Serra, 2015). This requires a focus on wall framing systems, insulation, building envelope colour, glazing, and shading devices (Stansfield, 2001; Cheung, Fuller and Luther, 2005; Elder, 2005).

2.7 Thermal Performance of the Building Envelope

2.7.1 Heat Transfer in Building Envelope

The building envelope gains heat from the external and internal environment due to convection and radiation (Raja *et al.*, 2001). Heat transfer through the building envelope is mainly through conduction (Boostani and Hancer, 2018). However, depending on the building envelope design, different heat transfer methods into the building environment are created (Sadineni, Madala and Boehm, 2011; Perino and Serra, 2015).

Heat transfer between the external and building environment is governed by the thermophysical properties of the building materials (Antonopoulos and Koronaki, 2000). Knowledge regarding the heat transfer mechanics of the building allows for climate-based design (Zrikem and Bilgen, 1986; Sharma *et al.*, 1989; Zalewski *et al.*, 1997, 2002; Jie *et al.*, 2007; Ji *et al.*, 2009). This knowledge also provides designers to anticipate the results of changes made to the thermophysical properties of materials (Balaji, Mani and Venkatarama Reddy, 2019).

2.7.2 Thermal Performance of the Building Envelope as an Area of Research

Although thermal performance can be viewed as separate from building performance, maximising efficiency requires investigating thermal performance (Kaur, Kaur and Aggarwal, 2017). This is because buildings consume a large amount of energy to meet thermal comfort demands (Nicol and Humphreys, 2002; Nicol, 2004; Ozay, 2005; CEN, 2007; Ferrari and Zanotto, 2012; Kumar *et al.*, 2019). Improving the thermal performance of the building envelope is done by improving the thermal properties of building envelope materials (e.g. increased thermal resistance, thermal capacity) or developing methods of reducing the thermal load on the building envelope (e.g. additional shading, and decreased exposed building envelope surface area, and buffer spaces in building envelopes) (Kaur, Kaur and Aggarwal, 2017). The research aims to propose design guidelines for various building typologies to minimize heat loss in winter and heat gain in summer (Huajin and Baohua, 2007).

Although thermal performance is studied through four areas: heat balance, thermal/energy efficiency, heat exchange efficiency, and Nusselt number (Wang, Shukla and Liu, 2017), methods used to study thermal performance vary. This not only applies to material properties but also to investigate the influence of building component integration. Some have examined the building envelope's dynamic thermal parameters by examining the building envelope's different parts (Antonopoulos and Koronaki, 2000). Others have studied both the steady-state and dynamic thermal parameters of the building envelope (Balaji, Mani and Venkatarama Reddy, 2019). Focusing on the material properties of the building envelope allows for general observations to be made regarding indoor thermal performance (Balaji, Mani and Venkatarama Reddy, 2019).

2.7.3 Thermal Properties of Building Components

The thermal properties of building materials can be classified as steady-state and dynamic (Balaji, Mani and Venkatarama Reddy, 2019). The thermal performance of a building cannot be described by steady-state thermal properties alone (Mohammad and Shea, 2013). This is because steady-state equations ignore dynamic processes affecting materials (Balaji, Mani and Venkatarama Reddy, 2019). Dynamic calculation methods capture these processes. Knowledge regarding the building envelope's various contributions towards dynamic performance is required for improved design measures during the building design stage (Antonopoulos and Koronaki, 2000).

Steady-state thermal properties are thermal conductivity, specific heat capacity, and density. These three properties can be used to calculate thermal transmittance, thermal diffusivity, thermal effectivity, and thermal mass. Dynamic thermal properties are the time lag, decrement factor, thermal admittance, decrement factor, surface factor, inside surface areal heat capacity, effective thermal capacitance, and a time constant (Antonopoulos and Koronaki, 1997; Asan, 1998; Balaji, Mani and Venkatarama Reddy, 2019). Dynamic thermal properties are calculated using analytical and numerical methods (Balaji, Mani and Venkatarama Reddy, 2019).

2.7.4 Measuring the Thermal Performance of Building Components

Building components' thermal performance can be measured either in situ or in a laboratory. Measurement methods are typically described under measurement standards (Andreotti *et al.*, 2020). Although methods to measure thermal characteristics exist, additional methods are still being researched (Lihakanga *et al.*, 2020).

Laboratory measurement methods include the hot-box method, heat flow method, infrared thermography, guarded hot plate method, guarded hot box method, calibrated hot box method, and calculation methods (International Organization for Standardization, 1994, 2007, 2014, 2018; Lucchi, 2018; Andreotti *et al.*, 2020). In-situ measurement methods include the heat flow method, infrared (IR) testing, and calculation methods (Antonopoulos and Koronaki, 2000; Sadineni, Madala and Boehm, 2011; International Organization for Standardization, 2018). However, research has shown that laboratory measurement methods can be adapted for in-situ measurement (Andreotti *et al.*, 2020). To measure the hygrothermal performance of building layers requires the use of direct (e.g. gravimetric analysis) or indirect methods (e.g. insertion of wooden dowels).

Careful consideration of the measurement method is required when thermal performance must be measured as the measurement methods are bound by their limitations. The heat flow method is used when constructions are composed of a homogenous material layer where heat flow is perpendicular to the surface (Lihakanga *et al.*, 2020). This method is, however, limited by the inability to collect data continuously and in real-time when done according to International Organization for Standardization (ISO) 6496 (Frei *et al.*, 2017; Márquez, Bohórquez and Melgar, 2017). This removes the possibility to observe and correct inconsistencies during measurements. In addition to accuracy concerns, the heat flow method's equipment is “bulky, hardwire”, and power-intensive. Calculation methods are limited by uncertainty regarding material property accuracy and the non-steady-state condition encountered in reality (International Organization for Standardization, 2007). The accuracy of IR is dependent on hardware limitations and environmental conditions (Kylili *et al.*, 2014; Fox, Goodhew and De Wilde, 2016). The adoption of IR is also hindered by its lack of integration with established platforms (Lihakanga *et al.*, 2020).

2.7.5 Role of Thermal Insulation in the Building Envelope

An easy strategy to improve the thermal performance of the building envelope, including roof systems, is to add thermal insulation to material layers (Sadineni, Madala and Boehm, 2011). Thermal insulation improves thermal performance by decreasing the effective thermal conductivity of a building component (Sadineni, Madala and Boehm, 2011). The thermal insulation material can be categorised into four different categories: inorganic, organic, metallic, and advanced (Al-Homoud, 2005; Papadopoulos, 2005). In addition to solid insulation material, certain gases are used as insulation in airspaces (Zhou and Chen, 2010; De Gracia *et al.*, 2015).

The choice of thermal insulation requires making a choice regarding insulation material, thickness, and location (Papadopoulos, 2005; Dylewski and Adamczyk, 2011; Jelle, 2011; Ozel, 2011; Kaynakli, 2012; Pacheco, Ordóñez and Martínez, 2012). The thermal insulation design influences thermal performance and influences the risk of surface condensation, flammability, and environmental impact (Aelenei and Henriques, 2008; Sadineni, Madala and Boehm, 2011). Preventing moisture penetration due to surface condensation is necessary to prevent degradation of material performance (Low, 1984).

When designing for improved thermal performance, factors influencing design is insulation positioning, insulation thickness, thermal properties of composite constructions, wall orientation, surface properties, and thermo-physical characteristics (Al-Regib and Zubair, 1995; Al-Sanea, 2000; Al-Sanea and Zedan, 2001, 2002; Ozel and Pihtili, 2007; Hall and Allinson, 2008; Ng, Low and Tioh, 2011; Ozel, 2011, 2012). When deciding on the insulation material, the insulation material's thermal inertia and thermal conductivity are considered the most critical factors towards thermal performance improvement (Sadineni, Madala and Boehm, 2011). Due to the influence of climate, design decisions related to insulation placement varies based on climate.

The thermal performance of insulation materials is researched by analysing the effective thermal capacitance, time constant, heat-loss coefficient, rate of temperature change, the amplitude of surface temperature, and influence of boundary conditions on temperature convergence of the building envelope (Antonopoulos and Koronaki, 2000). The optimal placement of insulation and insulation thickness is researched by analysing building performance in combination with economic models (Bolattürk, 2008).

2.8 Thermal Analysis Software as an Assessment Tool

2.8.1 Defining Building Performance Evaluation

Building performance evaluation is done through three methods: simulation studies, laboratory studies, and field studies (Hien *et al.*, 2005; Eicker *et al.*, 2008; Wong, Prasad and Behnia, 2008; Baldinelli, 2009; Chan *et al.*, 2009; Haase and Amato, 2009; Wei, Zhao and Chen, 2010). Field and laboratory studies are required to quantify building performance (Halawa *et al.*, 2018). The main drawback is that these studies often consider only a single aspect. In contrast, computer simulations can be used to investigate and validate improvements related to building performance by considering multiple aspects simultaneously (Wong *et al.*, 2003) and study the life cycle performance of a building (Jin *et al.*, 2019; Asatani *et al.*, 2020).

Building performance evaluation through simulation studies is performed by choosing a simulation software, deciding what the analysis's intended outcome will be, deciding upon which degree a building object will be analysed, and identifying the required inputs and outputs (Pang *et al.*, 2020).

Because the intended outcome of simulation studies is not always the same, specific software can be used to study single aspects of building performance (Sadineni, Madala and Boehm, 2011).

To simulate building energy performance, either simplified calculations or detailed dynamic simulation can be used (Kim, Yoon and Park, 2013). Although dynamic simulation can prove advantageous where a high level of control over the building simulation is required, simpler solution methods have proven to be capable of providing similar results to dynamic simulation software (Van der Veken *et al.*, 2004; Kim, Yoon and Park, 2013; Schito *et al.*, 2015) and only deviate slightly from the median when compared to a collection of dynamic simulation software (Magni *et al.*, 2021).

Successful application of simplified calculation methods on estimating the performance of low-energy buildings can be observed with the Passive House Planning Package (PHPP) tool. The PHPP tool is used to show compliance with the Passive House standard, a low energy building standard for residential and non-residential buildings (Passive House Institute, 2016). A review of the accuracy of the PHPP tool was presented by Johnston *et al.* (2020), comparing the average measured space heating demand of Passive House standard buildings against the design values calculated using the PHPP. The first part of the study considered three sets of settlements while the second part considered a case study of over 2000 newly built Passive Houses was considered. For the three settlements, the design value was within the uncertainty of the mean of the measured values. For the study considering over 2000 newly built Passive Houses, the average measured space heating demand fell within the range of uncertainty of the design values. Another study focused on 97 homes built in the United Kingdom according to the Passive House standard (Mitchell and Natarajan, 2020). The study concluded that when considering the average measured and average design space heating demand, a performance gap does not exist.

To comply with the building standards of South Africa to calculate design energy performance, only approved simulation software may be used (South African Bureau of Standards, 2011b). At the time of writing, three software products, all of which simulates building performance using dynamic simulation, were approved for use (Agrément South Africa, 2021), one of which is DesignBuilder which uses EnergyPlus as its energy simulation engine.

To improve upon existing energy simulation software at the time, the U.S. Department of Energy (DOE) started development of EnergyPlus in 1996 (U.S. Department of Energy, 2021). Collaboration on the project took place with the US Army Corps of Engineers’ Construction Engineering Research Laboratory (CERL), Lawrence Berkeley National Laboratory (LBNL), University of Illinois-Urbana Champaign (UIUC), Oklahoma State University (OSU), and GARD Analytics. The collaboration resulted in the release of EnergyPlus v.1 in 2001, a whole-building energy simulation engine which can be used to determine the energy performance of a building (U.S. Department of Energy, 2019a). The energy performance of buildings calculated by EnergyPlus is the sum of energy expenditure of HVAC equipment (e.g. cooling and heating loads for zone temperature to be maintained at specific temperatures) and electrical loads (e.g. lighting and plug loads).

EnergyPlus is based on the Building Loads Analysis and System Thermodynamics (BLAST) and DOE-2 programs (Crawley *et al.*, 2001). In contrast to the programs it is based on, EnergyPlus employs a modular structure which separates different aspects of building simulation into modules of code. The modular nature of EnergyPlus allows for specific aspects of simulation code (modules) to be changed without changing the code of other modules. The modules are responsible for simulating building loads influenced by weather, shading, building materials, adjacent building zones, HVAC systems etc. In addition to its modular nature, EnergyPlus simulates building zones, air handling systems, and central plant equipment simultaneously, rather than sequentially.

Because EnergyPlus is used as a simulation engine, a graphical user interface is not provided by the software. Instead third-party developers develop the graphical user interface for EnergyPlus. One such third-party developer is DesignBuilder (DesignBuilder Software Ltd, 2020). DesignBuilder software provides an easy-to-use graphical user interface for data input (DesignBuilder Software Ltd, 2018). The graphical user interface is supported by a range of modules which fulfil specific roles (DesignBuilder Software Ltd, 2021). These modules are related to data entry, visualisation, certification, simulation, daylight assessment, cost analysis, optimisation, and scripting. Depending on the need of the user, only specific modules are required for usage. A simplified validation analysis of DesignBuilder is reported in Appendix A.

2.8.2 The Accuracy of Building Performance Simulation

Although the accuracy of building performance simulation (BPS) is constantly improving due to advances in building simulation (Loonen *et al.*, 2014), simulation inaccuracies remain. Simulation inaccuracies can be attributed to building performance requirements, the accuracy of input data, user knowledge and skill, the chosen calculation method, and the ability of the BPS to simulate a given problem (Rittelmann and Ahmed, 1985; Judkoff and Neymark, 1995a, 1995b; Guyon, 1997; Karlsson, Rohdin and Persson, 2007; Judkoff *et al.*, 2008; Kalema *et al.*, 2008; Brohus *et al.*, 2009; Newsham, Mancini and Birt, 2009; Radhi, 2009; Raslan and Davies, 2010; John, 2010; Maile *et al.*, 2010; Yildiz and Arsan, 2011; Wang, Mathew and Pang, 2012; Sun *et al.*, 2014; Barthelmes *et al.*, 2017; Soares *et al.*, 2017). Although not contributing towards the accuracy of simulation output, the user-interface also influences simulation output as it contributes towards the ease-of-use of building simulation software (Mahdavi, 2020).

Input data for building simulation consists of building thermo-physical characteristics, climate, and occupant behaviour (Crawley *et al.*, 2020). Due to the computational time accompanied by simulation inputs, a balance between providing sufficient input for accurate building simulation and using minimal computational resources is needed (Pang *et al.*, 2020). A large amount of inputs also makes it challenging to identify which are more critical (Ricco, Rigoni and Turco, 2013; Tian, 2013; Pang and O'Neill, 2018), but too few inputs may result in omitting important inputs (Pang *et al.*, 2020).

The selection of simulation inputs is made difficult by its subjective nature (Fu *et al.*, 2016; Chong and Menberg, 2018; Gou *et al.*, 2018). Choices must be made regarding the base value and input range (Brembilla, Hopfe and Mardaljevic, 2018). Choices must also be made regarding how simulation output is expressed (Schwartz and Raslan, 2013), as the output determines how building performance is reported. To aid with selecting simulation input, case studies are typically analysed to identify which parameters are used together (Pang *et al.*, 2020). Design standards and measured data are also used to guide simulation input (de Wilde and Tian, 2009; Bre *et al.*, 2016). If the input aid is not available, software, specifically made to provide simulation input, is used (Boostani and Hancer, 2018).

When measured data is used for simulation input, the data is considered primary or secondary (Okafor and Onyegiri, 2019). Primary data is captured from the study location, whereas secondary data is captured from places in the study location's vicinity. Resistance to data capturing is due to it being complex, labour intensive, and does not guarantee increased simulation accuracy (Chapman, 1991; Gratzl-Michlmair, Graf and Goerth, 2012). If the accuracy of inputs of simulation models require testing, physical prototypes are developed to ensure the building simulation is modelled accurately (Crawford, 2010).

The accuracy of building performance simulation is improved through calibration (Huerto-Cardenas *et al.*, 2020). Calibration consists of adjusting the simulation inputs and minimising the difference between simulated building performance and measured building performance (Oberkampf and Roy, 2011; De Wilde, 2018).

2.8.3 Validating Predicted Performance

Building simulation models are considered valid when they adhere to the requirements of specific guidelines (ANSI/ASHRAE, 2002; FEMP, 2008, 2015; Efficiency Valuation Organization, 2012). This requires comparing simulated and measured building performance (ANSI/ASHRAE, 2002; Oberkampf and Trucano, 2002; Efficiency Valuation Organization, 2012; Baharvand *et al.*, 2013; FEMP, 2015). In the absence of technical guidelines, statistical indices are used for model validation (Cornaro *et al.*, 2019). Although similar to model calibration, model validation is different based on its primary objective (Shi *et al.*, 2019). The primary aim of research on model validation is to understand and reduce the performance gap. The primary aim of research on model calibration is to improve model accuracy and reliability. Building simulation is, however, not only used to minimise the performance gap, but is also used to assess possible building damage, contribute toward building code expansion, and stimulate building practice innovation (Huerto-Cardenas *et al.*, 2020).

Although standardised methods are absent for model validation using environmental parameters (Huerto-Cardenas *et al.*, 2020), it benefits from having data capturing methods that are widely available and accurate (CEN, 2010, 2012). Environmental parameters considered during validation is dry-bulb air temperature, surface temperature, relative humidity, absolute humidity, specific humidity, mixing ratio, and vapour pressure (Huerto-Cardenas *et al.*, 2020). Although model validation can be performed with few environmental parameters, complete model validation is only possible if all the environmental parameters are used during model validation (Coelho, Silva and Henriques, 2018). Ten statistical indices can be used for model validation (Huerto-Cardenas *et al.*, 2020): percentage error-index, Mean Bias Error (MBE), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Normalised Mean Bias Error (NMBE), Coefficient of Variation of the RMSE (CVRMSE), Normalised RMSE (NRMSE), Pearson correlation coefficient (r), coefficient of determination (R^2), and Inequality Coefficient (IC).

When building performance is measured by energy performance, measurements are provided by utility bills or energy meters (Shi *et al.*, 2019). The quality of measurements is partially determined by their time resolution (Crawley *et al.*, 2020). If the time resolution is not small enough, data must be modified or padded to match simulation data. The quality of measured data is also dependent on the independence of the data source, as this may influence bias (Halawa *et al.*, 2018).

2.8.4 Occupancy as a Parameter Input

Occupants are rarely addressed in building energy codes (O'Brien *et al.*, 2020) due to the complexity of occupants' perceptual and behavioural processes (Wagner, O'Brien and Dong, 2018). The complexity is attributed to the number of factors influencing occupancy (Yan *et al.*, 2015). The influencing factors are the parameters associated with thermal comfort, visual comfort, acoustic comfort, the air quality of their environment, water consumption, and movement according to job type (Andrews *et al.*, 2011; Lee, 2013; Linkola, Andrews and Schuetze, 2013; Alfakara and Croxford, 2014; Langevin, Wen and Gurian, 2014; Lee and Malkawi, 2014; Thomas, Menassa and Kamat, 2016; Barakat and Khoury, 2016; Schaumann *et al.*, 2017; Jia *et al.*, 2017, 2018, 2019). Although complex, accurate occupancy modelling is necessary to improve building performance as improvements towards the building envelope has reached a steady state (Hoes *et al.*, 2009; Fouquet and Pearson, 2012; Hafer, 2017). Improvements towards improving occupancy modelling are also needed to decrease the performance gap of buildings (Van Dronkelaar *et al.*, 2016).

Because of the associated complexity, building codes treat occupancy in a simplistic manner (O'Brien *et al.*, 2020). When comparing the occupancy model provided by building codes, they differ by occupancy values, degree of simplicity, acknowledgement of the occupants' role towards achieving energy efficiency, and the extent to which occupancy discussed. These differences can be grouped so that how building codes treat occupant behaviour is defined by one of five methods: 1. Building systems are not used by occupants, 2. Building systems are partially used by occupants, 3. Building systems that can be used by occupants are acknowledged, 4. Occupancy schedules and densities are provided, and 5. Rule-based assumptions regarding occupant behaviour are provided. In addition to building codes, occupancy data can be obtained by extracting occupant behaviour from surveys or performing statistical analysis on available occupancy data (Mora, Carpino and De Simone, 2018).

Improving how building codes approach occupancy modelling is a three-step process (O'Brien *et al.*, 2020). First, field studies should be conducted to collect occupancy data which could be used to update code schedules and develop occupant models. The second step requires field and simulation studies to be performed to confirm the accuracy of updated code schedules, models, and effectiveness of user-orientated building system requirements. Finally, a committee must be established to review the aspects of building codes and provide up to date requirements.

2.8.5 The Importance of Sensitivity Analysis in Building Simulation

Sensitivity analysis with advanced building software is used for model simplification, model-based optimisation, model calibration, model error diagnoses, and quantification of input-output relationship (Iooss and Lemaître, 2015; Menberg, Heo and Choudhary, 2016). A building performance analysis using sensitivity analysis consists of two parts: setting up the sensitivity analysis and setting up the building performance analysis (Pang *et al.*, 2020). The sampling and sensitivity analysis method is defined by their computational efficiency and modelling accuracy (Iooss and Lemaître, 2015; Pianosi *et al.*, 2016).

Uncertainties of the input or output are classified as aleatory or epistemic (Helton *et al.*, 2006; Eldred, Swiler and Tang, 2011; Hansen, Helton and Sallaberry, 2012). Aleatory uncertainty is associated with uncertainty resulting from the randomness of the input (Pang *et al.*, 2020). Epistemic uncertainty is associated with uncertainty due to a lack of knowing what the actual value is. Uncertainty can be integrated into models using either analytical propagation techniques, approximation techniques, or numerical propagation techniques (Mokhtari and Frey, 2005).

The sensitivity analysis consists of choosing which sampling method and sensitivity analysis method will be used, which input will be subject to sensitivity analysis, which tool will be used to perform sensitivity analysis, and how long will sensitivity analysis be carried out (Pang *et al.*, 2020). The analysis process is carried out over three steps. The first step requires creating a baseline model. The second step requires adding uncertainties to the baseline model. The last step requires collecting model inputs and outputs for model calibration.

The number of model evaluations required for sensitivity analysis is dependent on the inputs of the sensitivity analysis (Pang *et al.*, 2020). Because input parameters may be coupled (Shen *et al.*, 2019; Wang *et al.*, 2019), no standard value can be prescribed for the number of model evaluations required for sensitivity analysis (Xu and Gertner, 2011; Pudleiner and Colton, 2015). This also implies that the model is limited by its configurations and conditions (Ghabra, Rodrigues and Oldfield, 2017; Huang *et al.*, 2018). Because using a single sensitivity analysis method may result in the important parameter being left unidentified, it is suggested that multiple sensitivity analysis methods are used during sensitivity analysis (Pang *et al.*, 2020). Doing so will allow methods to validate, reject, or reinforce findings.

In addition to the subjective nature of choosing the number of model evaluations required for sensitivity analysis, modellers must also choose a sampling method that they consider the most appropriate (Pang *et al.*, 2020). This is due to the number of sampling methods available for sensitivity analysis.

When sensitivity analysis is used for building performance optimisation, a two-step process is followed (Gan *et al.*, 2020). The first step requires assessing the goodness of fit of building performance results. The second step requires identifying alternative design solutions. Alternative design solutions are identified by applying search algorithms to design variables that characterise building features. By changing the design variables, the impact of these variables on building performance can be observed (Crawford, 2010). Building performance optimisation is performed by identifying alternative designs and performing sensitivity analysis on ventilation control strategies (Pang *et al.*, 2020).

2.9 Comparing Heat-Only and Hygrothermal Studies

2.9.1 Presenting the Need Hygrothermal Analysis

Hygrothermal analysis is used to quantify building damage (Camuffo, 2014) and provide an overview of the environmental parameters of a building (Lucchi *et al.*, 2019). Quantification of building damage is necessary to avoid inaccurate assessment of building material properties (Bliuc *et al.*, 2017) and identify building damage that may negatively impact occupants' health (Boostani and Hancer, 2018). Obtaining a complete overview of a building’s environment is necessary to accurately assess thermal comfort (Yu *et al.*, 2019)

The modelling of moisture presence in building simulations can be modelled using different analysis methods. The choice of analysis method is subjective due to specific analysis methods prioritising computational efficiency over accuracy (Ascione *et al.*, 2016). Specific analysis methods only account for moisture presence in the air (e.g. Conduction Transfer Function (CTF) and conduction finite difference), while other analysis methods include moisture presence in building constructions (e.g. Combined Heat and Moisture Transfer (HAMT) and Effective Moisture Penetration Depth (EMPD)) (Yang, Fu and Qin, 2015; Damle and Rawal, 2019; Yu *et al.*, 2019). The complexity of hygrothermal models is due to the physical processes and the additional material properties needed to account for the influence of moisture on thermal transfer (Damle and Rawal, 2019; Mellado Mascaraque *et al.*, 2020).

To ensure the industry adopts hygrothermal analysis tools, it must fulfil specific requirements. These requirements ask that hygrothermal analysis tools should be easy to use, the software should be capable of simulating the physics associated with hygrothermal material behaviour, the software should have an integrated material property database, and the software should be capable of modelling hygrothermal environmental loads through building constructions (Karagiozis, Künzel and Holm, 2014).

2.9.2 Research Areas of Hygrothermal Performance of Buildings

Hygrothermal analysis research focuses on material behaviour (Tariku, Kumaran and Fazio, 2010; Maia *et al.*, 2015) and building performance (Pasztory *et al.*, 2012). When building design is the subject of hygrothermal analysis, two types of studies can be performed. The first type focuses on the building performance (Mahattanatawe and Charuchaimontri, 2015), either considering only a single or parametric model. The second type focuses on the comparison of analysis methods, comparing the accuracy and best application usage (Yang, Fu and Qin, 2015). But because hygrothermal behaviour is dependent on environmental conditions, conclusions regarding building performance are only valid for the regions investigated (Mascaraque, Pascual and Oteiza, 2020). Conclusions can be made regarding average and peak temperature, relative humidity, cooling, and heating values. Regarding accuracy in the different climate regions, a summary of the conclusions made by (Yang, Fu and Qin, 2015) is presented in Table 2.2. The table shows the heat transfer solution method which will provide simulated variables with higher accuracy compared to other heat transfer solution methods, e.g. simulating air temperature was found to be more accurate in a hot/humid climate using the HAMT heat transfer solution method.

Table 2.2: Optimal Heat Transfer Solution Methods for Different Climates (based on the work of (Yang, Fu and Qin, 2015)*)*

Variable	Hot/Humid	Temperate	Hot/Dry
Air Temperature	HAMT	HAMT	CTF
Relative Humidity	HAMT	HAMT	CTF
Peak Cooling Loads	CTF	HAMT	CTF

Studies that consider climate with humidity fluctuations, however, share similar conclusions regarding material behaviour. When hygroscopic building materials are exposed to environments with fluctuating humidity, the material serves as a moisture buffer (Qin *et al.*, 2009). Thus, humidity fluctuations are regulated, and humidification/dehumidification demand during building occupation is decreased (Allinson and Hall, 2010). This results in a change in cooling and heating peak demand and energy consumption when comparing CTF and HAMT analysis methods (Moon, Ryu and Kim, 2014). This is apparent for both sensible and latent cooling/heating (Yu *et al.*, 2019). The moisture buffering effect of materials is more prominent in models where mechanical conditioning is absent (Qin *et al.*, 2011).

Because hygrothermal analysis requires multiple inputs when performed with advanced building software, calibration is possible with a sensitivity analysis (Spitz *et al.*, 2013). When performing sensitivity analysis, changes are made to material properties, the number of surfaces with hygroscopic material layer, ventilation strategy, material thickness, the initial moisture content of hygroscopic materials, climate (Damle and Rawal, 2019; Mascaraque, Pascual and Oteiza, 2020). When boundary condition is kept the same, sensitivity analysis with hygrothermal modelling shows that temperature changes are influenced by parameters related to heat flow. In contrast, relative humidity changes are influenced by parameters related to room air (Spitz *et al.*, 2013).

Validation of hygrothermal models are performed by either comparing measured and simulated results (Allinson and Hall, 2010; Qin *et al.*, 2011; Liu *et al.*, 2013; Moon, Ryu and Kim, 2014; Goffart, Rabouille and Mendes, 2017), replicating experimental results (Yang, Fu and Qin, 2015), or replicating benchmark tests (Qin *et al.*, 2009; Liu *et al.*, 2015). Benchmarks can be analytical, numerical, or experimental in literature (Tariku, Kumaran and Fazio, 2010; Damle and Rawal, 2019).

2.10 Heat Balance Across the Building Envelope

EnergyPlus performs heat balance on the building envelope for the outside and inside surface. The construction of the heat balance at the outside and inside surface of building constructions is described in the EnergyPlus Engineering Reference Manual (U.S. Department of Energy, 2016a). The heat balance on the outside face of the construction is calculated using Equation 2.1.

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0 \qquad 2.1$$

From inspection, the heat balance on the outside face of any construction is composed of the shortwave radiation absorbed by the construction (both direct and diffuse), the longwave radiation heat exchange between the environment and the outside surface of the construction, the convective heat exchange between the outside air and outside surface of the construction, as well as the amount of heat conducted into the construction.

The heat balance on the inside face of the construction is calculated using Equation 2.2.

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \qquad 2.2$$

From inspection, the heat balance on the inside face of any construction is composed of the longwave radiation heat exchange between the inside surface of the construction and other interior surfaces as well as internal sources of longwave radiation, the shortwave radiation absorbed by the construction originating from lights and the sun, the convective heat exchange between the inside air and inside surface of the construction, as well as the amount of heat conducted from the outside surface of the construction.

2.10.1 External Shortwave Radiation

The shortwave radiation absorbed by the outside surface of any construction is calculated using Equation 2.3.

$$\mathrm{q}''_{\alpha\mathrm{sol}} = \alpha \cdot \left(I_b \cdot cos\theta \cdot \frac{A_s}{A} + I_s \cdot F_{ss} + I_g \cdot F_{sg} \right) \qquad 2.3$$

Where

$$F_{ss} = \frac{1 + cos\Sigma}{2} \qquad 2.4$$

$$F_{sg} = \frac{1 - cos\Sigma}{2} \qquad 2.5$$

Where ∑ is the surface tilt angle. The external shortwave radiation absorbed by the construction's outside surface is divided into three parts: direct solar radiation, diffuse solar radiation, and reflected diffuse solar radiation. The amount of solar radiation absorbed by the outside surface due to direct solar radiation is the product of the intensity of direct solar radiation, cosine angle of incidence of the sun’s rays, ratio of surface area to the sunlit surface area, and the solar absorptance property of the surface material. The amount of solar radiation absorbed by the outside surface due to sky diffuse radiation is the product of the intensity of sky diffuse radiation, cosine angle of the surface tilt angle, and solar absorptance property of the surface material. The amount of solar radiation absorbed by the outside surface due to reflected diffuse radiation is the product of the intensity of reflected diffuse radiation, cosine angle of the surface tilt angle, and solar absorptance property of the surface material.

2.10.2 External Convective Heat Exchange

The external convective heat exchange between the outside surface and outside air is calculated using Equation 2.6.

$$Q_c = h_c A (T_{surf} - T_{air}) \qquad 2.6$$

Although a selection of methods is available to calculate the exterior convective heat transfer coefficient, the default method employed by DesignBuilder is the DOE-2 Model. The DOE-2 Model is a combination of two previously developed models. The model calculates the exterior convective heat transfer coefficient for either a smooth (Equation 2.7) or uneven surface (Equation 2.8).

$$h_{c,glass} = \sqrt{h_n^2 + \left[aV_z^b \right]^2} \qquad 2.7$$

$$h_c = h_n + R_f \left(h_{c,glass} - h_n \right) \qquad 2.8$$

The natural convective heat transfer coefficient is dependent on temperature difference and surface tilt angle. A summary of the equations and conditions used to calculate the natural convective heat transfer coefficient is presented in Table 2.3.

Table 2.3: Natural convective heat transfer coefficient equations and conditions

Equation		ΔT	Surface Orientation
$h_n = 1.31\lvert\Delta T\rvert^{\frac{1}{3}}$	2.9	-	Vertical
$h_n = \frac{9.482\lvert\Delta T\rvert^{\frac{1}{3}}}{7.283-\lvert cos\sum\rvert}$	2.10	< 0	Upward Facing
		> 0	Downward Facing
$h_n = \frac{1.81\lvert\Delta T\rvert^{\frac{1}{3}}}{1.382+\lvert cos\sum\rvert}$	2.11	> 0	Upward Facing
		< 0	Downward Facing

2.10.3 External Longwave Radiation

The external longwave radiation exchanged between the outside surface and ground, sky, and the air is calculated using Equation 2.12.

$$q''_{LWR} = q''_{gnd} + q''_{sky} + q''_{air} \qquad 2.12$$

The three components of the external longwave radiation are solar radiation exchanged between the outside surface and ground, outside surface and sky, and outside surface and air. The Stefan-Boltzmann Law is applied to Equation 2.12 so that the external longwave radiation exchange is a function of the longwave emittance of the outside surface, Stefan-Boltzmann constant, view factors of radiation sources and temperature values of the outside surface, ground, sky, and air, resulting in Equation 2.13

$$q''_{LWR} = \varepsilon\sigma F_{ground}\left(T_{gnd}^4 - T_{surf}^4\right) + \varepsilon\sigma F_{sky}\left(T_{sky}^4 - T_{surf}^4\right) + \varepsilon\sigma F_{air}\left(T_{air}^4 - T_{surf}^4\right) \qquad 2.13$$

The view factor of the ground, sky, and air are calculated using Equations 2.14 to 2.16, with the view factor for the sky and air split by Equation 2.17.

$$F_{ground} = 0.5(1 - cos\sum) \qquad 2.14$$

$$F_{sky} = 0.5 \times \beta(1 + cos\sum) \qquad 2.15$$

$$F_{air} = 0.5(1 - \beta)(1 + cos\sum) \qquad 2.16$$

$$\beta = \sqrt{0.5(1 + cos\sum)} \qquad 2.17$$

If surrounding surfaces are also included in external longwave radiation calculations, an additional term is introduced, presented in Equation 2.18.

$$q''_{LWR} = \varepsilon\sigma\sum_{i=1}^{n} F_i\left(T_i^4 - T_{surf}^4\right) \qquad 2.18$$

Where F_i is the view factor of surrounding surface i, and T_i is the surface temperature of surrounding surface i.

2.10.4 Internal Longwave and Shortwave Radiation

The longwave radiation absorbed by the inside surface of any construction is calculated using Equation 2.19.

$$q''_{LWXij} = A_i F_{i,j}\left(T_i^4 - T_j^4\right) \qquad 2.19$$

Where i is the inside surface, j is a second surface, q"$_{LWXi}$ is the longwave radiation exchange between the two surfaces, A is the surface area, F is the view factor between the two surfaces, T is the surface temperature.

Due to the associated complexity of calculating the distribution of interior shortwave radiation and longwave radiation from internal sources, its calculation is not expanded here. Its calculation is fully explained in the Engineering Reference Manual and InputOutput Manual of EnergyPlus (U.S. Department of Energy, 2016a, 2016b).

2.10.5 Internal Convective Heat Exchange

The internal convective heat exchange between the inside surface and inside air is calculated using Equation 2.20.

$$q''_{conv} = h_c\left(T_{surf} - T_{air}\right) \qquad 2.20$$

Similar to the external convective heat exchange, although a selection of methods is available to calculate the interior convective heat transfer coefficient, the default method employed by DesignBuilder is the Thermal Analysis Research Program (TARP) Model. The TARP model correlates the convective heat transfer coefficient of a surface to the surface orientation and temperature difference between the surface and air temperature. The interior convective heat transfer coefficient is calculated using Equation 2.9 - 2.11.

2.10.6 Conduction Heat Transfer

Heat transfer through the building envelope can be calculated using a heat-only solution or a coupled heat-and-moisture solution method. The most common heat-only heat transfer method available in EnergyPlus is the CTF method, based on the work of (Seem, 1987). The most common coupled heat-and-moisture solution method available in EnergyPlus is the HAMT method, based on the work of (Künzel, 1995).

2.10.6.1CTF Model

The CTF is a transformation of the response factor equation in which the higher-order terms are replaced with flux history terms. An example of the conduction heat flux of the outside face calculated with the response factor formulation is presented in Equation 2.21.

$$q''_{ko}(t) = \sum_{j=0}^{\infty} X_j T_{o,t-j\delta} - \sum_{j=0}^{\infty} Y_j T_{i,t-j\delta} \qquad 2.21$$

Where δ is the time step. The transformation of the response factor equation results in two equations, Equations 2.22 and 2.23, which calculates the conduction heat flux on the inside and outside face of the construction.

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta} \qquad 2.22$$

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,t-j\delta} \qquad 2.23$$

The state-space method is employed to solve the heat flux coefficients in Equations 2.22 and 2.23. The basic formulation of the state space method is presented in Equations 2.24 and 2.25.

$$\frac{d[\boldsymbol{x}]}{dt} = [\boldsymbol{A}][\boldsymbol{x}] + [\boldsymbol{B}][\boldsymbol{u}] \qquad 2.24$$

$$[\boldsymbol{y}] = [\boldsymbol{C}][\boldsymbol{x}] + [\boldsymbol{D}][\boldsymbol{u}] \qquad 2.25$$

After applying a series of transformations to Equations 2.24 and 2.25, summarised in the Engineering Reference Manual (U.S. Department of Energy, 2016a), the final state-space formulation is created. The final state space method equations are presented in Equations 2.26 and 2.27. These two equations are used to calculate the conduction heat flux on the inside and outside face of the construction.

$$\frac{d\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix}}{dt} = [\boldsymbol{A}]\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} + [\boldsymbol{B}]\begin{bmatrix} T_i \\ T_o \end{bmatrix} \qquad 2.26$$

$$\begin{bmatrix} q''_i \\ q''_o \end{bmatrix} = [\boldsymbol{C}]\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} + [\boldsymbol{D}]\begin{bmatrix} T_i \\ T_o \end{bmatrix} \qquad 2.27$$

Where q”$_i$ and q”$_o$ are the heat flux across the interior and exterior surface of a wall.

2.10.6.2HAMT Model

The HAMT Model is a one-dimensional, finite element solution algorithm. The model can simulate the movement and storage of heat moisture to and from the environments to which the outside and the inside face of the construction are exposed. The heat and moisture balance equations used to calculate the transfer and storage of heat and moisture are presented in Equations 2.28 and 2.29.

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k^w \frac{\partial T}{\partial x}\right) + h_v \frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial T}{\partial x}\right) \qquad 2.28$$

$$\frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial \tau} = \frac{\partial}{\partial x}\left(D^w \frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial T}{\partial x}\right) \qquad 2.29$$

The vapour diffusion coefficient is calculated by Equation 2.30, and the moisture dependent heat storage capacity is calculated by Equation 2.31.

$$\delta = \frac{(2 \times 10^{-7} \times (T + 273.15)^{0.81})}{P_{ambient}} \qquad 2.30$$

$$\frac{\partial H}{\partial T} = c\rho + c^w w \qquad 2.31$$

The heat balance equation consists of three parts: the heat storage of a material ($\frac{\partial \mathrm{H}}{\partial \mathrm{T}}\frac{\partial \mathrm{T}}{\partial \tau}$), the heat transport through a material ($\frac{\partial}{\partial \mathrm{x}}\left(\mathrm{k^w}\frac{\partial \mathrm{T}}{\partial \mathrm{x}}\right)$), and the heat generation within a material ($\mathrm{h_v}\frac{\partial}{\partial \mathrm{x}}(\frac{\delta}{\mu}\frac{\partial \mathrm{T}}{\partial \mathrm{x}})$). Similarly, the moisture balance equation consists of three parts: the moisture storage of a material

$(\frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial \tau})$, the liquid moisture transport through a material $(\frac{\partial}{\partial x}\left(D^{w}\frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial x}\right))$, and vapour moisture transport through a material $(\frac{\partial}{\partial x}(\frac{\delta}{\mu}\frac{\partial T}{\partial x}))$.

Equation 2.28 can be applied to the construction to calculate the heat storage, heat transport, and heat generation of a cell within a construction. Rewriting Equation 2.28 in such a manner results in Equation 2.32.

$$(c_i\rho_i + c^w w_i)\Delta V_i \frac{T_i^{p+1}-T_i^{p}}{\Delta\tau} = \sum_j k_{ij}^{w} A_{ij}\frac{T_j^{p+1}-T_i^{p+1}}{x_{ij}} + \sum_j h_v \frac{\delta_{ij}}{\mu_{ij}} A_{ij}\frac{P_j^{p+1}-pP_i^{p+1}}{x_{ij}} \tag{2.32}$$

The heat generation can be rewritten as the heat generation due to heat of vaporisation or condensation, calculated by Equation 2.33.

$$q_i^{v} = \sum_j h_v \frac{\delta_{ij}}{\mu_{ij}} A_{ij}\frac{P_j^{p+1}-P_i^{p+1}}{x_{ij}} \tag{2.33}$$

To calculate the temperature of cell i at the next time step, Equation 2.32 can be rewritten as Equation 2.34 to make the aforementioned the subject of the equation and introducing three additional terms: the thermal Heat capacitance of a cell, C^h (calculated using Equation 2.35), the thermal resistance between two cells, R^h (calculated using Equation 2.36), and additional sources of heats at the surface, q^{adds}. Equation 2.34 is solved using the Gauss-Seidel iteration technique, with the temperature difference threshold set at 0.002°C.

$$T_i^{p+1} = \frac{\sum_j \frac{T_j^{p+1}}{R_{ij}^{h}} + q_i^{v} + q_i^{adds} + C_i^{h}\frac{T_i^{p}}{\Delta\tau}}{\frac{C_i^{h}}{\Delta\tau} + \sum_j \frac{1}{R_{ij}^{h}}} \tag{2.34}$$

$$C_i^{h} = (c_i\rho_i + c^w w_i)\Delta V_i \tag{2.35}$$

$$R_{ij}^{h} = \frac{x_{ij}}{k_{ij}A_{ij}} \tag{2.36}$$

Equation 2.29 can also be applied to the construction to calculate the moisture storage, liquid moisture transport, and vapour moisture transport of a cell within a construction. Rewriting Equation 2.29 in such a manner results in Equation 2.37.

$$\frac{dw}{d\phi_i}\Delta V_i \frac{\phi_i^{p+1}-\phi_i^{p}}{\Delta\tau} = \sum_j k_{ij}A_{ij}\frac{\phi_j^{p+1}-\phi_i^{p+1}}{x_{ij}} + \sum_j \frac{\delta_{ij}}{\mu_{ij}} A_{ij}\frac{P_j^{p+1}-P_i^{p+1}}{x_{ij}} \tag{2.37}$$

To calculate the relative humidity of cell i at the next time step, Equation 2.37 can be rewritten as Equation 2.38 to make the aforementioned the subject of the equation and introducing three additional terms: the moisture capacitance of a cell, C^w (calculated using Equation 2.39), the moisture resistance between two cells, R^w (calculated using Equation 2.40), and the vapour resistance between two cells, R^v (calculated using Equation 2.41). Equation 2.38 is used in conjunction with Equation 2.34 to calculate the heat and moisture balance across constructions.

$$\phi_i^{p+1} = \frac{\sum_j \frac{\phi_j^{p+1}}{R_{ij}^w} + \sum_j \frac{P_i^{p+1}}{R_{ij}^v} + C_i^w \frac{\phi_i^p}{\Delta\tau}}{\frac{C_i^w}{\Delta\tau} + \sum_j \frac{1}{R_{ij}^w} + \sum_j \frac{P_i^{sat}}{R_{ij}^v}} \qquad 2.38$$

$$C_i^w = \frac{dw}{d\phi_i}\Delta V_i \qquad 2.39$$

$$R_{ij}^w = \frac{x_{ij}}{A_{ij}D_{ij}^w \frac{dw}{d\phi}} \qquad 2.40$$

$$R_{ij}^v = \frac{\mu_{ij}x_{ij}}{A_{ij}\delta_{ij}} \qquad 2.41$$

The HAMT model accounts for moisture transport in porous building materials through vapour diffusion, surface diffusion and capillary conduction. Vapour diffusion occurs between the ambient air and surface, the surface and adjacent pores, and between the pores. Vapour diffuses from the higher pressure zone to the lower pressure zone. Surface diffusion is the transfer of adsorbed water molecules along the surface of sorbate film. As a result, water molecules travel from high concentration to lower concentration adsorbed water regions. Capillary conduction in pores is the result of capillary action.

2.11 The Relevance of Building Performance in South Africa

2.11.1 Thermal Studies in South Africa

Initial thermal studies in South Africa were done by EE Mathews, with early work also focusing on low-income housing (Mathews and Van Wyk, 1996). The focus of thermal studies on low-income housing in South Africa can be attributed to the amount of low-income houses. Although thermally high-performing buildings have increased due to green building investment in South Africa, computational studies for high-end South African buildings remain scarce. Regardless of focus area, advanced building software has become a primary tool for building performance assessment of buildings in South Africa. DesignBuilder has been used to study shading performance (Coleridge and Huh, 2017), energy profiles of low-income housing (Muringathuparambil, 2016), and energy performance of multi-level buildings (Neethling, 2012; Cunliffe, 2017). Input for the studies mainly used secondary data, and not primary data, regarding weather data, material data, and occupancy data.

Low-income housing has also been studied in South Africa using data capturing and analysing measured environmental parameters (Mabuya, 2019). These studies showed low-income housing experiencing uncomfortable temperature ranges (Naicker *et al.*, 2017; Overen, Meyer and Makaka, 2017; Qhekwana *et al.*, 2017; Matandirotya *et al.*, 2019, 2020; Adesina *et al.*, 2020). Due to the uncomfortable conditions experienced in low-income housing, alternatives to current low-income housing have been investigated (Overen, Meyer and Makaka, 2019, 2020). These studies have, however, also only focused on analysing captured environmental parameters without the use of advanced building software.

2.11.2 Resources for Building Performance in South Africa

The thermal and energy performance design of buildings in South Africa is guided by SANS 10400-XA:2011 and SANS 204:2011 (South African Bureau of Standards, 2011b, 2011c). These two standards provide the requirements for South African buildings to be considered sustainable.

Requirements for SANS 10400-XA:2011 (South African Bureau of Standards, 2011b) are divided into the hot water supply, energy usage and building envelope, design assumptions, and building envelope requirements. The requirements regarding energy usage can either be satisfied by adhering to the requirements of the other categories or by using certified advanced building software to show annual building energy demand and usage is less than a specific value. To aid in normalising building simulation input, design guidelines are provided by SANS 10400-XA:2011 (South African Bureau of Standards, 2011b) regarding occupancy, space temperature when using HVAC systems, fresh air requirements, internal heat gains, and hot water supply specifications.

Requirements for SANS 204:2011 (South African Bureau of Standards, 2011c) are divided into six categories: site orientation, building orientation, building design, building sealing, services, mechanical ventilation, and air conditioning. This standard provides guidance on building design to minimise energy demand and usage, and provide occupants control over their environment. When the building design meets the requirements of the standards, the building is deemed to be energy efficient.

Although sustainability and energy efficiency in the South African building codes are mainly guided by SANS 204:2011 and SANS 10400-XA:2011, the South African Bureau of Standards (SABS) also lists standards related to energy efficiency not referenced by these two standards.

The SABS website (South African Bureau of Standards, 2021) separates standards related to energy efficiency as standards used for certification and assessment, and standards used to identify minimum requirements during design. SABS lists 254 standards related to certification & assessment and 49 standards related to minimum requirements. Although these lists provide information about building energy efficiency, they contain multiple references to the same standard and outdated standards. It is immediately noticeable that standards related to minimum requirements are contained within certification and assessment standards.

Considering standards that focus on building sustainability and energy efficiency, standards are either relevant or irrelevant. Regarding Standards & Publications, 49 unique identified standards are identified. Of these 49 standards, 16 standards can be considered relevant to buildings' thermal and energy performance estimation, with 33 standards considered irrelevant to buildings' thermal and energy performance estimation. Inspecting the 16 relevant Standards & Publications, five have been superseded or withdrawn.

Regarding Certification & Assessment, 254 unique standards are identified. Of these 254 standards, 204 standards can be considered irrelevant to buildings' thermal and energy performance estimation, with 50 standards considered relevant to buildings' thermal and energy performance estimation. Inspecting the 50 relevant standards, 13 have been superseded or withdrawn. It can also be noticed that Standards & Publications and Certification & Assessment contain the same set of SANS standards.

A similar assessment can be made of the two primary SANS standards related to building sustainability and energy efficiency: SANS 204:2011 and SANS 10400-XA:2011. SANS 204:2011 contains 21 normative references, one of which is referenced by the Certification & Assessment of the SABS website, and 15 informative references. SANS 10400-XA:2011 contains 13 normative references. 11 of these normative references are referenced by SANS 204:2011: 10 normative references and one informative reference. A single normative reference is unique to SANS 10400-XA:2011, as SANS 10400-XA:2011 also references SANS 204:2011.

In addition to the standards referenced by the SABS website, SANS 204:2011 and SANS 10400-XA:2011, standards relevant to thermal and energy performance estimation of buildings have been introduced. Identified standards include (South Africa, 2010): SANS 1072:2010, SANS 8302:2010, SANS 8990:2010, SANS 9288:2010, SANS 12567-1 :2010, SANS 12567-2:2010, SANS 13788:2010, and SANS 13792:2010.

A summary of the standards made available by the SABS website or referenced within SANS 204:2011 and SANS 10400-XA:2011 is presented in the Sankey diagram in Figure 2.10.

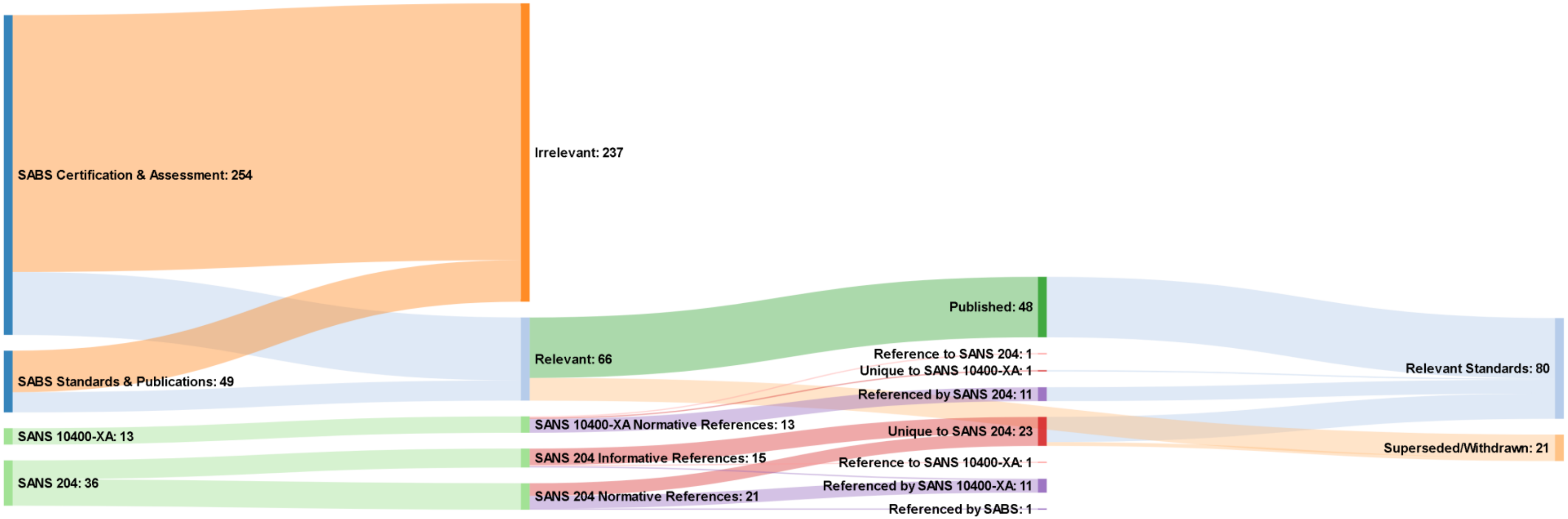


Figure 2.10: Sankey diagram of Relevant South African Standards

2.11.3 Green Building in South Africa

Building sustainability in South Africa is assessed by the GBCSA (The Green Building Council of South Africa, 2019). Assessments are performed using GBRTs, which rate building performance against a set of credits to establish a comparable rating. The rating uses 'Green Stars' as measurement and ranges from a minimum of 1 Green Star to a maximum of 6 Green Stars (The Green Building Council of South Africa, 2021).

Although the GBCSA offered two GBRTs initially, the number of GBRTs administered by the GBCSA as of 2021 is 11. A timeline of the release of GBRTs in South Africa is presented in Figure 2.11. Adopting GBRTs has also experienced steady growth based on survey and annual reports (The Green Building Council of South Africa, The Association Of South African Quantity Surveyors and The University of Pretoria, 2016, 2019; The Green Building Council of South Africa, 2018, 2019). The survey reports also showed the additional cost required to integrate green design measures into a building has decreased. This observation was attributed to the maturing green industry in South Africa.

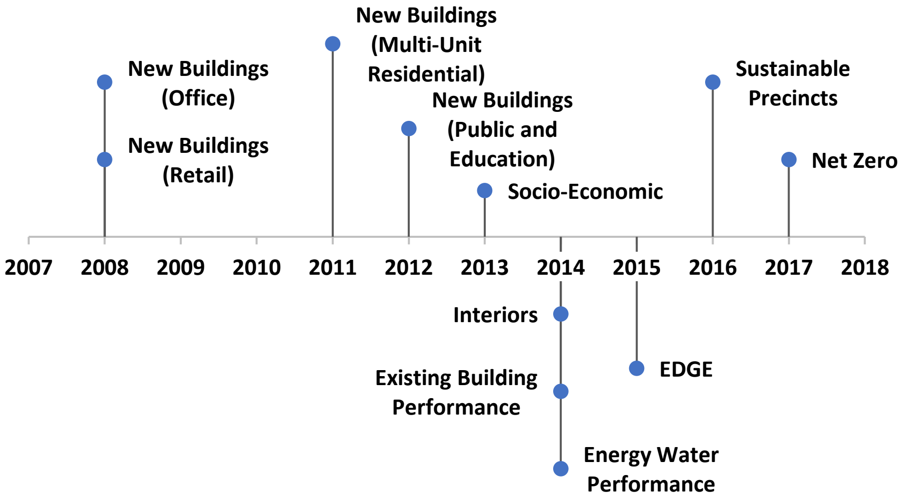


Figure 2.11: Launch of Different Green Building Rating Tools in South Africa

Similar to SANS 10400-XA:2011 (South African Bureau of Standards, 2011b), GBRTs that require building energy modelling offer design guidelines regarding advanced building software input. The credits awarded for energy performance is based on the difference between the simulated building performance of the actual building design and the simulated building performance of the same building using the notional design guidelines of SANS 10400-XA:2011 (South African Bureau of Standards, 2011b).

2.12 Concluding summary

This chapter sought to provide the necessary information to establish a connecting narrative between green buildings and building simulation. It serves as the background for the five themes: green buildings, building performance, the building envelope, building simulation, and studies of the aforementioned in South Africa. The chapter also serves to identify the aims of the study. The conclusion is divided into six parts, the first five parts summarising the critical aspects from the five themes of the literature review, and the sixth part providing concluding remarks regarding the void which needs to be filled in literature, as well as discussion on the contribution of the literature review towards the aims of the study.

2.12.1 Green Buildings in the Industry

Although no clear definition for green buildings can be provided, definitions for green buildings share common characteristics. They must maximise resource efficiency while limiting environmental impact and creating a comfortable environment for their occupants. Maximising resource efficiency requires a design philosophy defined as green building design.

Green building design is improved upon by advancing green building knowledge. Advancing green building knowledge requires research focusing on either the single aspects of green building design or the themes of green building design. However, advances also stem from sustainability requirements enforced by countries and recognition from the industry when adopting green building design philosophy.

Both sustainability requirements and the extent to which green building design philosophy is employed in a building is assessed through GBRTs. Assessments are done using measurements or theoretical values obtained through building simulation for either a conceptual or existing building. However, when designing a green building, success is challenged by government regulations and policies, lack of information, and complexity associated with green building design, technical knowledge, and the complexity of energy modelling.

2.12.2 Building Performance

When regulation requires buildings to be at a certain level of performance, compliance can be achieved through prescriptive or performance-based means. Prescriptive based design places limits on the design characteristics of the building. In contrast, the performance-based design limits building performance metrics, as in green buildings, and is the preferred compliance method in the industry.

Although regulation often requires building performance to be a certain level of performance, building standards do not always provide the necessary information to design for all the aspects of a green building. In such cases, building standards sharing similar climate characteristics are adopted. Not all aspects of building standards can be replicated, however. In such cases, it suggested that data be collected, building performance be simulated, and results compared to confirm accuracy.

Due to the number of factors affecting building performance and simulation accuracy, performance gaps exist within the industry. The performance gap refers to the difference between simulated building performance and actual building performance. However, reducing the performance gap is possible by improving the assumptions made during building simulation and improving the skills and knowledge of the individuals responsible for the design and construction of a building.

The design of the building should target performance improvement through five areas while considering local climate: materials, insulation, geometry, orientation, and openings. When successfully designed, a high-performing building envelope should be capable of regulating the building environment. When the building performance metric is the quality of the building environment, thermal comfort models are employed to assess performance.

2.12.3 Coupling the Building Envelope to Building Performance

Due to varying functional demands from the building envelope, two building envelope types exist: static and adaptive. Adaptive building envelopes are capable of changing envelope configuration, design, and material properties. In contrast, static building envelopes are incapable of doing so. Even though the design of static building envelopes is limited, their design is still climate-based.

The building envelope acts as a separation element between the building interior and exterior. This requires protecting, controlling, and regulating the building environment. The level of separation is measured by the functional performance of the building envelope.

The functional performance of the building envelope is, however, limited by the presence of building defects. When building defects are present, thermal bridges are created, and unwanted air and moisture enter the building environment.

When the focus of the functional performance is thermal performance, attention is placed on envelope design. This requires an assessment of design and material choice. The choice of building materials used for the building envelope is dependent on the required thermal properties. Thermal properties are either steady-state or dynamic. However, only characterising building material properties with steady-state properties ignores dynamic processes which can affect material behaviour.

2.12.4 Evaluating Building Performance Using Building Simulation

When evaluating building performance using building simulation, the theoretical building performance is calculated. Calculating the theoretical building performance is a five-step process. First, the desired outcome of the building simulation must be identified. Second, building simulation software that is capable of producing the desired outcome must be identified. Third, the degree of complexity to which building simulation will be performed must be decided upon. The final two steps require the identification of the required inputs and desired outputs.

Because building simulation produces a theoretical building performance value, performance gaps are created during analysis. Of the factors contributing to inaccurate building simulation, simulation input, particularly occupancy, is the most significant influencing factor. These inputs are guided by building standards, literature, and measured values. However, in several cases, guidelines presented by the software are used as a guideline for the selection of input data .

When uncertainties regarding simulation input exist, sensitivity analysis is used to account for inaccuracies. Sensitivity analysis allows for model simplification, model-based optimisation, model error diagnoses, and quantification of input-output relationship. When sensitivity analysis is performed, a baseline model must be established, uncertainties to be added to the baseline model, and the baseline model to be calibrated based on the simulation inputs and outputs. To ensure the results obtained from model calibration is correct, model validation is performed by comparing simulated building performance to measured building performance.

In addition to simulation input, the analysis method used for building simulation influences simulation output. The difference in analysis methods is associated with accuracy and computational time. Building simulation analysis often considers heat-only transfer through constructions due to its shorter computational time than hygrothermal analysis. The importance of hygrothermal analysis is attributed to the influence of moisture buffering constructions on building humidity levels.

2.12.5 The Complexity of Building Envelope Design In South Africa

Building thermal performance in South Africa has been researched using either heat-only analysis or using measured data. The reluctance to adopt hygrothermal analysis has been attributed to a lack of material data, as studies in South Africa typically rely on literature data for building simulation input. In addition to literature, thermal and energy-efficient design of buildings in South Africa are primarily guided by SANS 10400-XA:2011 and SANS 204:2011.

Low-income housing in South Africa has enjoyed the majority of focus in research. This can be attributed to the large share of low-income housing in the South African building stock and funding from the South African government to study low-income housing. However, building thermal performance is also essential for research related to green buildings in South Africa. Also, the importance of research regarding SA green buildings is increasing due to the increased adoption of green building in South Africa and the performance-based nature of building assessment.

2.12.6 Concluding Remarks

Against the backdrop of the literature review, questions remain regarding building performance and building simulation in South Africa. These questions are related to the simulation of buildings in the South African building stock and the performance gap of buildings simulated in South Africa. Regarding questions related to simulation of buildings in the South African building stock, questions remain regarding the modelling guidelines of South Africa, i.e. which aspects of South African guidelines lacks the information necessary to perform building simulation accurately. Regarding the questions related to the performance gap of South African building models, questions remain regarding how to assess model accuracy for building simulations, i.e. which aspects of South African guidelines lack the information necessary to validate building models to minimise the performance gap.

The literature review addresses each of the aims of the study. The second and third theme reviewed, building performance and the building envelope, partially address Aims 1 to 3. Literature under this theme provides the background necessary to identify how building performance can be defined, the factors influencing building performance, and which factors should be considered during building simulation. It also explains what to expect from building performance due to changes made to the building envelope. The fourth theme, building simulation, also partially address Aims 1 to 3. The discussions presented under this theme provides a detailed account of building simulation and HAMT modelling. The information provided by this discussion allows factors to be identified which can influence building simulation results and how building simulation should be performed to address the objective of the building analysis. The fifth theme of the literature review, thermal and building simulation studies in South Africa, partially addresses Aim 4. Examining the South African building standards provides the necessary background for building analysis requirements under these building standards. This provides the information required to establish a base case building and identifies building simulation requirements that are absent.

Chapter 3 The Modelling of Two Green Star Office Buildings: Alice Lane and Bridge Park Using Heat-Only Analysis

3.1 Introduction

The law of diminishing returns states that “given a fixed amount of one production factor, additional units of the other production factors bring diminishing yields until the point is reached at which the last, marginal unit of the factor will yield nothing“ (Giarini, 1977). Applying this law to building performance, it can be observed that continuously improving a single aspect of a building will eventually provide marginal improvement towards building performance. This law influences energy performance and affects economic performance, as energy efficiency is obtained from many building aspects.

In light of design decisions that may influence building thermal performance, this chapter is dedicated to investigating the apparent influence of building envelope design on building performance. Subsequently, this chapter addresses Aim 1 of this study. It provides a parametric analysis of the opaque and glazing components of the building envelope of two Green Star buildings located in South Africa.

The chapter is divided into four sections. Section 3.1 presents a discussion of the background for the chapter and a breakdown of the structure of the chapter. Section 3.2 describes the buildings used for analysis, simulation software, and model parameters provided for parametric analysis toward thermal optimisation of the building envelope. Section 3.3 presents computational results stemming from the parametric analysis. Five parameter studies are discussed, representing material properties or building design features encountered in literature. The five parameters studied are thermal conductivity (0.05 to 1.715 W/(m.K)), specific heat capacity (100 to 2350 J/(kg.K)), material density (10 to 2260 kg/m^3), the Solar Heat Gain Coefficient (SHGC) of external glazing (0.1 to 0.8), and the Window-To-Wall Ratio (WWR) of the building (0% to 100%).

Section 3.4 presents a discussion on the thermal analysis of the two Green Star buildings. The results show that increasing thermal conductivity, with a predominantly glass façade, allows solar heat gains to dissipate from the structure quicker. This is favourable during the summer but unfavourable during the winter. Increasing the specific heat capacity or density, which increases thermal capacitance, decreases the heat transferred through the building envelope. Although favourable initially during the summer, a large enough thermal capacitance will limit the heat transferred through the envelope to remove solar heat gains. During the winter, a balance is needed to limit heat flow during periods where the exterior is cooler than the interior and allow heat flow during periods when the exterior is warmer. As expected, increases to the SHGC is unfavourable during the summer but favourable during the winter. Regarding the WWR, changes made to the WWR result in mirroring results. This is attributed to the difference in heat removed through the building envelope and gained due to additional solar heat gains between the two buildings.

3.2 Buildings and Model Description

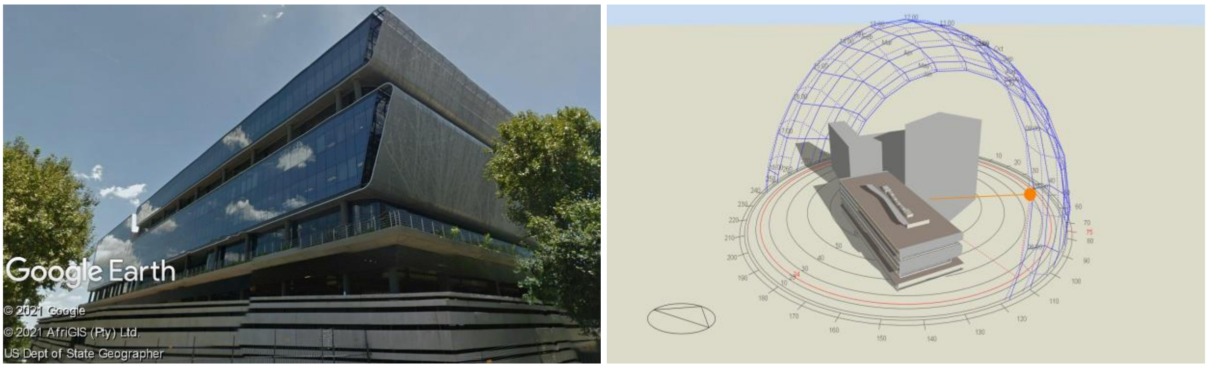
To address Aim 1 of the study, two buildings were investigated in a building simulation tool. The simulation tool used for the study is DesignBuilder. Although three software packages are certified for use for building thermal analysis in South Africa (Agrément South Africa, 2021), DesignBuilder was chosen because of local support being available for the software, and its usage for Green Star certification in South Africa. To validate the computational accuracy, and to understand the complexities of DesignBuilder, a simplified validation analysis was performed and reported in Appendix A. The complexities of DesignBuilder are the result of its range of inputs, including weather data files, material properties, and obscured simulation settings. Simplified validation analysis consisted of analysing a simple, single room building in DesignBuilder, and then analysing a single wall in Abaqus, a commercial finite element analysis software package. A constant air temperature value was applied to the outside and inside of the building for the analysis.

A focus point of the building model and study is the surface heat balance. For the models described in this chapter, the CTF solution method was used to calculate the heat conducted through building constructions. The CTF solution is a heat-only transfer solution method. This implies that the surface heat balance is coupled to only heat changes (or temperature changes). A description of the CTF method is presented in Section 2.10.6.1.

In addition to the surface heat balance used for analysis, DesignBuilder requires many inputs from the user. These inputs can be broken down into a series of steps. Models were obtained that were originally used for Green Star certification. These models were then adapted as specified in Sections 3.2.1 to 3.2.9. A description of the calculation methods and simulation input and output methods used in DesignBuilder is provided in Appendix B.

The outputs requested from the building models allowed for the cooling and heating loads to be captured. Obtaining these values allow comparisons between building configurations and material property variation based on the difference between cooling and heating loads of model outputs.

The first adopted office building in this study is the Alice Lane office building. The building was chosen because it was a Green Star rated building and because the building model was available to be modified. The Alice Lane office building is situated in Sandton, Johannesburg. The model coordinates from the weather file are 26.2°S and 28.03°E at an elevation of 1730 m. Furthermore, the building is oriented 30° east of north. The building is pictured in Figure 3.1 (a) with the building model presented in Figure 3.1 (b).



(a) (b)

Figure 3.1: (a) Ground view of Alice Lane (Google Earth Pro 7.3.4.8248, 2015) *(b) Sun path diagram for Alice Lane*

From the weather file, October to December is considered the summer season, while April to June constitutes the winter season. According to Koppen-Geiger classification, Sandton is a warm temperate, dry winter, warm summer climate (Cwb) (Conradie, 2012). Under SANS 204:2011 (South African Bureau of Standards, 2011c), this region is classified as a cold interior zone.

The second adopted office building in this study is the Bridge Park East office building, hereinafter referred to as Bridge Park for the sake of brevity. Similar to the Alice Lane office building, the building was chosen because it was a Green Star rated building and because the building model was available to be modified. The Bridge Park office building is situated in Cape Town, South Africa. The model coordinates from the weather file are 33.97°S and 18.60°E at an elevation of 44 m. Furthermore, the building is oriented 135° east of north. The building is pictured in Figure 3.2 (a) with the building model presented in Figure 3.2 (b).

(a) (b)

Figure 3.2: (a) Ground view of Bridge Park (Google Earth Pro 7.3.4.8248, 2017) *(b) Sun path diagram for Bridge Park*

From the weather file, December to February is considered the summer season, while June to August constitutes the winter season. According to Koppen-Geiger classification, Cape Town is a warm temperate, dry summer, warm summer climate (Csb) (Conradie, 2012). Under SANS 204:2011 (South African Bureau of Standards, 2011c), this region is classified as a temperate coastal zone.

The model description of both office building models consists of 3 sets of inputs: weather data, model data, and simulation settings. The following sections of the model description will provide details regarding assumptions made on building simulation model inputs of site weather conditions, internal heat gain sources, occupancy patterns, details regarding natural ventilation, air infiltration/leakage, and building materials. The section concludes with a discussion of building models used for parametric analysis.

3.2.1 Weather

The primary source of weather data is Meteonorm 6 data obtained from Meteonorm (Meteonorm, 2020). Weather data is presented in Appendix C.1 for the Alice Lane building and Appendix C.2 for the Bridge Park building.

3.2.2 Internal Heat Gains

Internal heat gains in the Alice Lane office building and Bridge Park office building consist of heat gains due to equipment and miscellaneous sources. Heat gains of both buildings are summarised in Appendix C.3.

3.2.3 Occupancy

Details regarding the occupancy schedule of Alice Lane and Bridge Park are summarised in Appendix C.4. Appendix C.4 also contains details regarding the heat gain associated with human metabolic rate. Due to how holes are connected in the Alice Lane building to create the atrium, any area inside atrium zones is modelled with the same occupancy, resulting in additional heat gains. This heat gain is, however, negligible due to the floor area: hole area ratio.

3.2.4 Lighting

Details regarding Alice Lane's lighting schedule and Bridge Park office building are summarised in Appendix C.5. Appendix C.5 also contains details regarding the heat gain associated with lighting. Although a return air fraction is erroneously specified in the model, an error is not reported during simulations.

3.2.5 Heating/Cooling

Details regarding the artificial heating and cooling of the Alice Lane office building and Bridge Park office building are summarised in Appendix C.6.

3.2.6 Air Infiltration/Air Leakage

Airflow within the model is achieved through air infiltration and leakage. A constant rate of 0.5 air changes per hour is assumed for the Alice Lane office building and Bridge Park office building. A summary of the zones subjected to continuous air infiltration/leakage is presented in Appendix C.7.

3.2.7 Building Materials

Due to the large amount of building construction and building materials used, only the material properties of building materials used for the parametric analysis are discussed. Although the construction thickness of materials was changed, geometric thickness from the original model was left unchanged. Thus, the surface area and, subsequently, room volume were kept the same.

3.2.8 Base Case Analysis

Before a parametric analysis is done, a base case must be constructed. The base case assumptions will be broken down into an analysis period, internal heat gains, lighting, occupancy, ventilation, air infiltration/leakage, HVAC usage, and the heat balance method.

The analysis period of the base case is a year, i.e. 1 January to 31 December. Regarding internal heat gains, the base case assumes the details contained within the overview provided in Section 3.2.2. Lighting assumptions are discussed in two parts: magnitude and schedule. Details are included in the overview provided in Section 3.2.4. Assumptions regarding occupancy are discussed in two parts: magnitude and schedule. Details are contained within the overview provided in Section 3.2.3. Air infiltration/leakage and HVAC systems usage assume the details contained within the overview provided in Section 3.2.5 and Section 3.2.6. A base set of values for building material properties is not provided due to the parametric analysis's nature.

The heat balance method used for the base case analysis is the CTF method. Because the analysis's focus was the influence of thermal properties, the analysis was carried out using CTF for the solution method for heat transfer through opaque building components.

3.2.9 Parametric Analysis

For parametric analysis, five variables were chosen to be analysed: conductivity, specific heat capacity, density, SHGC, WWR. Value ranges are based on the thermal bulk properties of building materials listed in Chartered Institution of Building Services Engineers (CIBSE) Guide A Tables 3.35 to 3.38 (Butcher and Craig, 2015). As the parametric analysis focused on the relative change of energy performance due to changing a selected variable's value, five sets of parametric analyses were performed. Changes made to the building models are summarised in Tables C.11 to C.15. The first three sets of analyses are performed by assuming base thermal bulk property values for the two thermal bulk properties not subject to change and increasing the third thermal bulk property value, starting from a minimum value. During these analyses, glazing is left unchanged, and the wall construction thickness kept at 0.15. For the fourth parametric analysis, the WWR and external walls are left unchanged, but the SHGC of external glazing is increased, starting from a minimum value. For the final parametric analysis, glazing properties and external wall construction are left unchanged, but the WWR of all external glazing is increased starting from a minimum value.

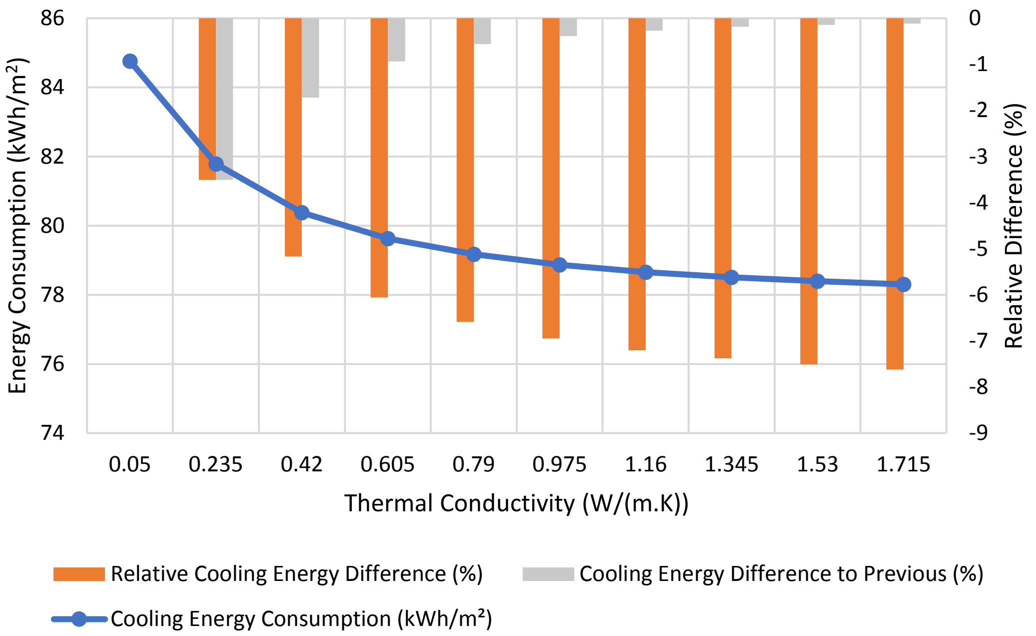
3.3 Results

Five sets of results are analysed, each set focusing on a parameter subject to change during the parametric study. Results are presented on a graph, the x-axis presenting the value of the parameter subject to change, the 1st y-axis (left side) presenting the thermal energy removed with cooling and added with heating, and the 2nd y-axis (right side) presenting the percentage change in energy expenditure compared to the base case of each set of results. Two groups of percentage change are presented: relative energy difference, depicting the change in energy expenditure of the parameter variation and base case of the set of results, and energy difference to previous, depicting the change in energy expenditure of the parameter variation and the previous parameter variation.

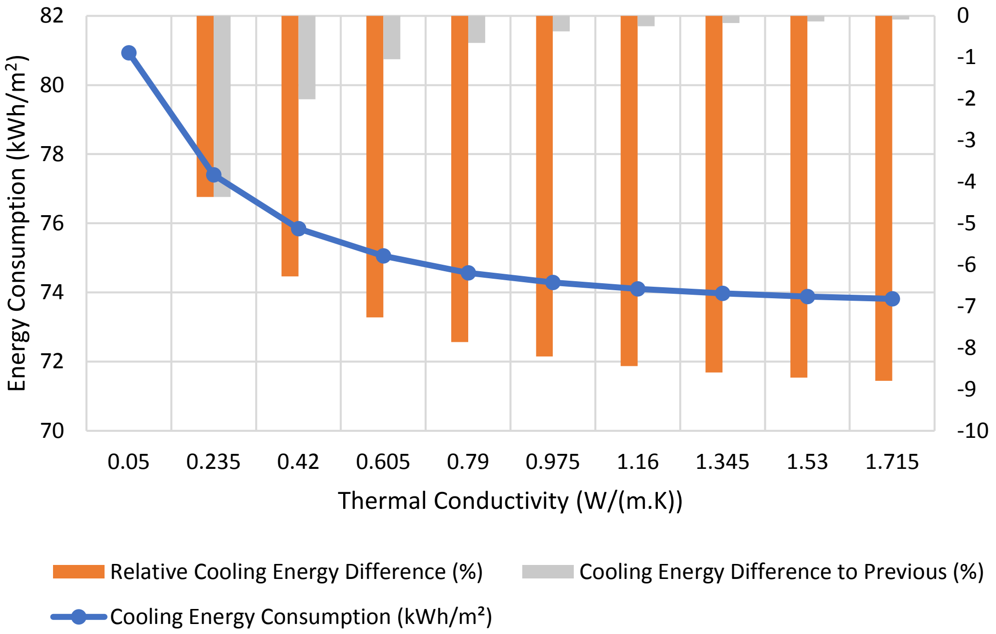
In addition to the five sets of analysis, a discussion regarding the thermal diffusivity of the building envelope is presented. The thermal diffusivity $\left(\alpha = \frac{k}{\rho \cdot c}\right)$ of a material is a measure of the rate of heat transfer. The combined effect of material properties is investigated by calculating the thermal diffusivity of each analysis. The thermal diffusivity is then plotted with the associated cooling or heating load.

3.3.1 Thermal Conductivity

Figure 3.3 (a) shows a continuous decrease in annual cooling loads for the Alice Lane building, when increasing the thermal conductivity, using the parameter values contained in Table C.11. However, the rate of decrease in annual cooling loads decreases when increasing the thermal conductivity. This trend is also observed for the Bridge Park building, with annual cooling loads presented in Figure 3.3 (b).



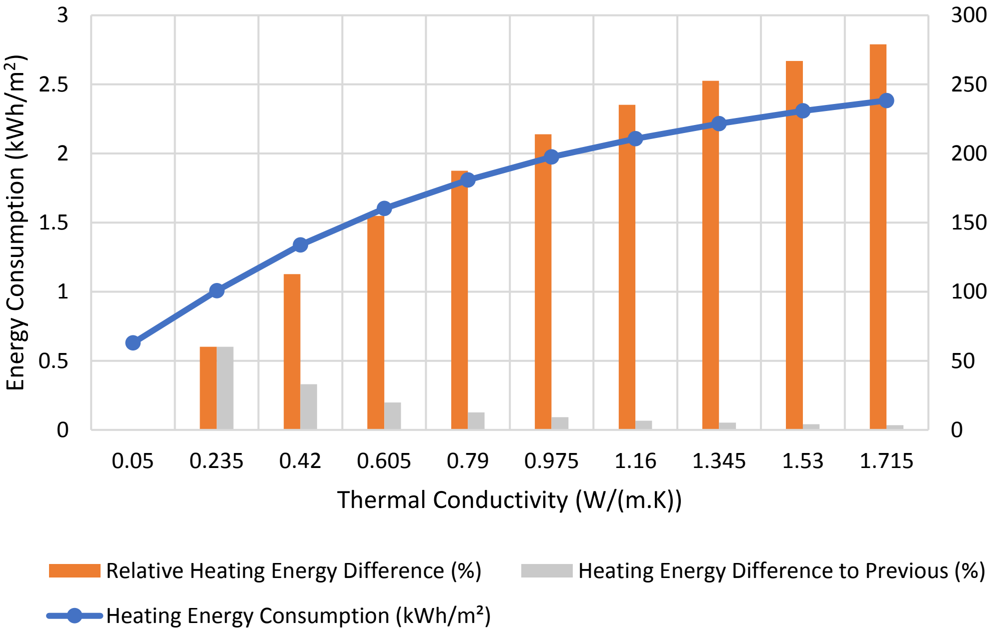
(a)



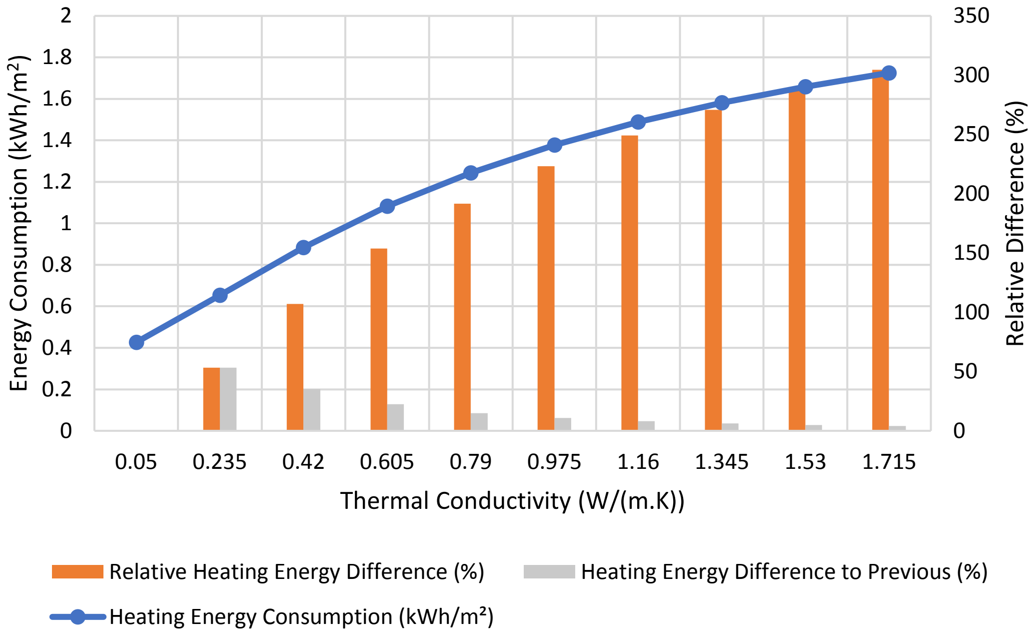
(b)

Figure 3.3: (a) Absolute and relative annual cooling loads of Alice Lane, with thermal conductivity subject to parametric study (b) Absolute and relative annual cooling loads of Bridge Park, with thermal conductivity subject to the parametric study

Figure 3.4 (a) shows a continuous increase in annual heating loads for the Alice Lane building, when increasing the thermal conductivity. However, the rate of increase in annual heating loads decreases when increasing the thermal conductivity. This trend is also observed for the Bridge Park building, with annual heating loads presented in Figure 3.4 (b).



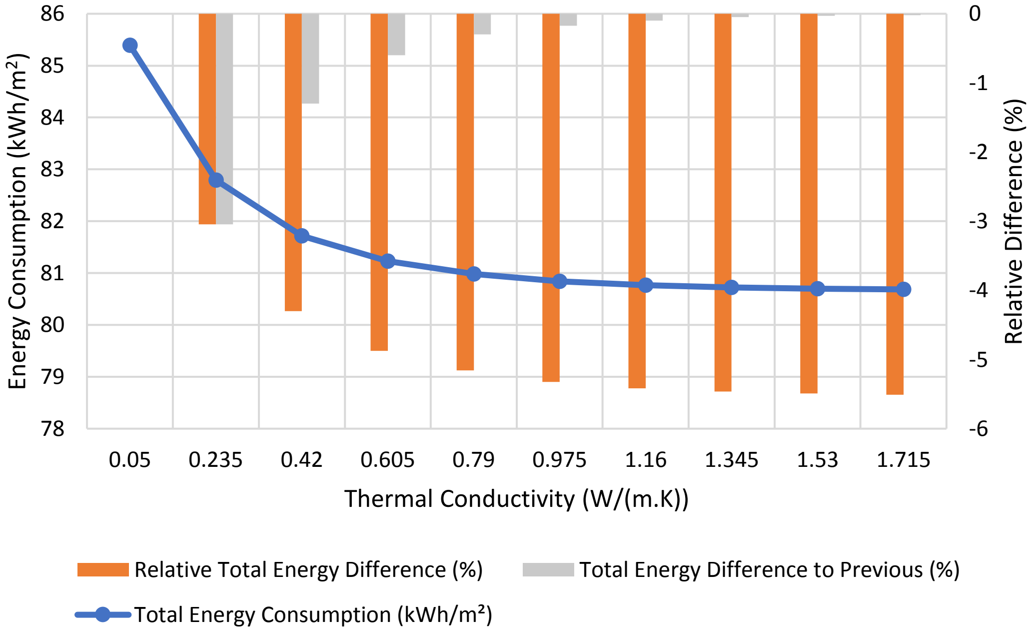
(a)



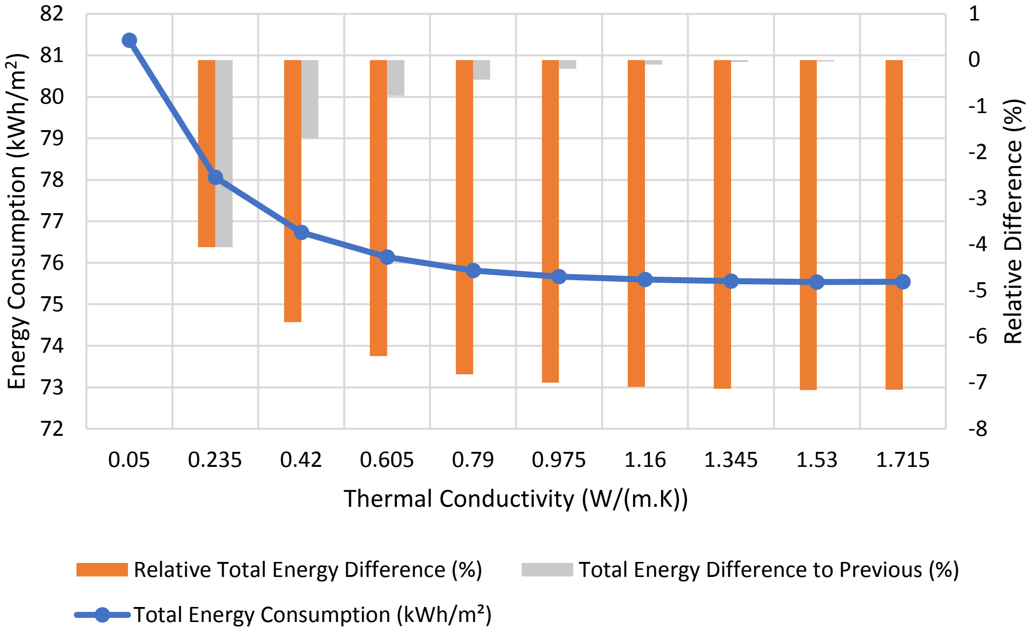
(b)

Figure 3.4: (a) Absolute and relative annual heating loads of Alice Lane, with thermal conductivity subject to parametric study (b) Absolute and relative annual heating loads of Bridge Park, with thermal conductivity subject to the parametric study

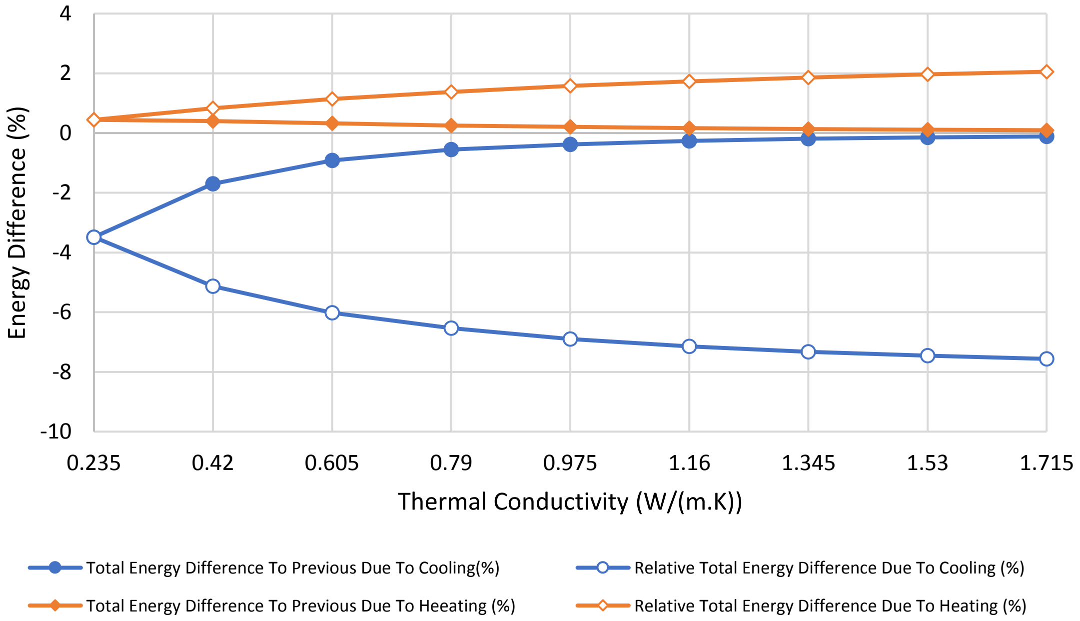
When combining the annual cooling and heating loads, it is observed that energy consumption is dominated by the cooling load. This is observed for Alice Lane and Bridge Park, as presented in Figure 3.5. Figures 3.5 (a) and (b) displays the relative difference in combined annual cooling and heating loads, with Figures 3.5 (c) and (d) displaying the relative difference in combined annual cooling and heating loads due to annual cooling and heating loads, e.g. from Figure 3.5 (c) it can be observed that increasing thermal conductivity to 0.235 W/(m.K) results in a 3.49% decrease and 0.44% increase in combined annual cooling and heating loads due to annual cooling and heating loads.



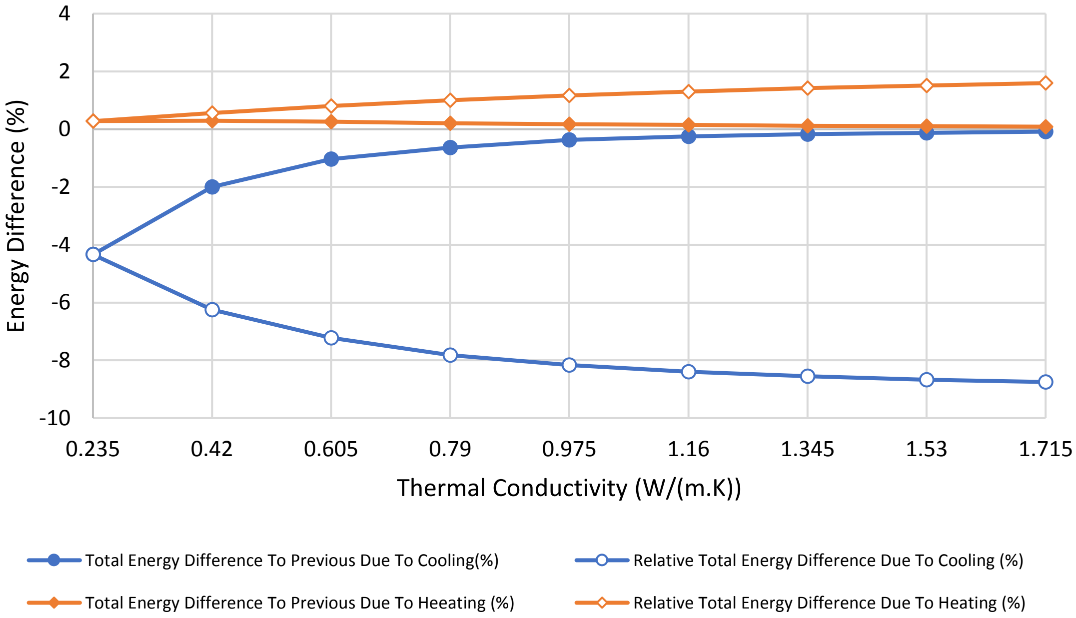
(a)


Energy Consumption (kWh/m²)
82
81
80
79
78
77
76
75
74
73
72
Relative Difference (%)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0.05
0.235
0.42
0.605
0.79
0.975
1.16
1.345
1.53
1.715
Thermal Conductivity (W/(m.K))
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

(b)


Energy Difference (%)
4
2
0
-2
-4
-6
-8
-10
0.235
0.42
0.605
0.79
0.975
1.16
1.345
1.53
1.715
Thermal Conductivity (W/(m.K))
Total Energy Difference To Previous Due To Cooling(%)
Relative Total Energy Difference Due To Cooling (%)
Total Energy Difference To Previous Due To Heeating (%)
Relative Total Energy Difference Due To Heating (%)

(c)

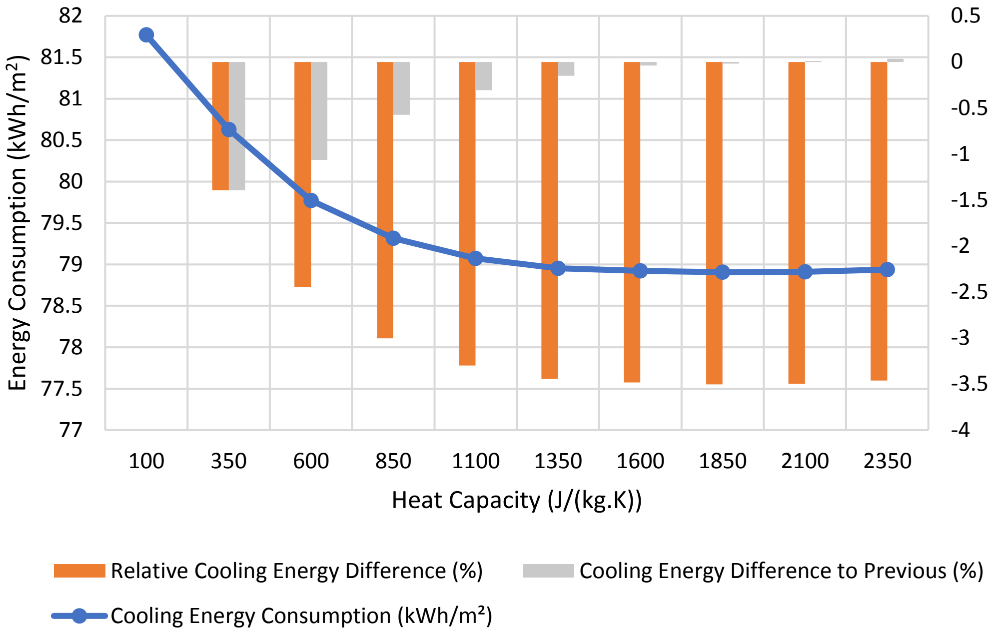


(d)

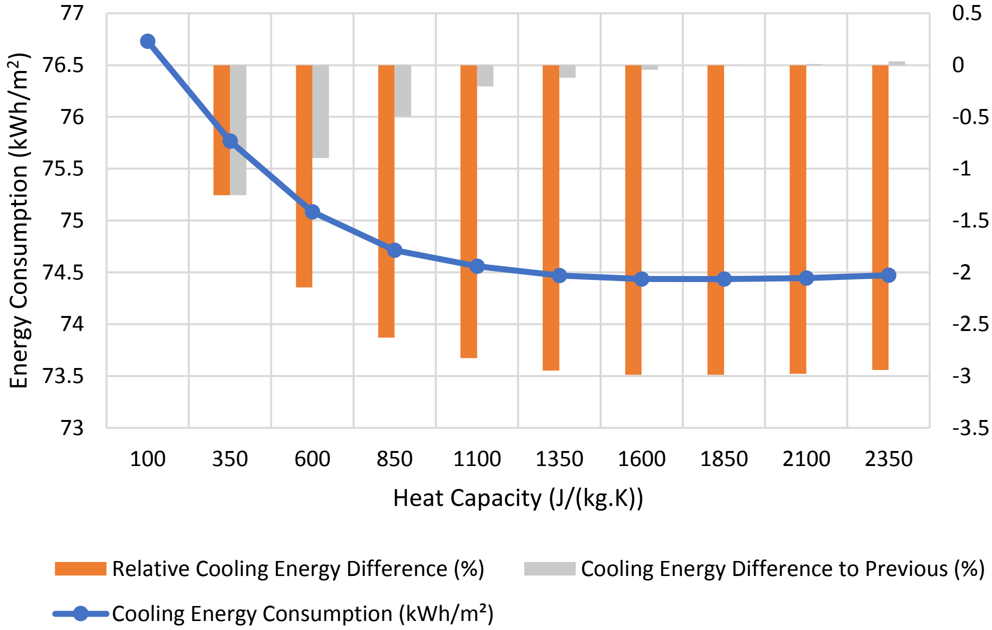
Figure 3.5: (a) Absolute and relative combined annual cooling and heating loads of Alice Lane, with thermal conductivity subject to parametric study (b) Absolute and relative combined annual cooling and heating loads of Bridge Park, with thermal conductivity subject to the parametric study (c) Relative combined annual cooling and heating loads of Alice Lane due to cooling and heating, with thermal conductivity subject to parametric study (d) Relative combined annual cooling and heating loads of Bridge Park due to cooling and heating, with thermal conductivity subject to the parametric study

3.3.2 Heat Capacity

From Figure 3.6 (a), a continuous decrease in annual cooling loads is observed for the Alice Lane building, when increasing the specific heat capacity, using the parameter values contained in Table C.12. However, the rate of decrease in annual cooling loads decreases when increasing the specific heat capacity, up until an upper limit. Once the upper limit is exceeded, a rate of increase in annual cooling loads is observed. This trend is also observed for the Bridge Park building, with annual cooling loads presented in Figure 3.6 (b).



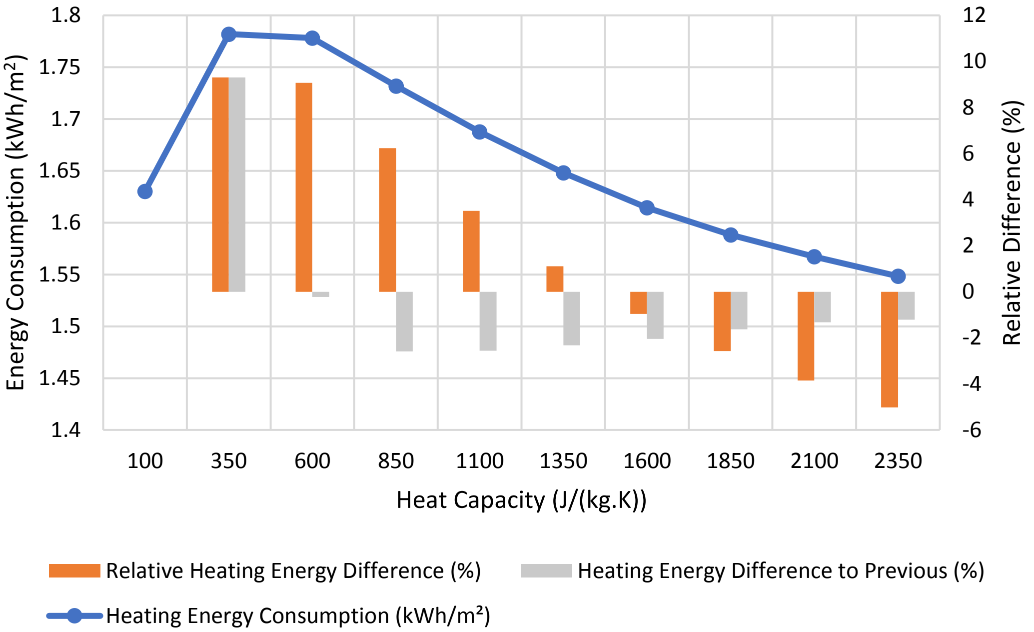
(a)



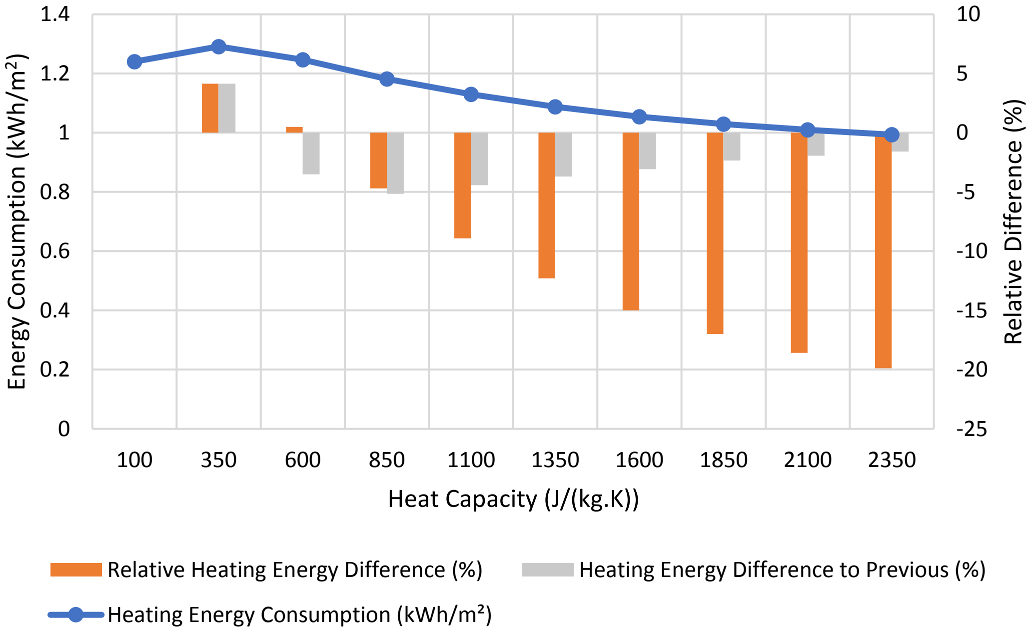
(b)

Figure 3.6: (a) Absolute and relative annual cooling loads of Alice Lane, with heat capacity subject to parametric study (b) Absolute and relative annual cooling loads of Bridge Park, with heat capacity subject to the parametric study

From Figure 3.7 (a), a sudden large increase in annual heating loads is observed for the Alice Lane building, when increasing the specific heat capacity, followed by a decrease in annual heating loads. However, after the initial spike, the rate of decrease in annual heating loads decreases when increasing the specific heat capacity. This trend is also observed for the Bridge Park building, with annual heating loads presented in Figure 3.7 (b).



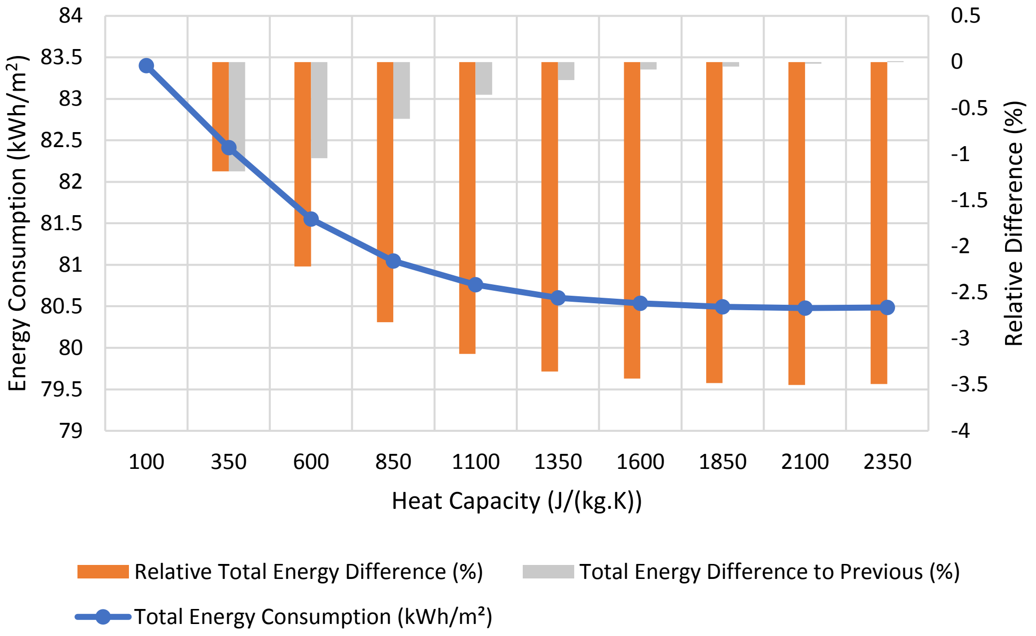
(a)



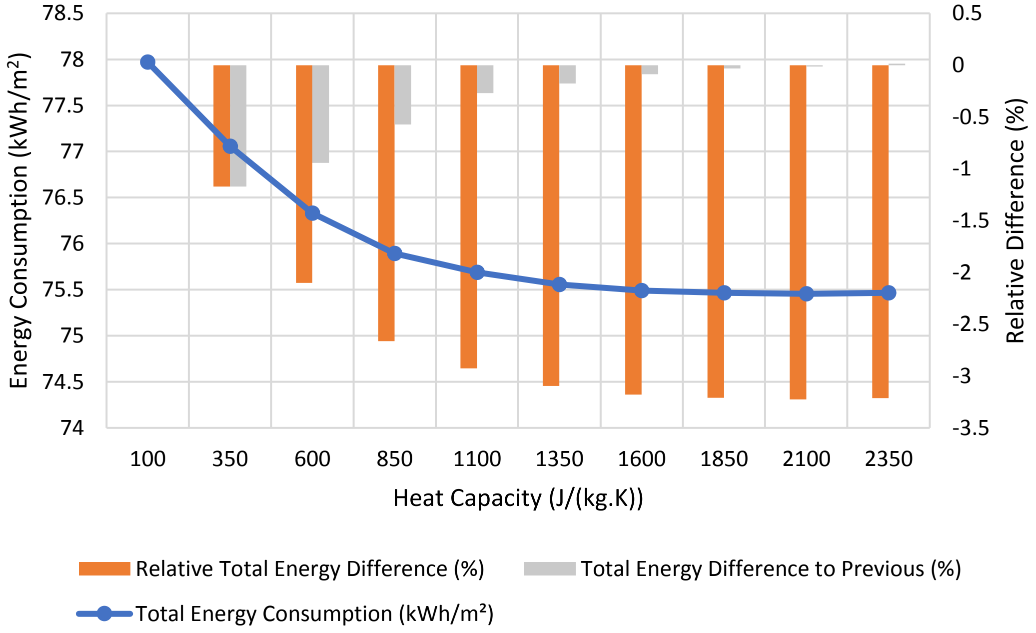
(b)

Figure 3.7: (a) Absolute and relative annual heating loads of Alice Lane, with heat capacity subject to parametric study (b) Absolute and relative annual heating loads of Bridge Park, with heat capacity subject to the parametric study

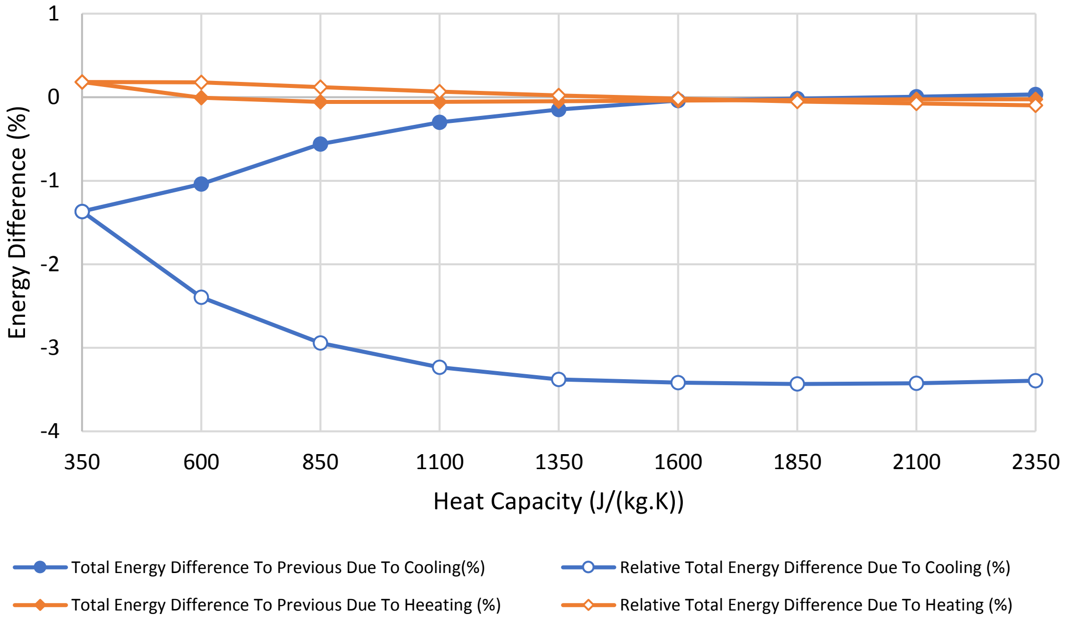
When combining the annual cooling and heating loads, it is observed that energy consumption is dominated by the cooling load. This is observed for Alice Lane and Bridge Park, as presented in Figure 3.8.


84
83.5
83
82.5
82
81.5
81
80.5
80
79.5
79
Energy Consumption (kWh/m²)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
Relative Difference (%)
100
350
600
850
1100
1350
1600
1850
2100
2350
Heat Capacity (J/(kg.K))
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

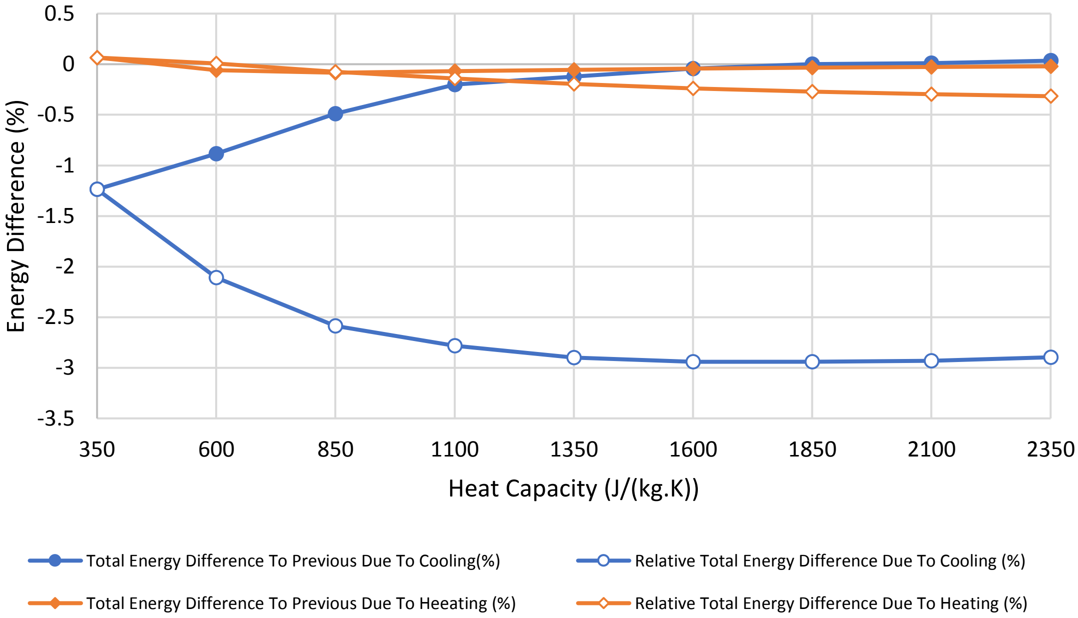
(a)


78.5
78
77.5
77
76.5
76
75.5
75
74.5
74
Energy Consumption (kWh/m²)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
Relative Difference (%)
100
350
600
850
1100
1350
1600
1850
2100
2350
Heat Capacity (J/(kg.K))
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

(b)



(c)



(d)

Figure 3.8: (a) Absolute and relative combined annual cooling and heating loads of Alice Lane, with heat capacity subject to parametric study (b) Absolute and relative combined annual cooling and heating loads of Bridge Park, with heat capacity subject to the parametric study (c) Relative combined annual cooling and heating loads of Alice Lane due to cooling and heating, with heat capacity subject to parametric study (d) Relative combined annual cooling and heating loads of Bridge Park due to cooling and heating, with heat capacity subject to the parametric study

3.3.3 Density

Figure 3.9 (a) shows a continuous decrease in annual cooling loads for the Alice Lane building, when increasing the density, using the parameter values contained in Table C.13. Although the rate of decrease in annual cooling loads experiences an initial increase when increasing the density, it is followed by a continuous decrease. This trend is also observed for the Bridge Park building, with annual cooling loads presented in Figure 3.9 (b).

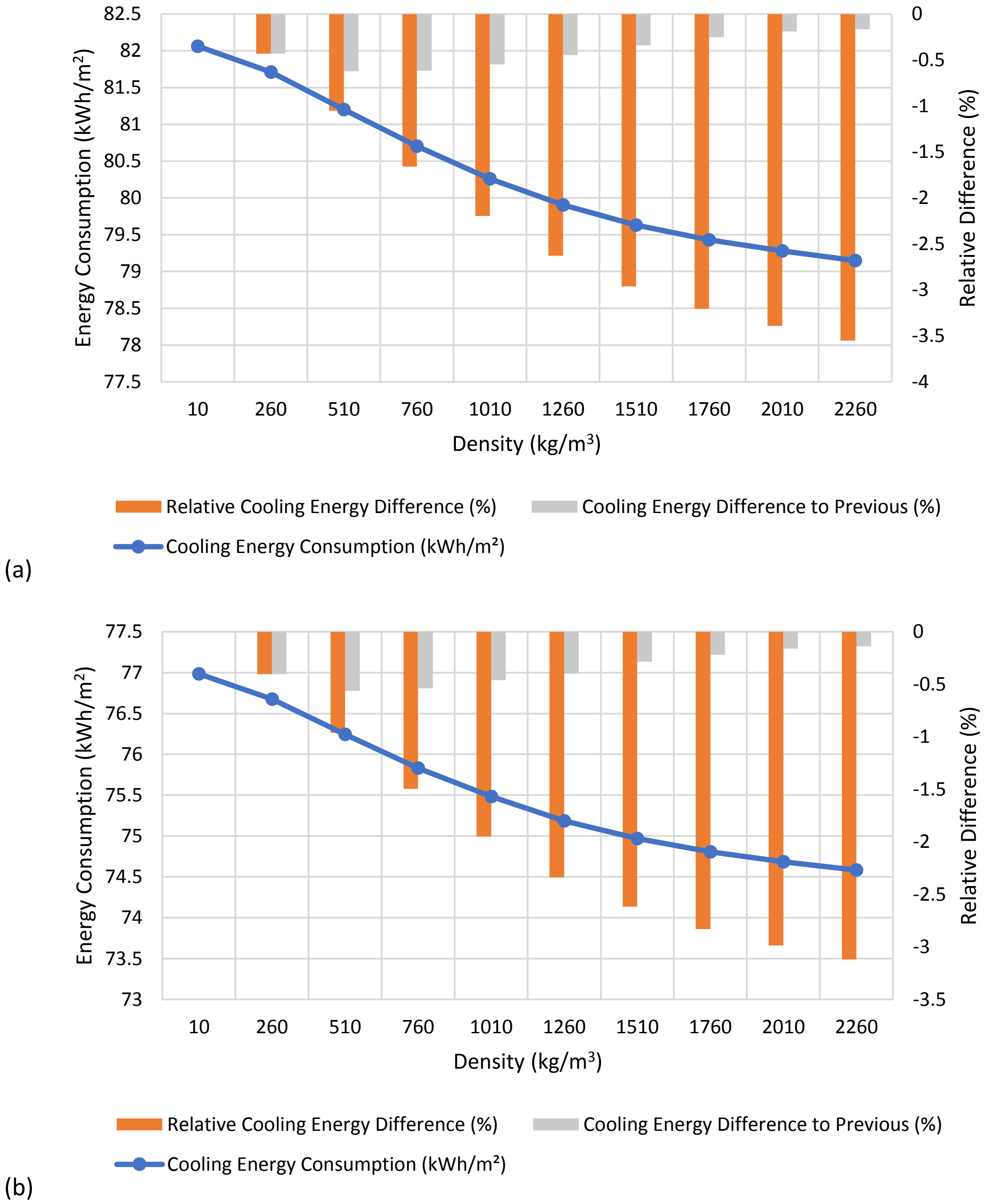
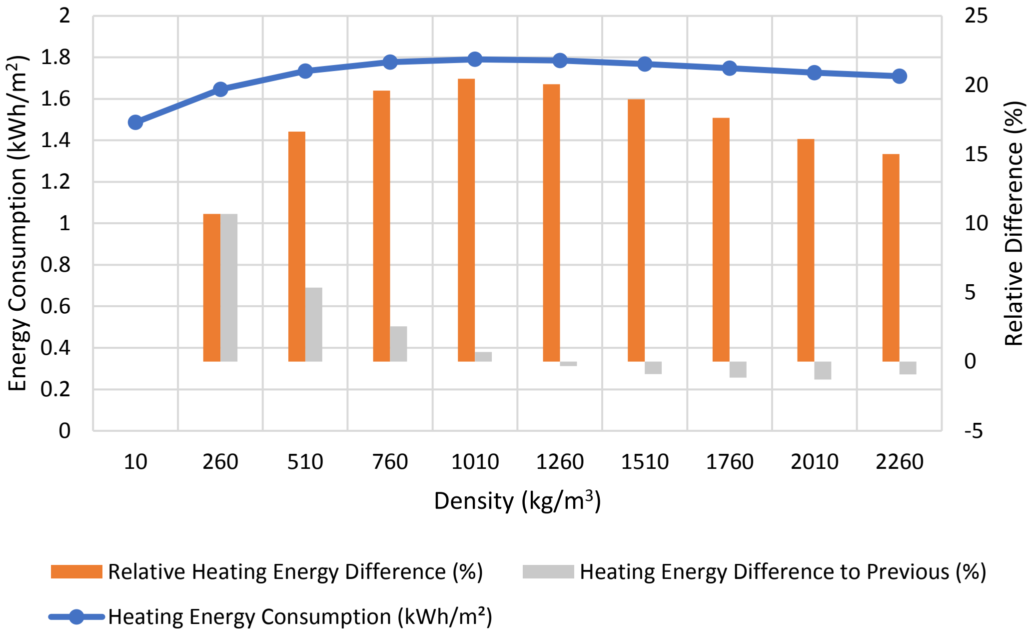
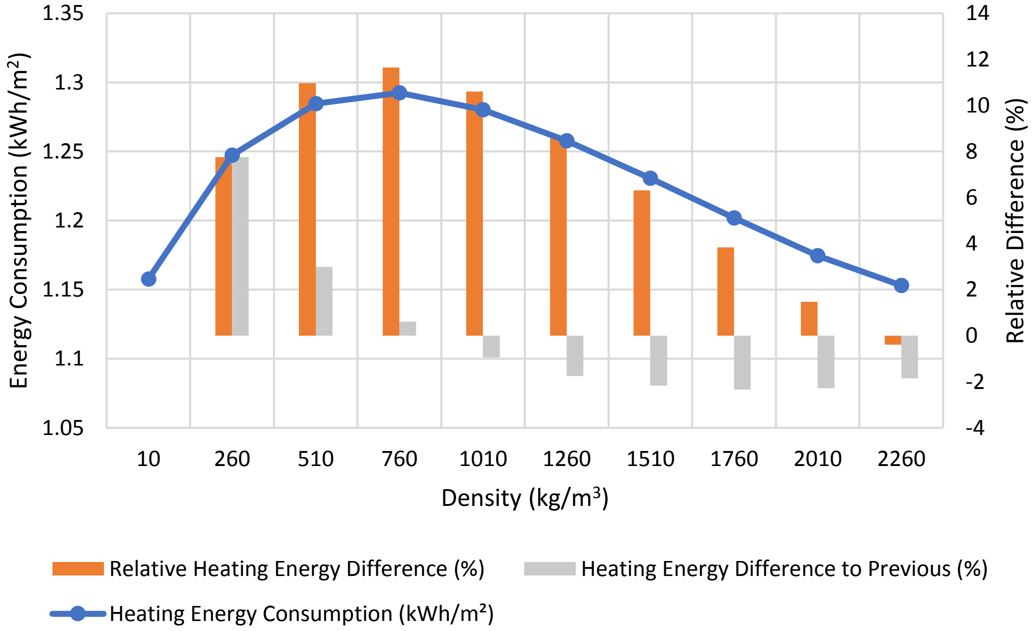


Figure 3.9: (a) Absolute and relative annual cooling loads of Alice Lane, with density subject to parametric study (b) Absolute and relative annual cooling loads of Bridge Park, with density subject to the parametric study

Figure 3.10 (a) shows a continuous increase in annual heating loads for the Alice Lane building, when increasing the density. After an upper limit is reached, a constant decrease in annual heating loads is observed. The rate of increase in annual heating loads decreases when increasing the density, up until an upper limit. After the upper limit is exceed, the rate of decrease in annual heating increases when increasing the density. This trend is also observed for the Bridge Park building, with annual heating loads presented in Figure 3.10 (b).



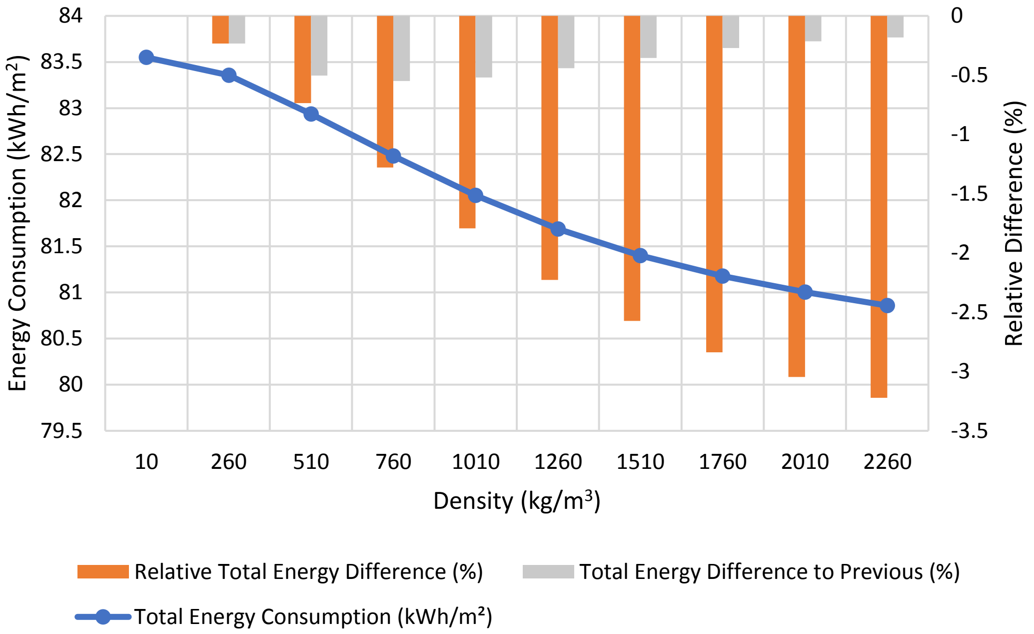
(a)



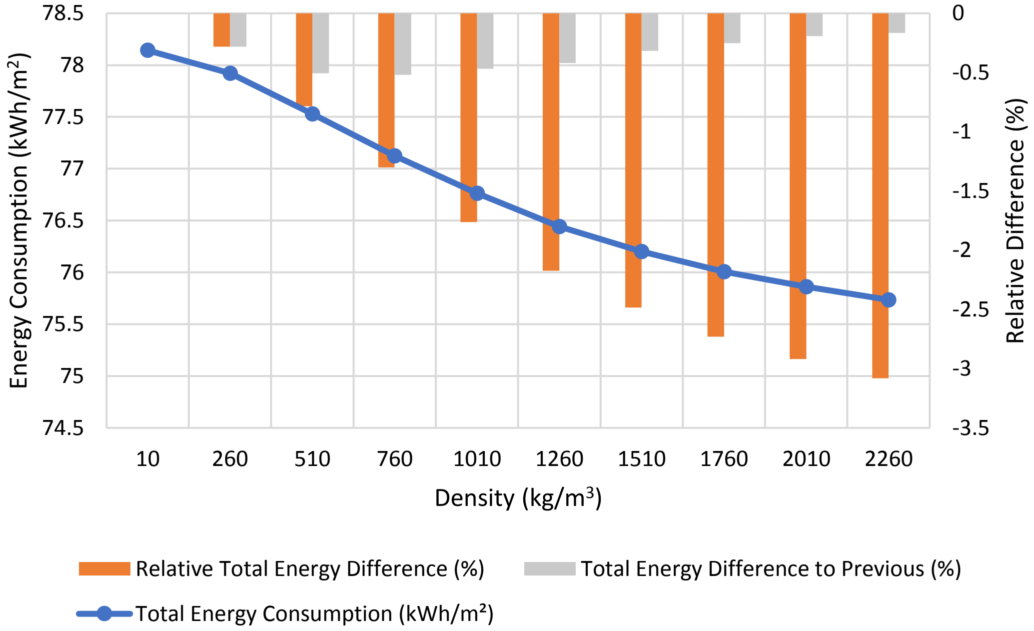
(b)

Figure 3.10: (a) Absolute and relative annual heating loads of Alice Lane, with density subject to parametric study (b) Absolute and relative annual heating loads of Bridge Park, with density subject to the parametric study

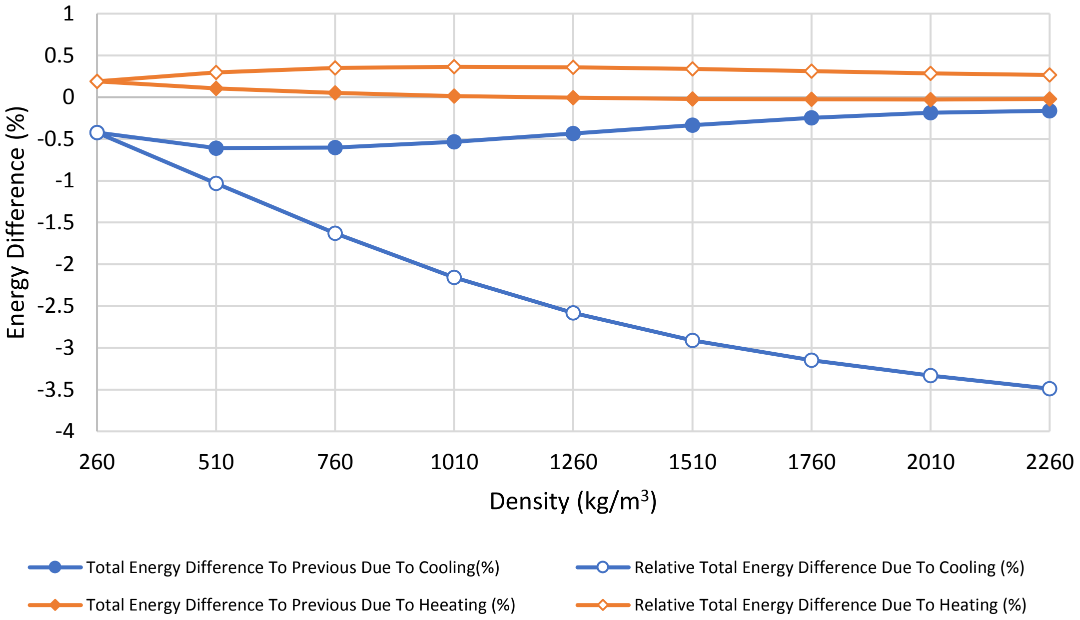
When combining the annual cooling and heating loads, it is observed that energy consumption is dominated by the cooling load. This is observed for Alice Lane and Bridge Park, as presented in Figure 3.11.


84
83.5
83
82.5
82
81.5
81
80.5
80
79.5
Energy Consumption (kWh/m²)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
Relative Difference (%)
10
260
510
760
1010
1260
1510
1760
2010
2260
Density (kg/m³)
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

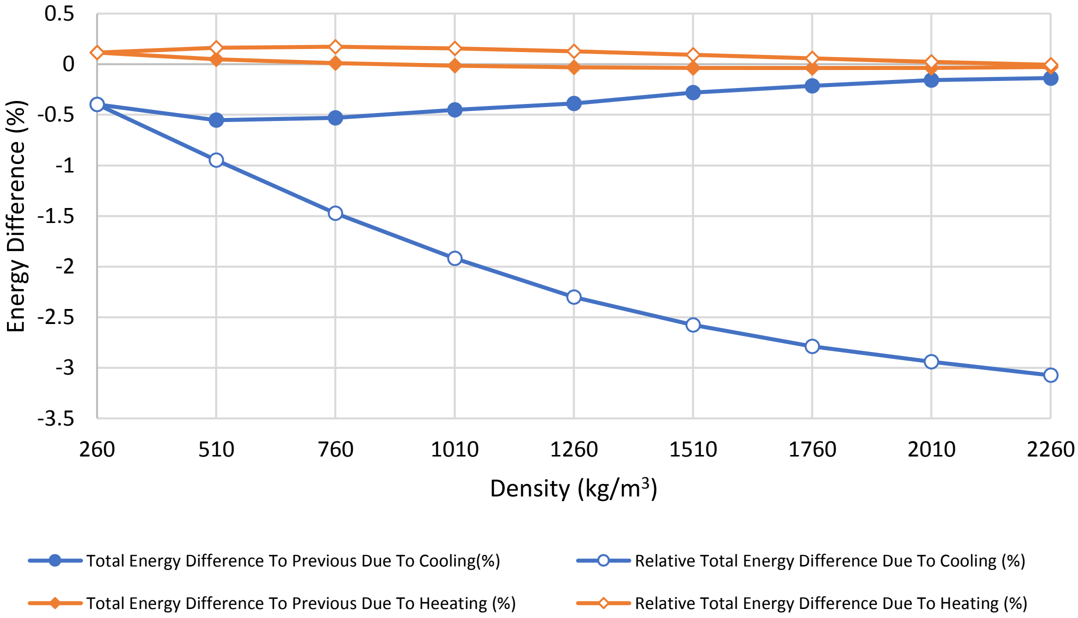
(a)


78.5
78
77.5
77
76.5
76
75.5
75
74.5
Energy Consumption (kWh/m²)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
Relative Difference (%)
10
260
510
760
1010
1260
1510
1760
2010
2260
Density (kg/m³)
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

(b)



(c)

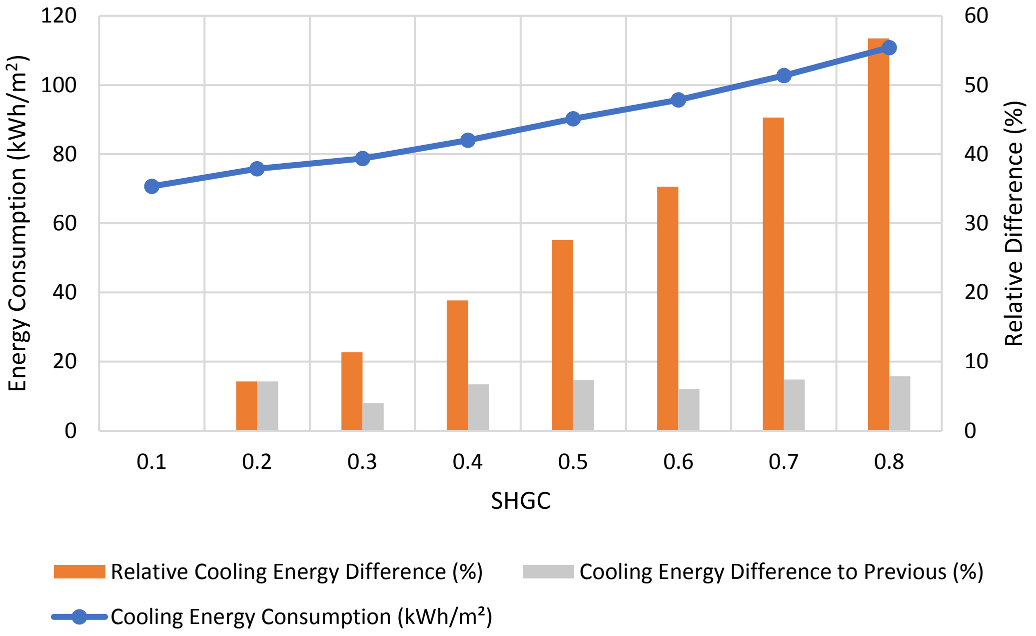


(d)

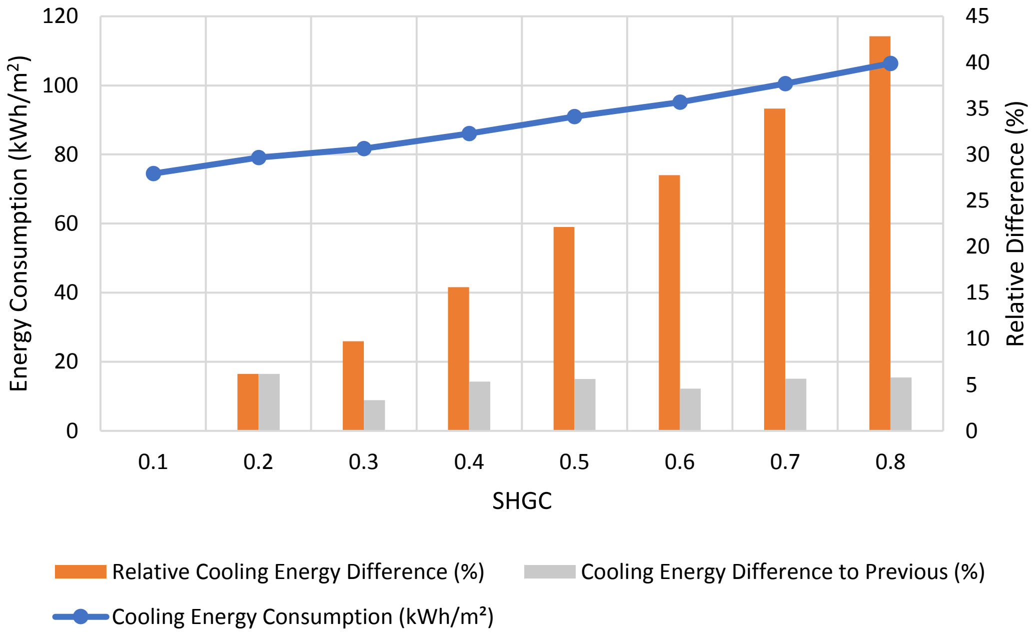
Figure 3.11: (a) Absolute and relative combined annual cooling and heating loads of Alice Lane, with density subject to parametric study (b) Absolute and relative combined annual cooling and heating loads of Bridge Park, with density subject to the parametric study (c) Relative combined annual cooling and heating loads of Alice Lane due to cooling and heating, with density subject to parametric study (d) Relative combined annual cooling and heating loads of Bridge Park due to cooling and heating, with density subject to the parametric study

3.3.4 Solar Heat Gain Coefficient (SHGC)

Figure 3.12 (a) shows a continuous increase in annual cooling loads for the Alice Lane building, when increasing the SHGC, using the parameter values contained in Table C.14. However, the rate of increase in annual cooling loads is inconsistent when increasing the SHGC. This trend is also observed for the Bridge Park building, with annual cooling loads presented in Figure 3.12 (b).



(a)



(b)

Figure 3.12: (a) Absolute and relative annual cooling loads of Alice Lane, with SHGC subject to parametric study (b) Absolute and relative annual cooling loads of Bridge Park, with SHGC subject to parametric study

Figure 3.13 (a) shows a continuous decrease in annual heating loads for the Alice Lane building, when increasing the SHGC. However, the rate of decrease in annual heating loads is inconsistent when increasing the SHGC. This trend is also observed for the Bridge Park building, with annual heating loads presented in Figure 3.13 (b).

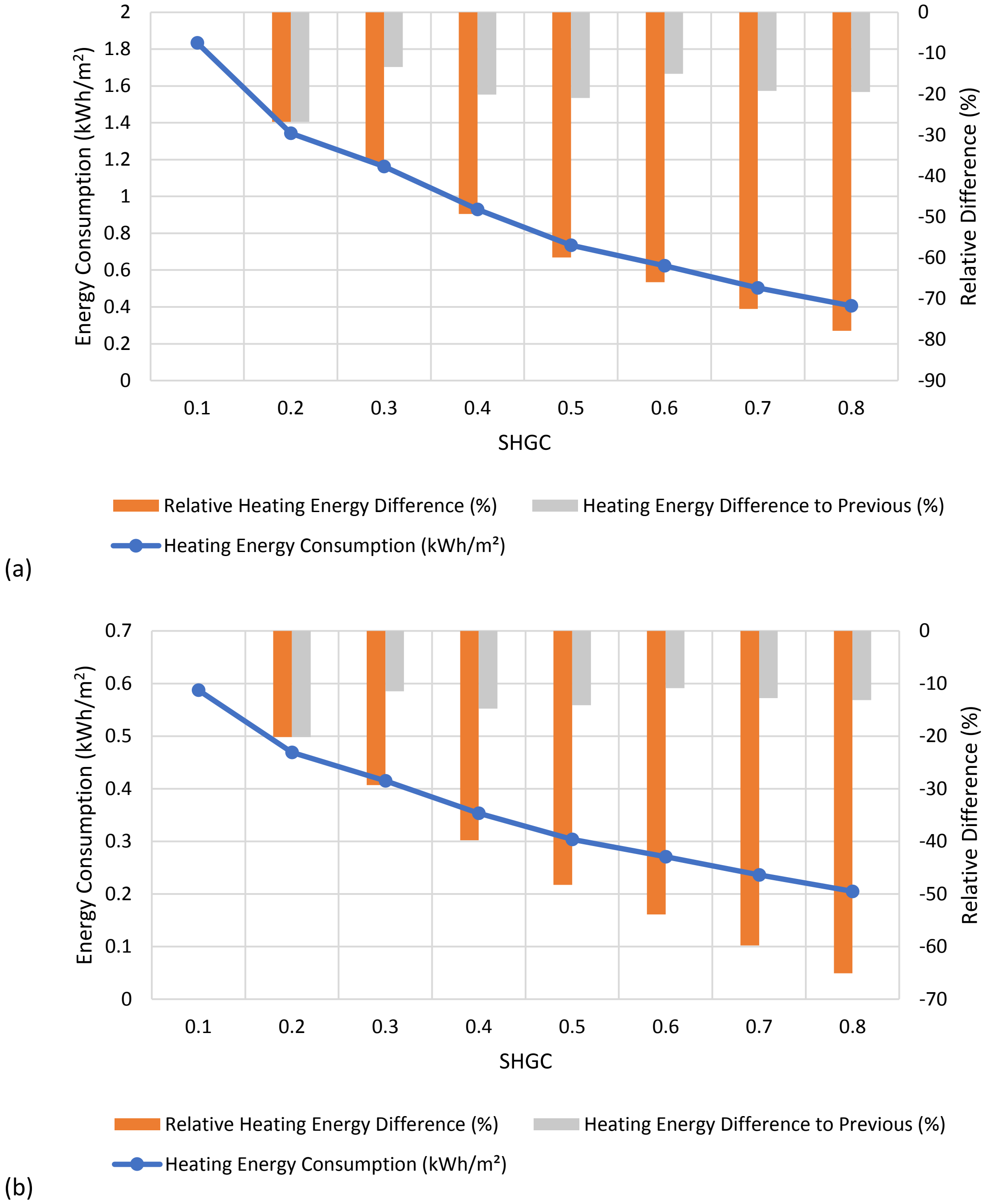
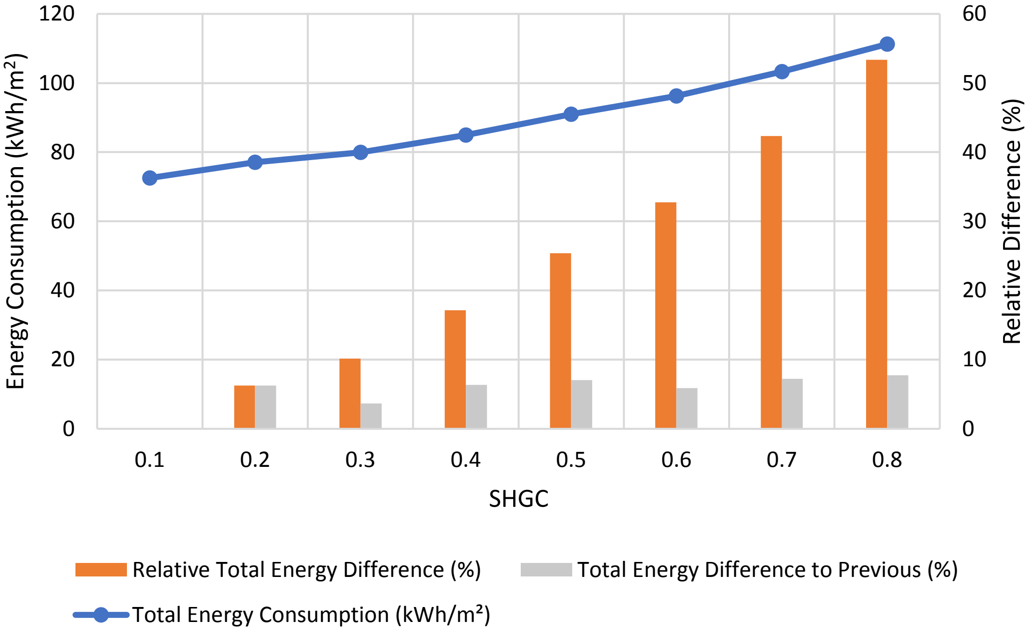
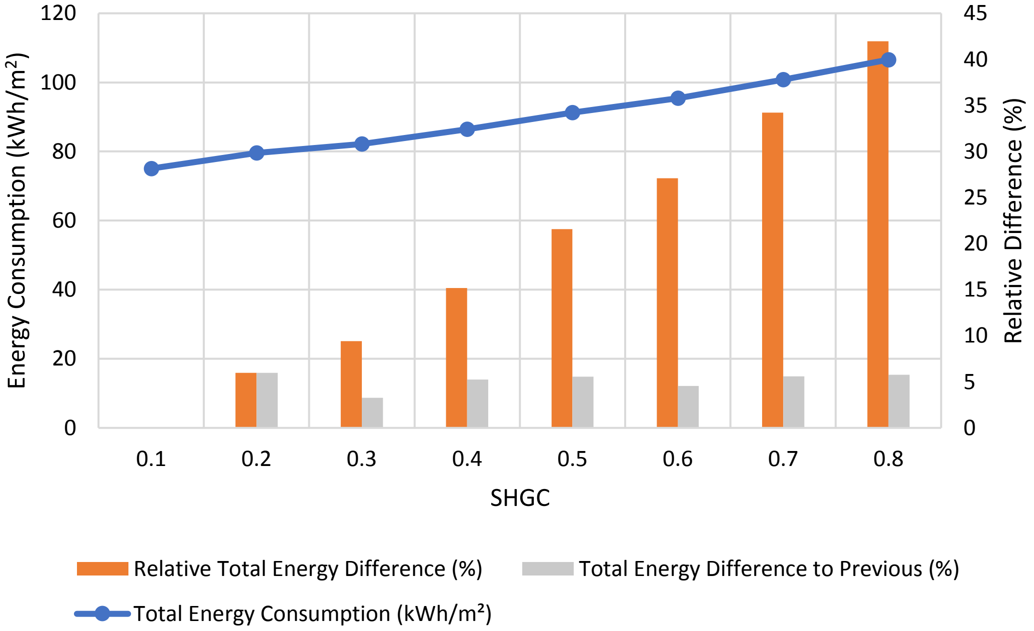


Figure 3.13: (a) Absolute and relative annual heating loads of Alice Lane, with SHGC subject to parametric study (b) Absolute and relative annual heating loads of Bridge Park, with SHGC subject to parametric study

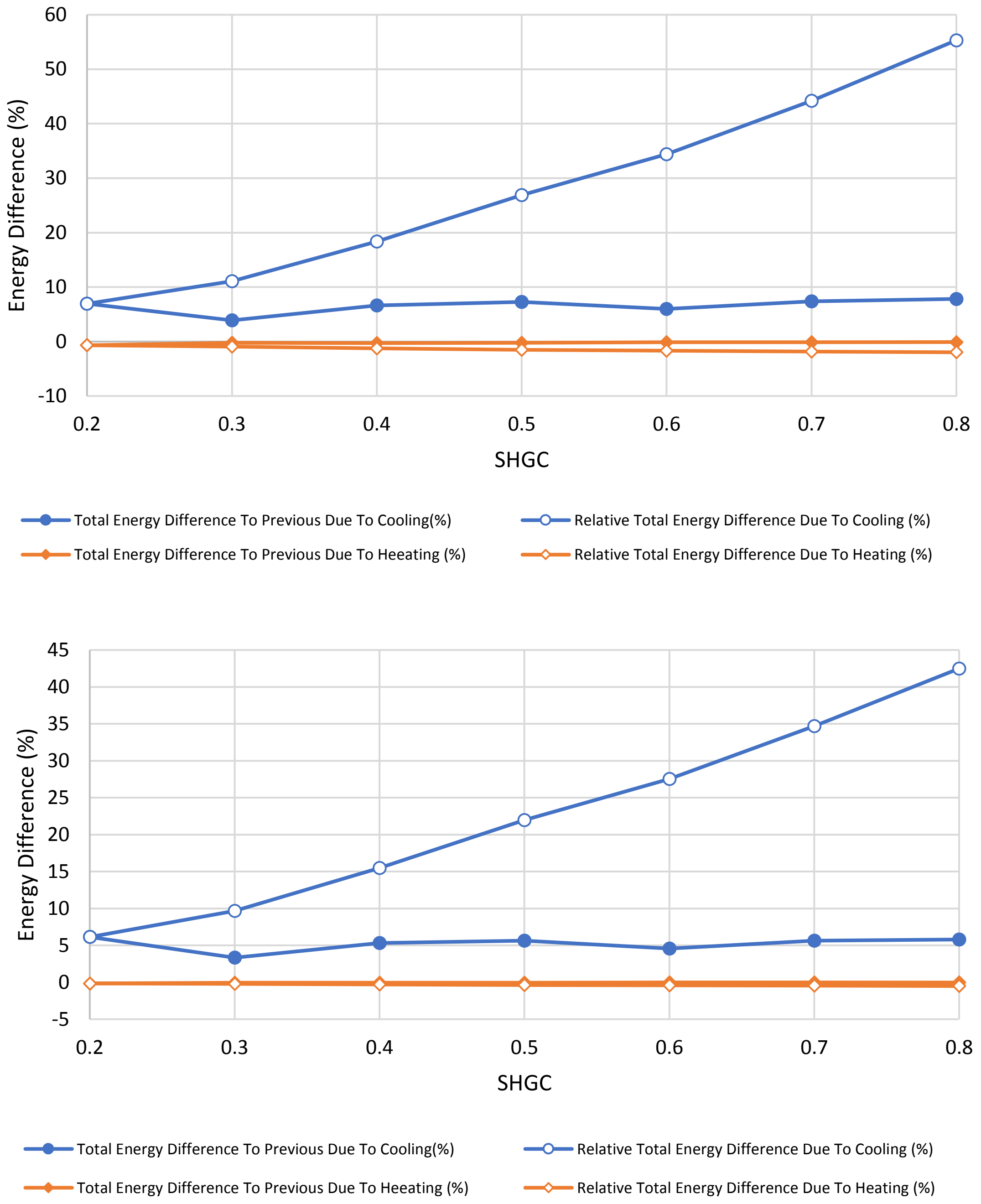
When combining the annual cooling and heating loads, it is observed that energy consumption is dominated by the cooling load. This is observed for Alice Lane and Bridge Park, as presented in Figure 3.14.


120
100
80
60
40
20
0
Energy Consumption (kWh/m²)
60
50
40
30
20
10
0
Relative Difference (%)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
SHGC
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

(a)


120
100
80
60
40
20
0
Energy Consumption (kWh/m²)
45
40
35
30
25
20
15
10
5
0
Relative Difference (%)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
SHGC
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

(b)



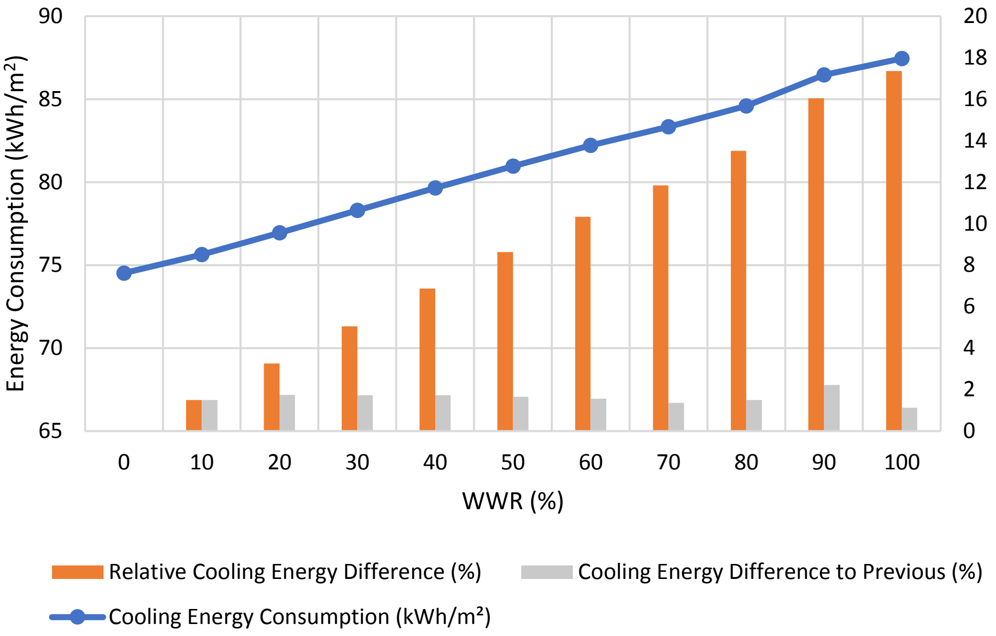
(c)

(d)

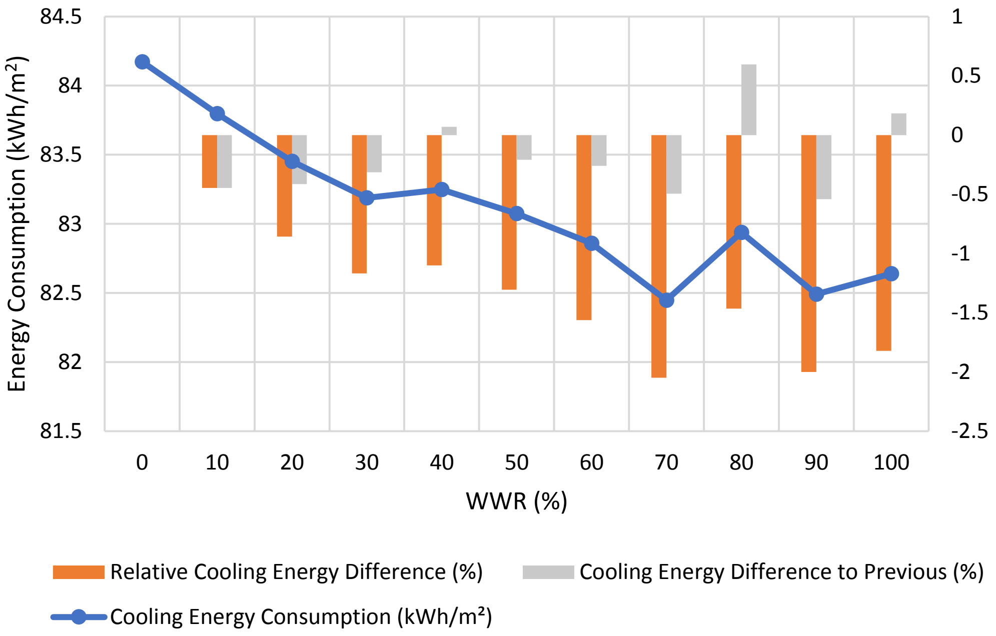
Figure 3.14: (a) Absolute and relative combined annual cooling and heating loads of Alice Lane, with SHGC subject to parametric study (b) Absolute and relative combined annual cooling and heating loads of Bridge Park, with SHGC subject to the parametric study (c) Relative combined annual cooling and heating loads of Alice Lane due to cooling and heating, with SHGC subject to parametric study (d) Relative combined annual cooling and heating loads of Bridge Park due to cooling and heating, with SHGC subject to the parametric study

3.3.5 Window-to-Wall Ratio (WWR)

Figure 3.15 (a) shows a continuous increase in annual cooling loads for the Alice Lane building, when increasing the WWR, using the parameter values contained in Table C.15. However, the rate of increase in annual cooling loads is inconsistent when increasing the WWR. From Figure 3.15 (b), a continuous decrease in annual cooling loads can be observed for the Bridge Park building, up to a WWR of 30%. A slight increase in annual cooling loads with 40% WWR is followed by a continuous decrease in annual cooling loads up to a WWR of 70%. Annual cooling loads show a pattern of increase/decrease in annual cooling loads with WWR between 80% and 100%. The varying nature of annual cooling loads may be attributed to the effect that the WWR has on the heat balance of the building exterior.



(a)



(b)

Figure 3.15: (a) Absolute and relative annual cooling loads of Alice Lane, with WWR subject to parametric study (b) Absolute and relative annual cooling loads of Bridge Park, with WWR subject to parametric study

Figure 3.16 (a) shows a continuous decrease in annual heating loads for the Alice Lane building, when increasing the WWR. However, the rate of decrease in annual heating loads is inconsistent when increasing the WWR. In contrast, Figure 3.16 (b) shows a continuous increase in annual heating loads for the Bridge Park building, when increasing the WWR. However, the rate of increase in annual heating loads is inconsistent when increasing the WWR.

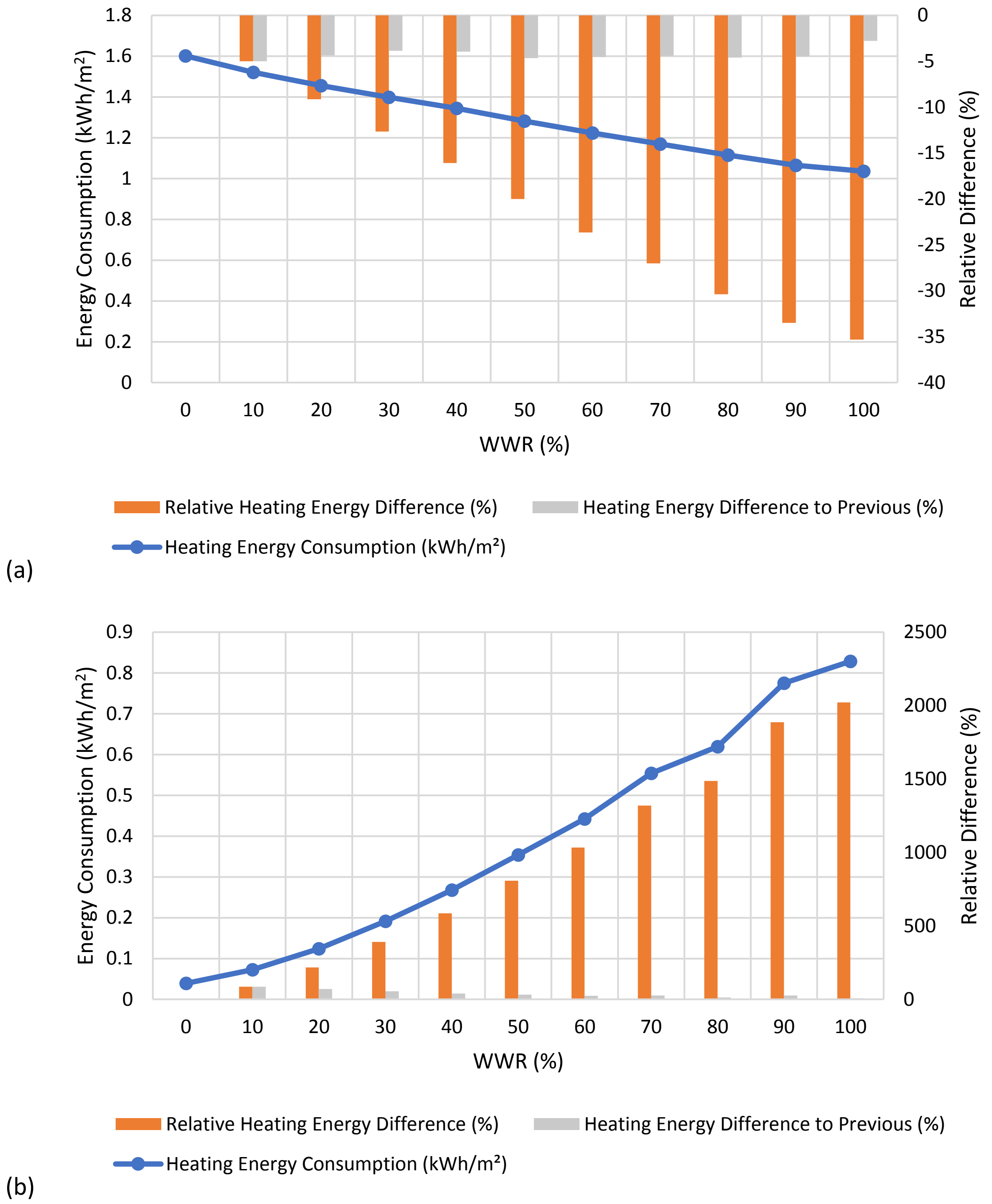
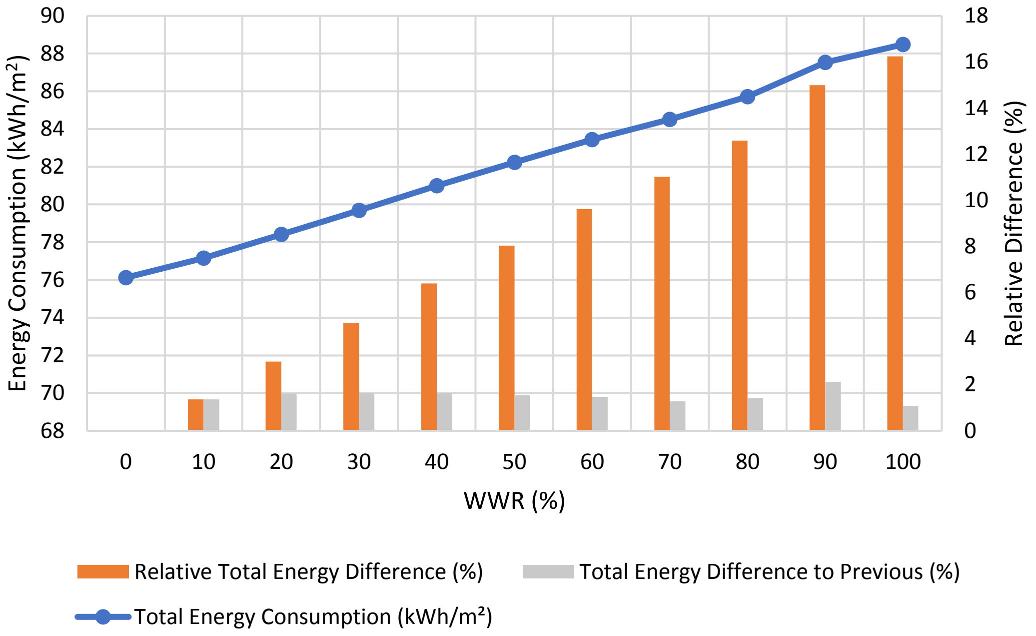
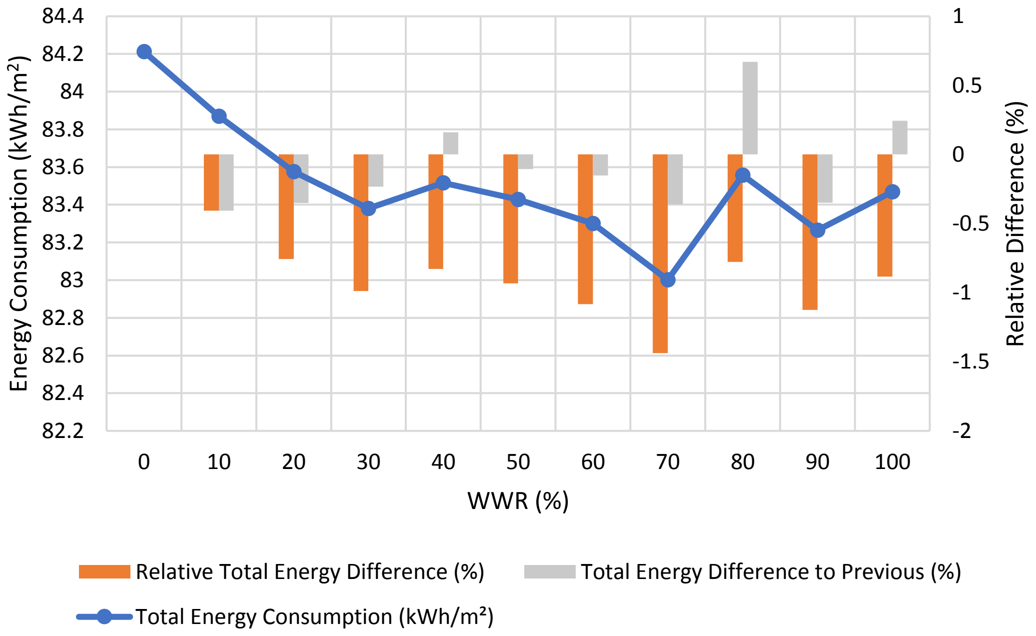


Figure 3.16: (a) Absolute and relative annual heating loads of Alice Lane, with WWR subject to parametric study (b) Absolute and relative annual heating loads of Bridge Park, with WWR subject to parametric study

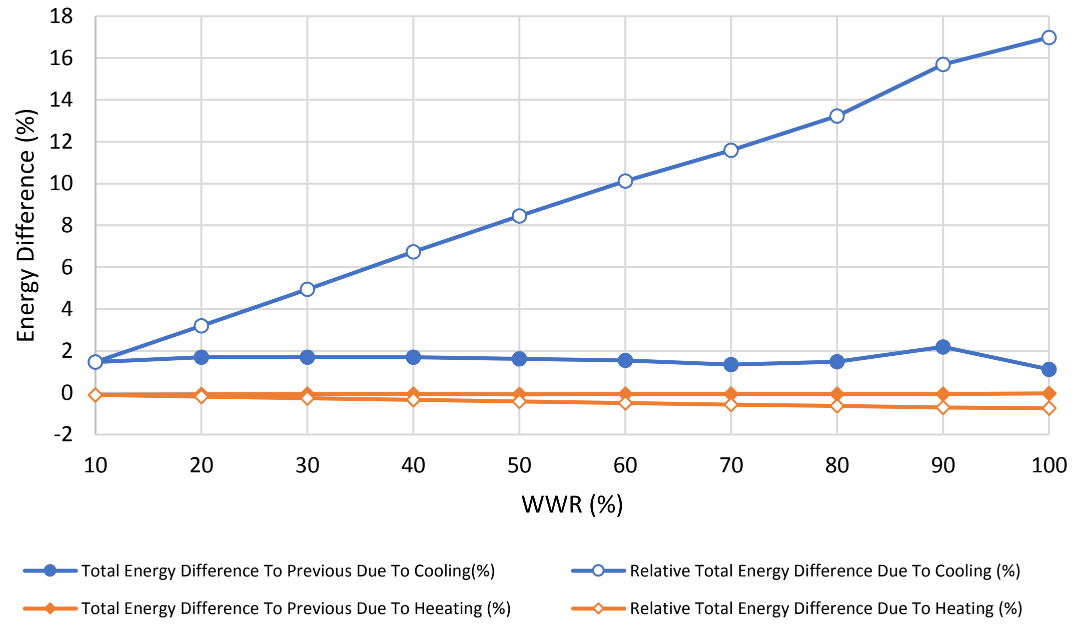
When combining the annual cooling and heating loads, it is observed that energy consumption is dominated by the cooling load. This is observed for Alice Lane and Bridge Park, as presented in Figure 3.17.


Energy Consumption (kWh/m²)
90
88
86
84
82
80
78
76
74
72
70
68
Relative Difference (%)
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
WWR (%)
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

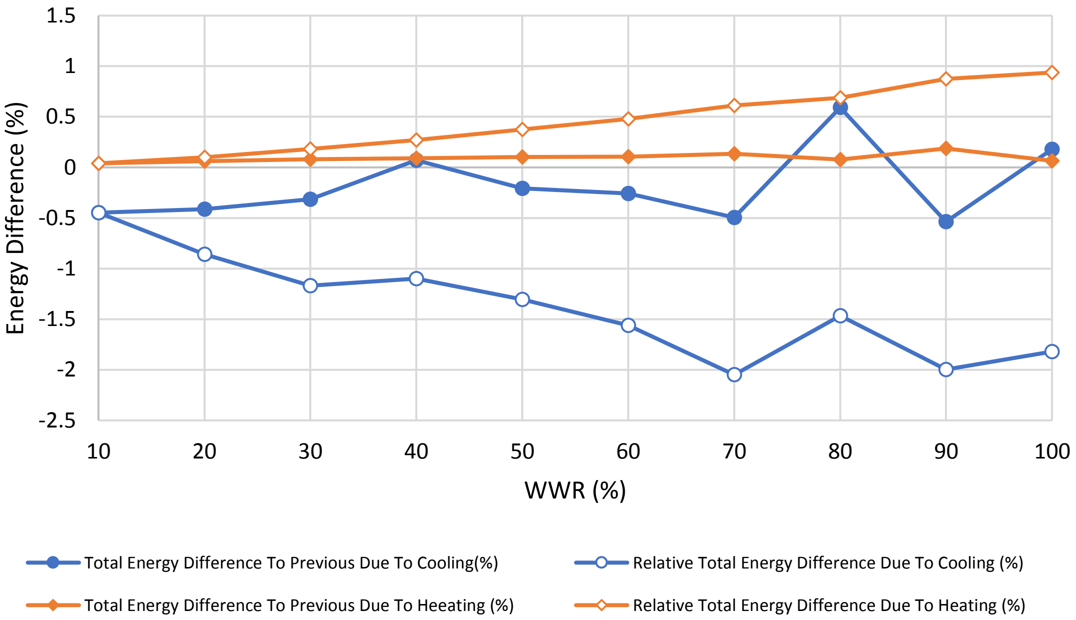
(a)


Energy Consumption (kWh/m²)
84.4
84.2
84
83.8
83.6
83.4
83.2
83
82.8
82.6
82.4
82.2
Relative Difference (%)
1
0.5
0
-0.5
-1
-1.5
-2
0
10
20
30
40
50
60
70
80
90
100
WWR (%)
Relative Total Energy Difference (%)
Total Energy Difference to Previous (%)
Total Energy Consumption (kWh/m²)

(b)



(c)



(d)

Figure 3.17: (a) Absolute and relative combined annual cooling and heating loads of Alice Lane, with WWR subject to parametric study (b) Absolute and relative combined annual cooling and heating loads of Bridge Park, with WWR subject to the parametric study (c) Relative combined annual cooling and heating loads of Alice Lane due to cooling and heating, with WWR subject to parametric study (d) Relative combined annual cooling and heating loads of Bridge Park due to cooling and heating, with WWR subject to the parametric study

3.3.6 Thermal Diffusivity

Figure 3.18 (a) shows two different trends for cooling loads, depending on the thermal bulk property changed. When increasing the thermal conductivity, the cooling load applied to the building environment decreases. In contrast, when decreasing the specific heat capacity or density, the cooling load applied to the building environment increases. An inflection point for thermal diffusivity values, with specific heat subject to change, occurs at a thermal diffusivity of 2.34 x 10^{-7} m/s^2. Although the thermal diffusivity values, calculated with density subject to change, do not reach similar values to that of specific heat, they follow the same trend as specific heat. The observations made for Figure 3.18 (a) are also present in Figure 3.18 (b).

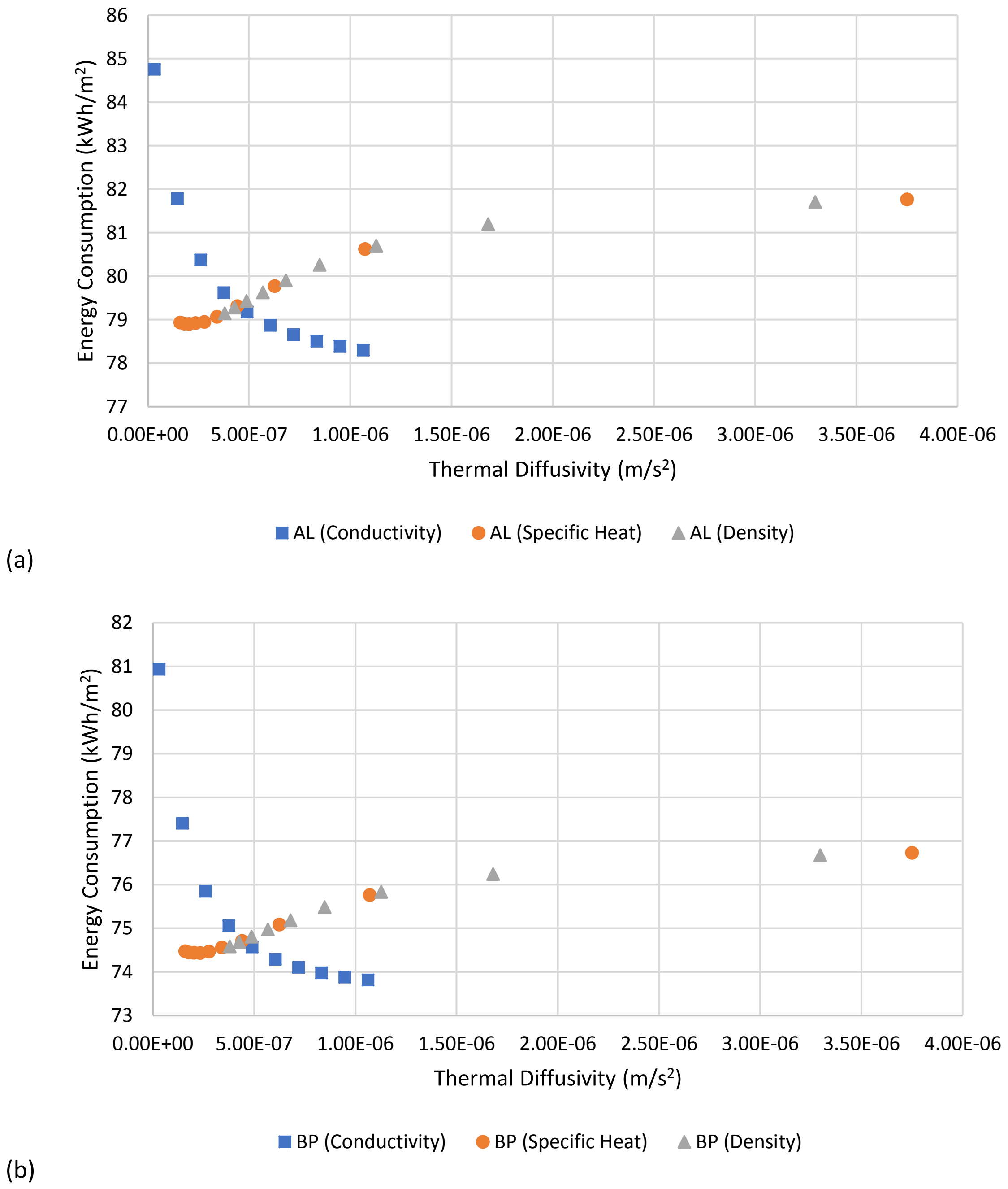
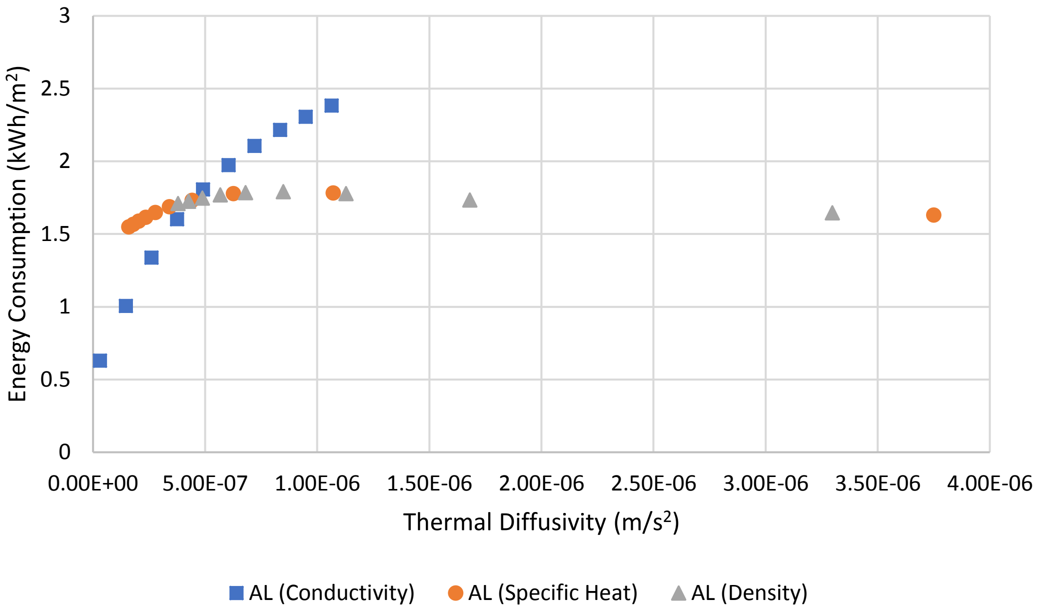
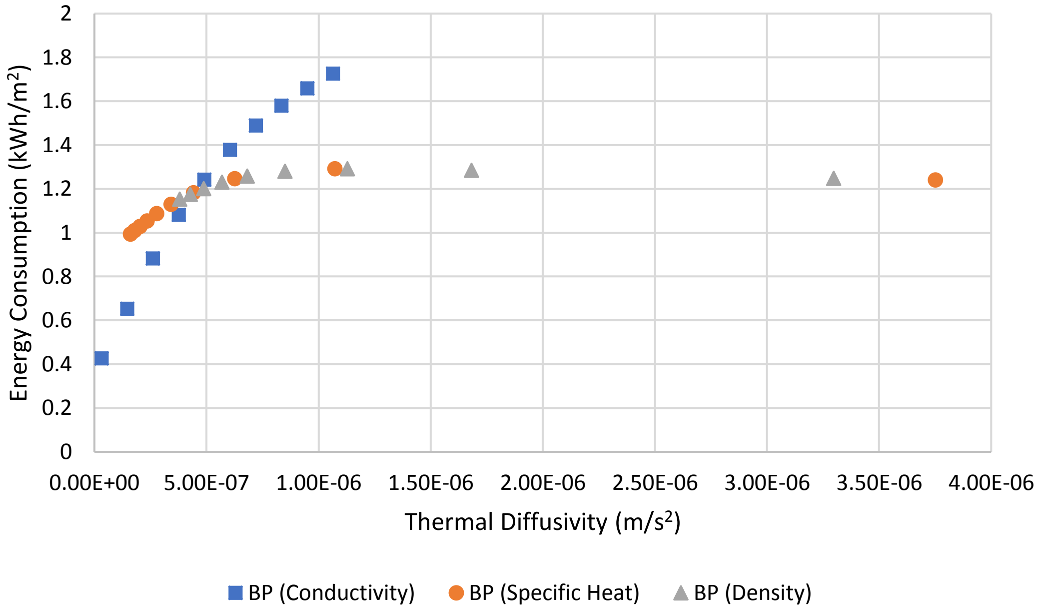


Figure 3.18: (a) Absolute cooling loads of Alice Lane, with Thermal Diffusivity subject to parametric study (b) Absolute cooling loads of Bridge Park, with Thermal Diffusivity subject to parametric study

In contrast to the results of cooling loads, Figure 3.19 (a) shows similar trends for heating loads regardless of the thermal bulk property changed. When increasing the thermal conductivity, the heating load applied to the building environment increases. Similarly, when decreasing the specific heat capacity or density, the heating load applied to the building environment increases. An inflection point for thermal diffusivity values, with specific heat and density subject to change can be observed. These inflection point values are 1.06 x 10^{-6} m/s^2 and 8.49 x 10^{-7} m/s^2. The observations made for Figure 3.19 (a) are also present in Figure 3.19 (b).



(a)



(b)

Figure 3.19: (a) Absolute heating loads of Alice Lane, with Thermal Diffusivity subject to parametric study (b) Absolute heating loads of Bridge Park, with Thermal Diffusivity subject to parametric study

3.4 Results Discussion

The first variable analysed is thermal conductivity. Increasing the thermal conductivity results in additional heat being transferred from a warm to cold surface. For Alice Lane and Bridge Park, increasing thermal conductivity acts favourably for annual cooling energy consumption but unfavourably for annual heating energy consumption. This behaviour can be attributed to additional solar and internal heat gains being removed through the building envelope due to the increased thermal conductivity.

Observations for Alice Lane are:

- Increasing the thermal conductivity from 0.05 W/(m.K) to 0.235 W/(m.K) results in a decrease of 3.51% in cooling energy consumption. Further increasing the thermal conductivity from 0.235 W/(m.K) to 1.715 W/(m.K) decreases energy consumption by an additional 4.26%.
- Increasing the thermal conductivity from 0.05 W/(m.K) to 0.235 W/(m.K) results in an increase of 60.05% in heating energy consumption. Further increasing the thermal conductivity from 0.235 W/(m.K) to 1.715 W/(m.K) increases energy consumption by an additional 136.85%.
- Increasing the thermal conductivity from 0.05 W/(m.K) to 0.235 W/(m.K) results in a decrease of 3.04% in combined cooling and heating energy consumption. Further increasing the thermal conductivity from 0.235 W/(m.K) to 1.715 W/(m.K) decreases energy consumption by an additional 2.54%.

Observations for Bridge Park are:

- Increasing the thermal conductivity from 0.05 W/(m.K) to 0.235 W/(m.K) results in a decrease of 4.36% in cooling energy consumption. Further increasing the thermal conductivity from 0.235 W/(m.K) to 1.715 W/(m.K) decreases energy consumption by an additional 4.64%.
- Increasing the thermal conductivity from 0.05 W/(m.K) to 0.235 W/(m.K) results in an increase of 53.26% in heating energy consumption. Further increasing the thermal conductivity from 0.235 W/(m.K) to 1.715 W/(m.K) increases energy consumption by an additional 164.01%.
- Increasing the thermal conductivity from 0.05 W/(m.K) to 0.235 W/(m.K) results in a decrease of 4.06% in combined cooling and heating energy consumption. Further increasing the thermal conductivity from 0.235 W/(m.K) to 1.715 W/(m.K) decreases energy consumption by an additional 3.22%.

The second variable analysed is specific heat capacity. Increasing the specific heat capacity allows the material to store additional heat. For Alice Lane and Bridge Park, increasing specific heat capacity acts favourably for annual cooling energy consumption and unfavourably for annual heating energy consumption. However, increasing the heat capacity beyond 350 J/(kg.K) acts favourably for annual heating energy consumption.

Observations for Alice Lane are:

- The most significant decrease in cooling energy consumption is observed for the initial increase in specific heat capacity. Increasing the specific heat capacity from 100 J/(kg.K) to 350 J/(kg.K) results in a decrease of 1.39% in cooling energy consumption. Further increasing the specific heat capacity from 350 J/(kg.K) to 1850 J/(kg.K) decreases energy consumption by an additional 2.14%. At specific heat capacities of 2100 and 2350 J/(kg.K), an increase in energy consumption of only 0.008% and 0.034% is observed compared to the cooling energy consumption associated with specific heat capacities of 1850 and 2100 J/(kg.K).
- Increasing the increasing the specific heat capacity from 100 J/(kg.K) to 350 J/(kg.K) results in an increase of 9.31% in heating energy consumption. Further increasing the specific heat capacity from 350 J/(kg.K) to 2350 J/(kg.K) decreases energy consumption by 13.11%.
- Increasing the specific heat capacity from 100 J/(kg.K) to 350 J/(kg.K) results in a decrease of 1.19% in combined cooling and heating energy consumption for Alice Lane. Further increasing the specific heat capacity further from 350 J/(kg.K) to 2350 J/(kg.K) decreases energy consumption by an additional 2.33%.

Observations for Bridge Park are:

- Similar to Alice Lane, the most significant decrease in cooling energy consumption for Bridge Park is observed for the initial increase in specific heat capacity. Increasing the specific heat capacity from 100 J/(kg.K) to 350 J/(kg.K) results in a decrease of 1.26% in cooling energy consumption. Further increasing the specific heat capacity from 350 J/(kg.K) to 1600 J/(kg.K) decreases energy consumption by an additional 1.75%. At specific heat capacities of 1850, 2100 and 2350 J/(kg.K), an increase in energy consumption of 0.00038%, 0.01158%, and 0.03521% is observed.
- Increasing the specific heat capacity from 100 J/(kg.K) to 350 J/(kg.K) results in an increase of 4.13% in heating energy consumption. Further increasing the specific heat capacity from 350 J/(kg.K) to 2350 J/(kg.K) decreases energy consumption by 23.07%.
- Increasing the specific heat capacity from 100 J/(kg.K) to 350 J/(kg.K) results in an decrease of 1.17% in combined cooling and heating energy consumption. Further increasing the specific heat capacity further from 350 J/(kg.K) to 2350 J/(kg.K) decreases energy consumption by an additional 2.07%.

The third variable analysed is material density. Like the specific heat capacity, increasing material density allows the material to store additional heat. As a result, the general observations made for the specific heat capacity is the same for material density.

Observations for Alice Lane are:

- Increasing the material density from 10 kg/m^3 to 2260 kg/m^3 results in a decrease of 3.55% in cooling energy consumption for Alice Lane.
- Increasing the material density from 10 kg/m^3 to 1010 kg/m^3 results in an increase of 20.44% in heating energy consumption. Further increasing the material density from 1010 kg/m^3 to 2260 kg/m^3 decreases energy consumption by 4.50%.
- Increasing the material density from 10 kg/m^3 to 2260 kg/m^3 results in a decrease of 3.22% in combined cooling and heating energy consumption for Alice Lane.

Observations for Bridge Park are:

- Increasing the material density from 10 kg/m^3 to 2260 kg/m^3 results in a decrease of 3.12% in cooling energy consumption for Bridge Park.
- Increasing the material density from 10 kg/m^3 to 760 kg/m^3 results in an increase of 11.65% in heating energy consumption. Further increasing the material density from 760 kg/m^3 to 2260 kg/m^3 decreases energy consumption by 10.79%.
- Increasing the density from 10 kg/m^3 to 2260 kg/m^3 results in a decrease of 3.08% in combined cooling and heating energy consumption.

The fourth variable analysed is the SHGC of external glazing. Increasing the SHGC allows for additional solar heat gains. Increasing the solar heat gains acts unfavourably for annual cooling energy consumption but favourably for annual heating energy consumption.

Observations for Alice Lane are:

- Increasing the SHGC of glazing from 0.1 to 0.8 results in an increase of 56.76% in cooling energy consumption.
- The most significant decrease in heating energy consumption for Alice Lane is observed for the initial increase in SHGC. Increasing the SHGC of glazing from 0.1 to 0.2 results in a decrease of 26.79% in heating energy consumption. Further increasing the SHGC of glazing from 0.2 to 0.8 decreases energy consumption by an additional 69.76%.

- Increasing the SHGC from 0.1 to 0.8 results in an increase of 53.35% in combined cooling and heating energy consumption for Alice Lane.

Observations for Bridge Park are:

- Increasing the SHGC of glazing from 0.1 to 0.8 results in an increase of 42.83% in cooling energy consumption.
- Like Alice Lane, the most significant decrease in heating energy consumption for Bridge Park is observed for the initial increase in SHGC. Increasing the SHGC of glazing from 0.1 to 0.2 results in a decrease of 20.16% in heating energy consumption. Further increasing the SHGC of glazing from 0.2 to 0.8 decreases energy consumption by an additional 56.27%.
- Increasing the SHGC from 0.1 to 0.8 results in an increase of 41.98% in combined cooling and heating energy consumption.

The final variable analysed is building WWR. Increasing the WWR increases the maximum amount of solar heat gains which can enter a building and increases the heat transferred through the glazing. This balance in heat transfer mechanisms results in two different sets of observations. Thus a reduction in annual cooling energy consumption is observed when more heat is removed through the building envelope than gained due to additional solar heat gains. The inverse is true for reductions in heating energy consumption.

Observations for Alice Lane are:

- Increasing the WWR from 0% to 100% results in an increase of 17.35% in cooling energy consumption.
- Increasing the WWR from 0% to 100% results in a decrease of 35.33% in heating energy consumption.
- Increasing the WWR from 0% to 100% results in an increase of 16.24% in combined cooling and heating energy consumption.

Observations for Bridge Park are:

- Increasing the WWR from 0% to 100% results in a decrease of 1.82% in cooling energy consumption. An increase of 0.07%, 0.60%, and 0.18% in energy consumption is experienced at a WWR of 40%, 80%, and 100% compared to cooling energy consumption calculated with a WWR of 30%, 70%, and 90%.
- Increasing WWR from 0% to 50% results in an increase of 806.78% in heating energy consumption. Further increasing WWR from 50% to 100% increases energy consumption by an additional 134.06%.
- Increasing the WWR from 0% to 100% results in a decrease of 0.88% in combined cooling and heating energy consumption.

Regarding the analysis of thermal diffusivity, the first analysed variable is thermal conductivity. Observations are made for the thermal diffusivity range of 3.10×10^{-8} to 1.06×10^{-6} m/s^2.

Observations for Alice Lane are:

- Cooling energy consumption decreases by 7.62%.
- Heating energy consumption increases by 279.08%.
- Combined cooling and heating energy consumption decreases by 5.51%.

Observations for Bridge Park are:

- Cooling energy consumption decreases by 8.80%.
- Heating energy consumption increases by 304.63%.
- Combined cooling and heating energy consumption decreases by 7.15%.

When changing specific heat capacity, observations are made for the thermal diffusivity range of 1.6 x 10^{-7} to 3.75 x 10^{-6} m/s^2.

Observations for Alice Lane are:

- Increasing thermal diffusivity from 1.6 x 10^{-7} to 2.03 x 10^{-7} m/s^2 decreases cooling energy consumption by 0.04%. Further increasing thermal diffusivity from 2.03 x 10^{-7} to 3.75 x 10^{-6} m/s^2 increases energy consumption by 3.63%.
- Increasing thermal diffusivity from 1.6 x 10^{-7} to 1.07 x 10^{-6} m/s^2 increases heating energy consumption by 15.09%. Further increasing thermal diffusivity from 1.07 x 10^{-6} to 3.75 x 10^{-6} m/s^2 decreases energy consumption by 8.52%.
- Increasing thermal diffusivity from 1.6 x 10^{-7} to 2.03 x 10^{-7} m/s^2 results in combined cooling and heating energy consumption increasing by 0.01%. Further increasing thermal diffusivity from 2.03 x 10^{-7} to 3.75 x 10^{-6} m/s^2 increases energy consumption by an additional 3.61%.

Observations for Bridge Park are:

- Increasing thermal diffusivity from 1.6 x 10^{-7} to 2.34 x 10^{-7} m/s^2 decreases cooling energy consumption by 0.05%. Further increasing thermal diffusivity from 2.34 x 10^{-7} to 3.75 x 10^{-6} m/s^2 increases energy consumption by 3.08%.
- Increasing thermal diffusivity from 1.6 x 10^{-7} to 1.07 x 10^{-6} m/s^2 increases heating energy consumption by 29.99%. Further increasing thermal diffusivity from 1.07 x 10^{-6} to 3.75 x 10^{-6} m/s^2 decreases energy consumption by 3.96%.
- Increasing thermal diffusivity from 1.6 x 10^{-7} to 2.34 x 10^{-7} m/s^2 results in combined cooling and heating energy consumption increasing by 0.03%. Further increasing thermal diffusivity from 2.34 x 10^{-7} to 3.75 x 10^{-6} m/s^2 increases energy consumption by an additional 3.28%.

When changing density, observations are made for the thermal diffusivity range of 3.79 x 10^{-7} to 3.3 x 10^{-6} m/s^2.

Observations for Alice Lane are:

- Increasing thermal diffusivity from 3.79 x 10^{-7} to 3.3 x 10^{-6} m/s^2 increases cooling energy consumption by 3.24%.
- Increasing thermal diffusivity from 3.79 x 10^{-7} to 8.49 x 10^{-7} m/s^2 increases heating energy consumption by 4.71%. Further increasing thermal diffusivity from 8.49 x 10^{-7} to 3.3 x 10^{-6} m/s^2 decreases energy consumption by 8.1%.
- Increasing thermal diffusivity from 3.79 x 10^{-7} to 8.49 x 10^{-7} m/s^2 results in combined cooling and heating energy consumption increasing by 1.48%. Further increasing thermal diffusivity from 8.49 x 10^{-7} to 3.3 x 10^{-6} m/s^2 increases energy consumption by an additional 1.59%.

Observations for Bridge Park are:

- Increasing thermal diffusivity from 3.79 x 10^{-7} to 3.3 x 10^{-6} m/s^2 increases cooling energy consumption by 2.81%.
- Increasing thermal diffusivity from 3.79 x 10^{-7} to 1.13 x 10^{-6} m/s^2 increases heating energy consumption by 12.09%. Further increasing thermal diffusivity from 1.13 x 10^{-6} to 3.3 x 10^{-6} m/s^2 decreases energy consumption by 3.49%.

- Increasing thermal diffusivity from 3.79 x 10^{-7} to 1.13 x 10^{-6} m/s^2 results in combined cooling and heating energy consumption increasing by 1.83%. Further increasing thermal diffusivity from 1.13 x 10^{-6} to 3.3 x 10^{-6}m/s^2 increases energy consumption by an additional 1.03%.

The behaviour of thermal diffusivity can be attributed to how the components of thermal diffusivity are integrated within the heat balance equation. Whereas thermal conductivity influences heat transfer due to conduction, thermal capacitance provides inertia against all forms of heat transfer.

3.5 Conclusion

The design of structures requires careful consideration of the materials used. Not only for structural purposes but also for environmental comfort and energy usage purposes. As with structural design, designing for environmental comfort and optimal energy usage requires knowledge of building material properties and boundary conditions imposed on the building materials.

This chapter investigated the thermal performance of two office building designs by using building energy analysis software. A building located in Sandton and a building located in Cape Town, built for SA Green Star certification, were analysed. Parametric analysis was performed on five variables: thermal conductivity, specific heat capacity, density, SHGC, and WWR. Results were analysed comparing annual sensible cooling and heating loads. Comparisons were made using the energy difference between the first and subsequent configurations and the energy difference between consecutive configurations.

Results have shown that building thermal performance can be predictive, with quick changes possible by adjusting the materials' thermal bulk properties. However, caution is needed when targeting a specific thermal property as targeting a specific thermal property may result in unintended changes to the building environment. Changes to building glazing have been observed to be less predictive due to different building orientations and surrounding buildings obstructing the sun’s solar rays.

Chapter 4 The Modelling of a Base Case Low-Income House Using Heat-Only and Hygrothermal Analysis

4.1 Introduction

The thermal and moisture properties of building materials have a direct influence on occupancy comfort. Building materials are exposed to changing environmental conditions. Although attempts are made to limit exposure, complete environmental protection is either not provided or bypassed by building defects.

A 40 m^2 house is modelled to investigate the impact of environmental exposure. The building is representative of low-income housing built in the Western Cape in the South African Reconstruction and Development Programme (RDP) (Mayisela, 2018) to which local governmental regulations apply. This chapter aims to quantify the influence of building material exposure to moisture regarding simulated environmental variables, quantify the impact of changes to hygric material properties, and establish the importance of hygric properties of the building envelope and internal partitions. Subsequently, this chapter addresses Aim 2 of this study.

The purpose of the chapter is not to find and investigate the response of all buildings over a period of a week in extreme environmental conditions in South Africa. Rather, the purpose of the chapter is to investigate the response of a low-income building over a period of a week in typical environmental conditions in Cape Town, and provide insight into the inclusion of moisture in heat transfer when analysing a low-income building over a period of a week. Although only typical conditions are investigated, Chapter 5 reflects that extreme environmental conditions exist for low-income housing in South Africa. Investigating the response of a low-income building over a period of a week in extreme environmental conditions in Cape Town would require additional analysis.

The chapter is divided into five sections. Section 4.1 presents a brief discussion on the background of the chapter, as well as a breakdown of the structure of the chapter. Section 4.2 provides a model description, composed of a general overview of the building, a description of the input weather, assumptions made regarding internal heat gains, occupancy, lighting, ventilation, air infiltration/leakage, and building material properties, as well as a description of the base case analysis and parametric analysis of the building model. Section 4.3 presents a discussion of the results, focusing on the output of the building model analysis. This discussion includes descriptions of the outputs and observations of trends. The analysis of results focuses on evaluating the building model's relative performance, comparing the base case analysis results to the parametric analyses. Section 4.4 presents a discussion of the impact of assumptions made regarding building materials' hygric properties and how they are modelled.

4.2 Model Description

The adopted RDP house is based on the design of an RDP house modelled by Vosloo *et al.* (2015). Decisions regarding model input were guided by the Housing Standards of the Western Cape Government of South Africa (Rughubar, 2014). The model coordinates from the weather file are 33.98°S and 18.6°E at an elevation of 42 m. Furthermore, the house is oriented north. A depiction of the model is presented in Figure 4.1.

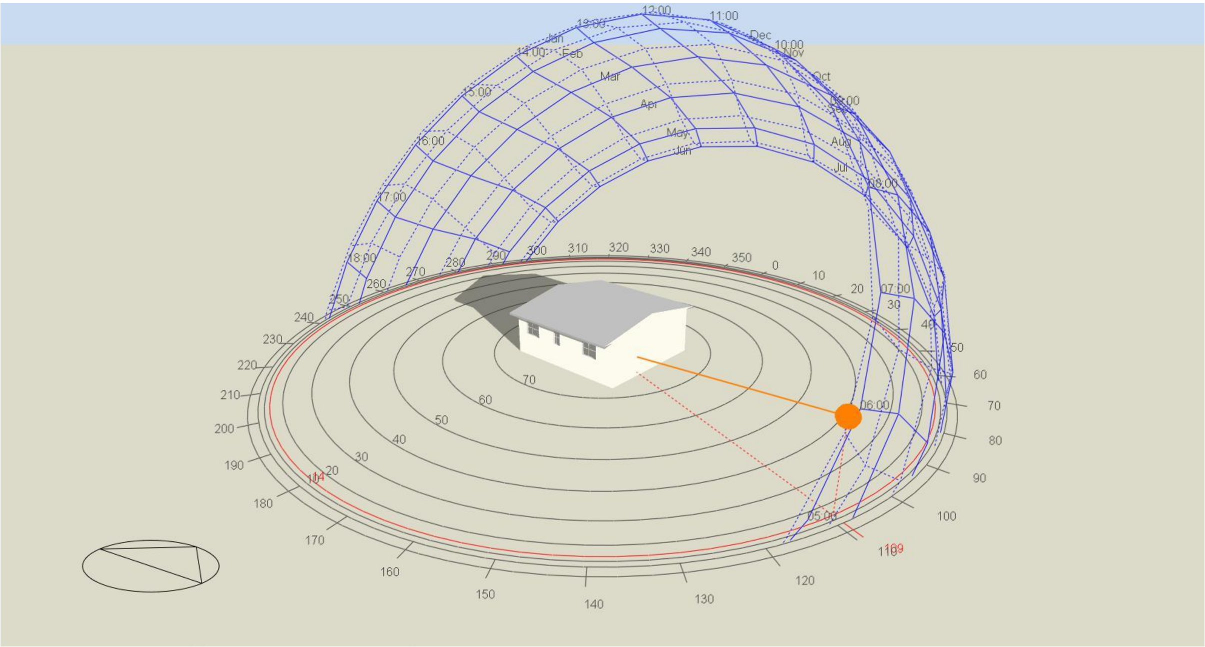


Figure 4.1: Sun Path Diagram of RDP House

The RDP house model description consists of three sets of inputs: weather data, model data, and simulation settings. The following sections of the model description provide details regarding assumptions made on building simulation model inputs of site weather conditions, internal heat gain sources, occupancy patterns, details regarding natural ventilation, air infiltration/leakage, and building materials. The section concludes with a discussion of the base case used for analysis and a discussion of building models used for parametric analysis.

4.2.1 Weather

A description of the characteristics of the weather of the Cape Town region is provided in Section 3.2.

The primary source of weather data is Cape Town IWEC data obtained from EnergyPlus (U.S. Department of Energy, 2019b). Weather data is presented in Appendix D.1.

4.2.2 Internal Heat Gains

No internal heat gains were modelled for the RDP house except for the heat gains resulting from occupants and lighting. This assumption is justified by typical usage in such houses. In Chapter 5, the influence of simple cooking and heating devices is considered.

4.2.3 Occupancy

Two adults were assumed to occupy each room at any given time. Complexity and impact of actual occupancy on thermal conditions in a house are acknowledged. Here, the attention is focussed on the typical building materials and their moisture content, rather than simulating occupant behaviour. Chapter 5 devotes careful attention to occupancy simulation, given its importance in validation of actual building thermal performance. Each person's metabolic rate was assumed to be 75 W (South African Bureau of Standards, 2011b). The occupancy schedule is summarised in Appendix D.2.

4.2.4 Lighting

Lighting loads of 5 W/m^2 are assumed in all rooms for each hour of the day. These loads were based on the guidelines of SANS 10400-XA:2011 and SANS 204:2011 (South African Bureau of Standards, 2011b, 2011c). The lighting fixtures are assumed to be surface mounted. As a result, the lighting density's heat fractions are a return air fraction of 0, a radiant fraction of 0.72, a visible fraction of

0.18, and a convected fraction of 0.1. The lighting schedules follow that of occupancy, detailed in Appendix D.3.

4.2.5 Ventilation and Air Infiltration/Air Leakage

Natural ventilation is scheduled to occur at times, specified in Appendix D.4. Details regarding the free aperture of ventilation components are summarised in Table D.3 and Table D.10. A minimum fresh airflow requirement of 5 l/s per person is specified in line with the recommendations of SANS 10400-XA:2011 and SANS 10400-O:2011 (SANS, 2011b, 2011a). This airflow requirement limits the ventilation rate to the minimum permitted. For the infiltration/air leakage, a constant value of 7 $m^3/(h.m^2)$ is used.

4.2.6 Building Materials

The building structure comprises eight building constructions: external walls, internal partitions, internal doors, external doors, external glazing, a ceiling, a roof, and a ground floor. An overview of the building constructions is summarised in Appendix D.5. The material properties of opaque materials are classified as thermal bulk properties, moisture transfer properties, and surface properties.

4.2.6.1 Thermal Bulk Properties

The thermal bulk properties of materials are thermal conductivity (with SI units W/(m.K)), density (kg/m^3), and specific heat capacity (J/(kg.K)). The thermal bulk properties for the building materials are summarised in Table D.4.

4.2.6.2 Moisture Transfer Properties

The moisture transfer properties of materials are initial moisture content (kg/kg), porosity (m^3/m^3), moisture content (kg/m^3), liquid transport coefficient (m^2/s), diffusion resistance factor, and thermal conductivity. Assumptions made are guided by Kumaran (1996). The moisture transfer properties for the building materials are summarised in Table D.6 and Table D.7. Moisture transfer properties are constructed from a set of formulas. For cement plaster, the sorption isotherm is based on Equation 4.1.

$$w(kg/m^3) = \frac{\varphi}{-0.052 \times \varphi^2 + 0.052 \times \varphi + 0.005} \qquad 4.1$$

Where w is the moisture content, and φ is the relative humidity fraction. The porosity of the cement plaster was chosen as 0.327 m^3/m^3. The suction and redistribution liquid transport coefficient is calculated using Equation 4.2.

$$D_w(m^2/s) = 1.4 \times 10^{-9} \times e^{0.22 \times w} \qquad 4.2$$

Where D_w is the moisture diffusivity value. The diffusion resistance factor is calculated using Equation 4.3.

$$\mu = \frac{1}{7.69 \times 10^{-2} + 2.43 \times 10^{-3} \times e^{3.61 \times \varphi}} \qquad 4.3$$

Where μ is the diffusion resistance factor. The moisture dependent thermal conductivity is calculated using Equation 4.4.

$$\lambda(W/(m.K)) = 0.854 + 0.0045 \times w \qquad 4.4$$

Where λ is the thermal conductivity. For lightweight concrete, the sorption isotherm, suction and redistribution coefficient, diffusion resistance and moisture dependent thermal conductivity are calculated using Equations 4.5 to 4.8. The porosity chosen for the lightweight concrete was 0.51 m^3/m^3.

$$w(kg/m^3) = \frac{\varphi}{-0.047 \times \varphi^2 + 0.055 \times \varphi + 0.006} \tag{4.5}$$

$$D_w(m^2/s) = 1.3 \times 10^{-9} \times e^{0.0351 \times w} \tag{4.6}$$

$$\mu = \frac{1}{6.76 \times 10^{-2} + 1.21 \times 10^{-3} \times e^{3.94 \times \varphi}} \tag{4.7}$$

$$\lambda(W/(m.K)) = 0.511 + 0.00255 \times w \tag{4.8}$$

4.2.6.3 Surface Properties

The building materials' surface properties are thermal absorptance (emissivity), solar absorptance, visible absorptance, and roughness. The surface properties for the building materials are summarised in Table D.5.

4.2.6.4 Glazing Properties

The simple method of defining transparent materials' properties consists of defining the following properties: SHGC, Light Transmission, and the U-Values (expressed as W/(m^2.K)). The glazing properties for the transparent building materials are summarised in Table D.9. Details regarding window constructions are summarised in Table D.10.

4.2.7 Base Case Analysis

Before parametric analysis, a base case is constructed to which all other analyses are compared. The base case fixes an analysis period, internal heat gains, lighting, occupancy, ventilation, building material properties, air infiltration/leakage, and the heat balance method.

The analysis period is divided into two parts: a summer week and a winter week. The summer and winter week periods are extracted from the weather file, as 1 to 7 December and 8 to 14 June respectively.

The base case assumes no internal heat gains, except standard lighting and occupancy.

Lighting assumptions are discussed in two parts: magnitude and schedule. The lighting density, heat fractions, and lighting schedule are assumed to be the same as those detailed in Section 4.2.4.

Assumptions regarding occupancy are discussed in two parts: magnitude and schedule. The metabolic rate (emitted as either sensible or latent heat as computed by the software) and occupancy schedules are assumed to be the same as those detailed in Section 4.2.3.

Ventilation is assumed to be scheduled with the maximum ventilation rate associated with the minimum fresh air requirement. The ventilation schedule is the same as that detailed in Section 4.2.5.

The building material properties are discussed for the opaque and transparent building components. The building material properties for the opaque building components are divided into thermal bulk properties, moisture transfer properties, and surface properties. All three sets of properties for all the building constructions are the same as those detailed in Section 4.2.6.1, Section 4.2.6.2, and Section 4.2.6.3. The building material properties for the transparent building material properties are detailed in Section 4.2.6.4.

The heat balance method used for the base case analysis is the HAMT method. Because the analysis focused on moisture content, the analysis was first carried out using HAMT for the solution method for heat transfer through opaque building components.

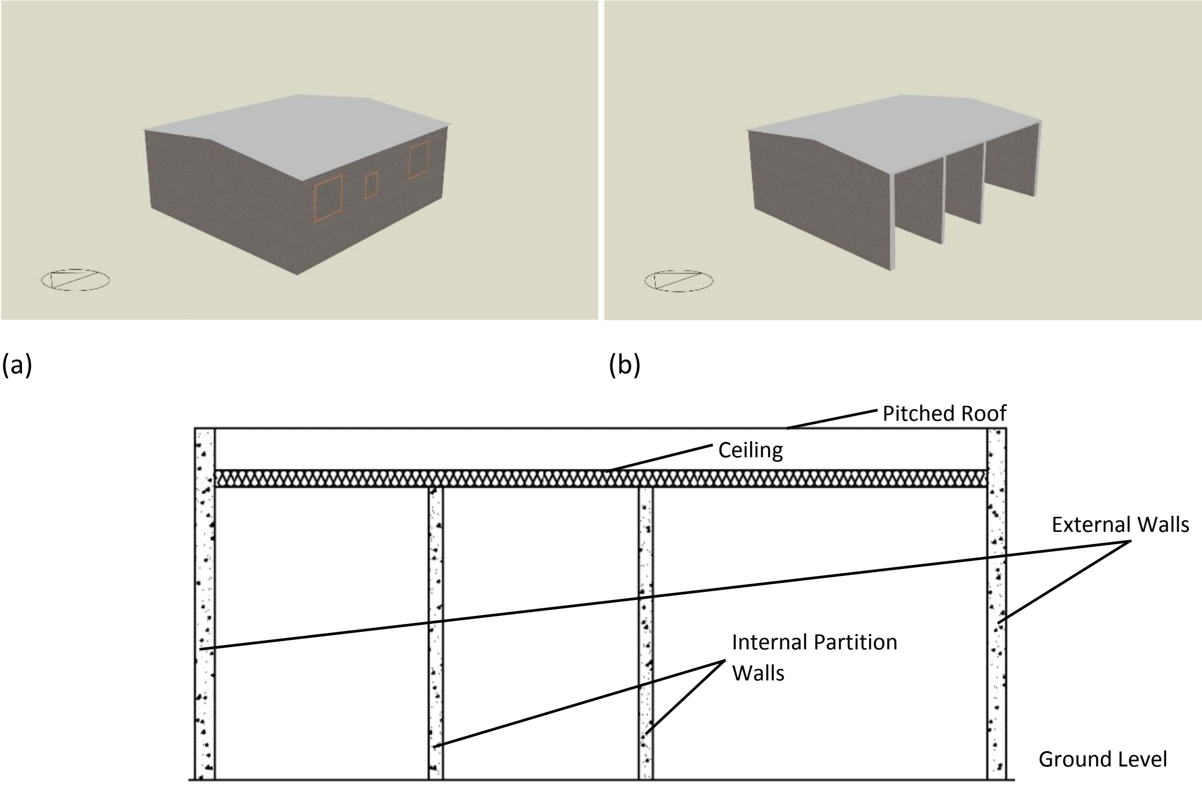
Air infiltration was modelled with a constant infiltration value. The value is detailed in Section 4.2.5.

4.2.8 Parametric Analysis

The purpose of the parametric analysis was to understand the impact of moisture content on environmental conditions. For this purpose, four scenarios were analysed:

- Scenario 1: external walls with HAMT and internal walls with HAMT
- Scenario 2: external walls with HAMT and internal walls with CTF
- Scenario 3: external walls with CTF and internal walls with HAMT
- Scenario 4: external walls with CTF and internal walls with CTF

The scenarios described in the previous paragraph, are visualised in Figures 4.2 and 4.3. Walls traced with a red outline are modelled using the CTF solution algorithm. Walls traced with a blue outline are modelled using the HAMT solution algorithm.



(a)

(b)

(c)

Figure 4.2: (a) DesignBuilder model of the RDP house and (b) section through the Southern part of the house. (c) Visual depiction of external and internal walls, ceiling and pitched roof.

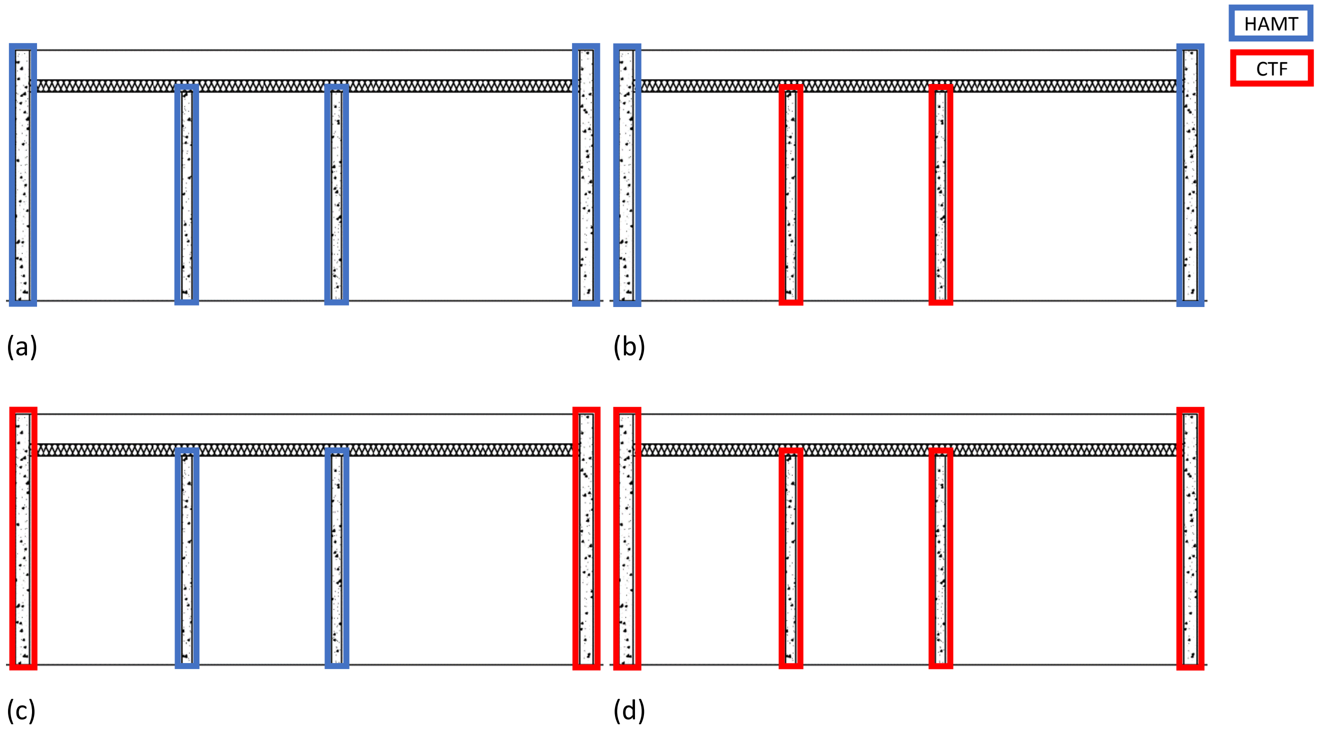


Figure 4.3: (a) Visual depiction of Scenario 1 (b) Visual depiction of Scenario 2 (c) Visual depiction of Scenario 3 (d) Visual depiction of Scenario 4

For the first three scenarios, 11 configurations were created. Each configuration had a base moisture transfer property value of materials adjusted by a percentage. Configurations are summarised in Table 4.1. As a result, 34 building models were made. In addition to adjustments on material moisture transfer properties, the initial moisture content of hygroscopic materials was adjusted. Four initial moisture contents were studied: 0%, 1%, 5%, and 10%.

Table 4.1: Base Value Changes of Moisture Transfer Properties

Configuration No.	Sorption Isotherm	Suction Liquid Transport Coefficient	Redistribution Liquid Transport Coefficient	Vapour Resistance Factor	Thermal Conductivity (W/m-K)
Configuration 1	-20%	0%	0%	0%	0%
Configuration 2	0%	-20%	0%	0%	0%
Configuration 3	0%	0%	-20%	0%	0%
Configuration 4	0%	0%	0%	-20%	0%
Configuration 5	0%	0%	0%	0%	-20%
Configuration 6 (Base Case)	0%	0%	0%	0%	0%
Configuration 7	0%	0%	0%	0%	+20%
Configuration 8	0%	0%	0%	+20%	0%
Configuration 9	0%	0%	+20%	0%	0%
Configuration 10	0%	+20%	0%	0%	0%
Configuration 11	+20%	0%	0%	0%	0%

4.3 Results

The results from the parametric analysis are divided into eight sections. Each section provides a comparison between the lounge air and radiant temperature of different building models. To be concise, scenarios defined in Section 4.2.8 are used to describe comparisons. However, the term "configuration" is omitted and replaced with a quantitive description for simplicity, e.g. decreased value, increased value or base case.

Results are analysed for three periods: morning, day and evening. The morning period ranges from 01:00 to 06:00, the day period ranges from 06:00 to 18:00, and the evening period ranges from 18:00 to 24:00. The periods were identified based on inflection points from results.

The first five sections, Sections 4.3.1.1 to 4.3.1.5, focus on comparing changes made to the hygrothermal properties of building walls. The first section compares the CTF and HAMT solution method applied to building walls. The second section compares different sorption isotherm data sets. A comparison between different liquid transport coefficient and different vapour diffusion resistance factor data sets are provided in sections three and four. These sections are followed by a comparison between different moisture dependent thermal conductivity data sets.

The final three sections, Sections 4.3.2.1 to 4.3.2.3, focus on comparing changes made to the initial moisture content of building walls. The first section presents an analysis of both the external and internal walls subject to hygrothermal analysis. An analysis of external walls subject to hygrothermal analysis is presented in the second section. The final section presents an analysis of internal walls subject to hygrothermal analysis.

4.3.1 Parametric Analysis of Hygrothermal Properties

4.3.1.1 Comparisons between HAMT and CTF

When comparing the HAMT and CTF solution methods, comparisons are made regarding the initial relative temperature, heat gain/heat loss rate, and the final relative temperature. Six sets of results are compared, with three sets of results being similar. Comparisons for the results of the summer base case analysis are presented in Table 4.2, Table 4.3, and Table 4.4. Comparisons for the results of the winter base case analysis are presented in Table 4.3 and Table 4.5. The cells of the table are coloured according to the value they contain. If the compared value were higher, it would be assigned a light red colour. If the value were lower, it would be assigned a light blue colour. However, if values were similar or varied, they were assigned a light grey colour.

These comparisons are made based on the temperatures simulated for the HAMT solution algorithm relative to the temperatures simulated for the CTF solution algorithm. However, if a comparison has more than one observation, different observations were made for the associated timeframe of the comparison. E.g. The 1st comparison of Table 4.4 for HAMT simulated temperatures with an initial moisture content set to 1% has two observations. Thus on certain days, between 01:00 – 06:00, the initial HAMT simulated temperature is higher compared to the CTF simulated temperature. However, this is not always true as other days are observed to have a lower HAMT simulated temperature than the CTF simulated temperature.

Table 4.2: Comparison between lounge air and radiant temperatures for the summer base case analysis (Scenario 1).

Time	Comparison of HAMT to CTF	Moisture Content				
		0%	1%	5%	10%	20%
01:00 – 06:00	Initial Temperature	Higher	Higher	Lower	Lower	Lower
	Rate of Heat Loss	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Higher	Varies	Lower	Lower
06:00 – 18:00	Initial Temperature	Higher	Higher	Varies	Lower	Lower
	Rate of Heat Gain	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Varies	Varies	Lower	Lower
18:00 – 24:00	Initial Temperature	Higher	Varies	Varies	Lower	Lower
	Rate of Heat loss	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Higher	Lower	Lower	Lower

Table 4.3: Comparison between lounge air and radiant temperatures for the winter base case analysis (Scenario 1 and Scenario 2) and summer base case analysis (Scenario 3).

Time	Comparison of HAMT to CTF	Moisture Content				
		0%	1%	5%	10%	20%
01:00 – 06:00	Initial Temperature	Higher	Lower/Higher	Lower	Lower	Lower
	Rate of Heat Loss	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Higher	Lower/Higher	Lower	Lower
06:00 – 18:00	Initial Temperature	Higher	Higher	Lower/Higher	Lower	Lower
	Rate of Heat Gain	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Lower/Higher	Lower/Higher	Lower	Lower
18:00 – 24:00	Initial Temperature	Higher	Lower/Higher	Lower/Higher	Lower	Lower
	Rate of Heat loss	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Lower/Higher	Lower	Lower	Lower

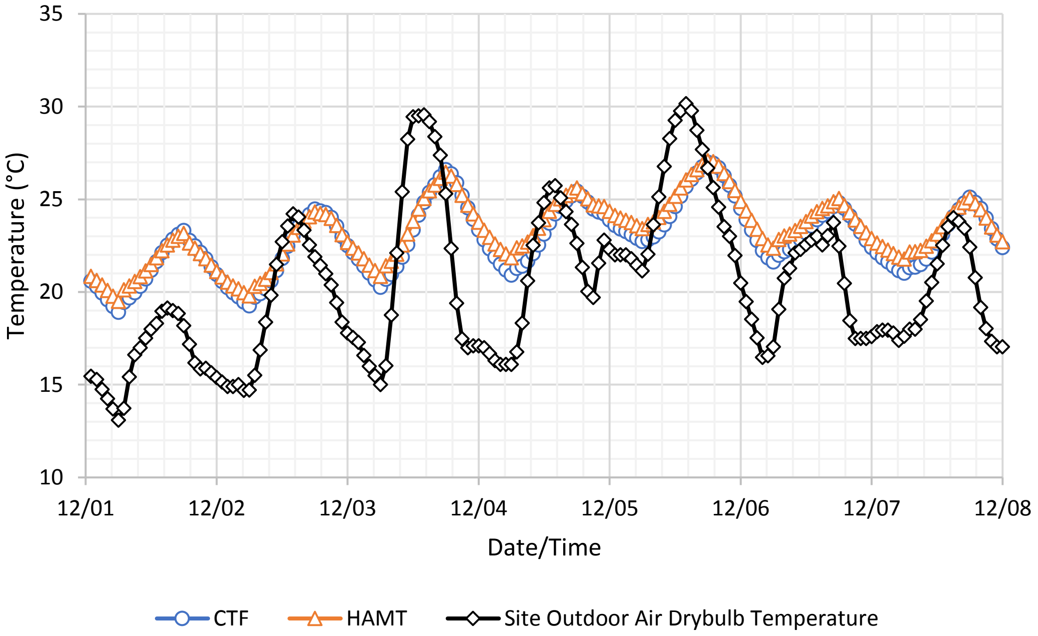
Table 4.4: Comparison between lounge air and radiant temperatures for the summer base case analysis (Scenario 2).

Time	Comparison of HAMT to CTF	Moisture Content				
		0%	1%	5%	10%	20%
01:00 – 06:00	Initial Temperature	Higher	Lower/Higher	Lower	Lower	Lower
	Rate of Heat Loss	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Higher	Lower/Higher	Lower	Lower
06:00 – 18:00	Initial Temperature	Higher	Higher	Lower/Higher	Lower	Lower
	Rate of Heat Gain	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Lower/Higher	Lower/Higher	Lower/ Higher	Lower
18:00 – 24:00	Initial Temperature	Higher	Lower/Higher	Lower/Higher	Lower/ Higher	Lower
	Rate of Heat loss	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Lower/Higher	Lower	Lower	Lower

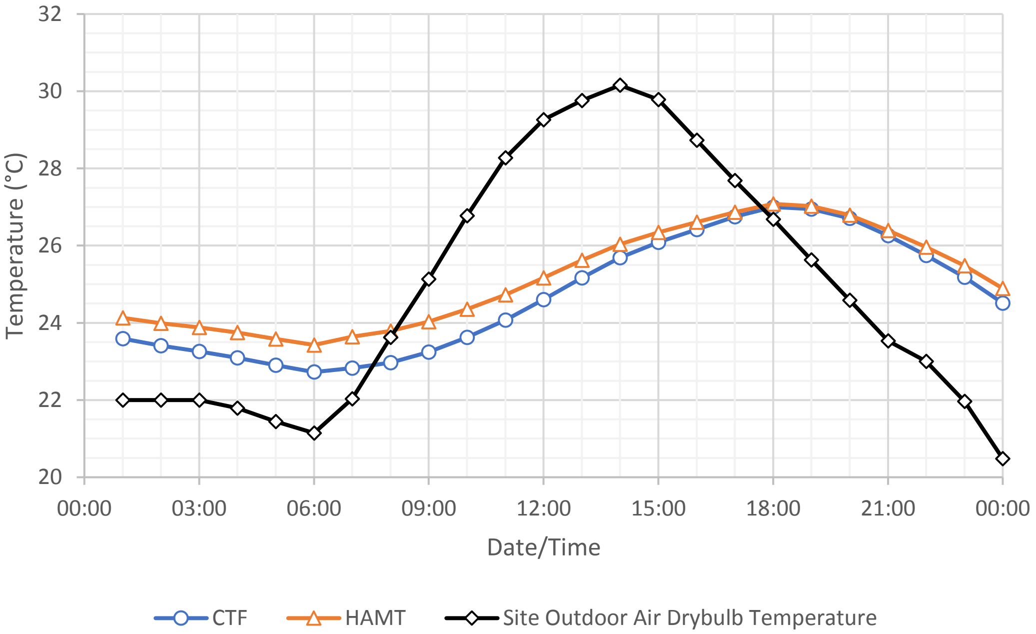
Table 4.5: Comparison between lounge air and radiant temperatures for the winter base case analysis (Scenario 3).

Time	Comparison of HAMT to CTF	Moisture Content				
		0%	*1%*	*5%*	*10%*	*20%*
01:00 – 06:00	Initial Temperature	Higher	Higher	Lower/Higher	Lower	Lower
	Rate of Heat Loss	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Higher	Lower	Lower	Lower
06:00 – 18:00	Initial Temperature	Higher	Higher	Lower	Lower	Lower
	Rate of Heat Gain	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Lower/ Higher	Lower (Lower/Higher for Radiant Temperature)	Lower	Lower
18:00 – 24:00	Initial Temperature	Higher	Lower/ Higher	Lower (Lower/Higher for Radiant Temperature)	Lower	Lower
	Rate of Heat loss	Lower	Lower	Lower	Lower	Lower
	Final Temperature	Higher	Higher	Lower/Higher	Lower	Lower

Results are obtained from examining graphs. They depict the typical relative behaviour between CTF and HAMT, as described in Tables 4.2 to 4.5. A set results obtained for the summer week are visualised in Figure 4.4 (a). The fifth day of the summer week is visualised in Figure 4.4 (b), depicting the lounge air temperature progression for the CTF solution and HAMT solution with the base configuration. Scenario 1 is considered with the initial moisture content set to 1%, thus serving to illustrate some of the findings contained in Table 4.2. By inspection, the morning period of the fifth day of the summer week is characterised by higher temperature values calculated for the HAMT solution method. However, the rate of heat loss for the CTF solution method is larger. Although the period from 06:00 to 18:00 is characterised by higher temperature values calculated for the HAMT solution method, the rate of heat gain for the CTF solution is larger. The evening period is also characterised by higher temperature values calculated for the HAMT solution method due to the rate of heat loss associated with the CTF solution.



(a)



(b)

Figure 4.4: (a) Summer Week for the base case analysis with initial moisture content set to 1% (Scenario 1) (b) Day 5 of the Summer Week for the base case analysis with initial moisture content set to 1% (Scenario 1)

4.3.1.2 Comparisons Between Different Sorption Isotherm Properties

Comparisons can be made regarding relative temperature values when increasing the moisture content associated with relative humidity (sorption isotherm values). Six sets of results are compared, with four sets of results being similar. Comparisons for the results of the summer sorption isotherm analysis are presented in Table 4.6, Table 4.7, and Table 4.8. Comparisons for the results of the winter sorption isotherm analysis are presented in Table 4.6, Table 4.8, and Table 4.9.

Table 4.6: Comparison between lounge air and radiant temperatures for the summer and winter sorption isotherm analysis (Scenario 1).

Time	Comparison of Increasing Sorption Isotherm Values	Moisture Content			
		0%	5%	10%	20%
01:00 – 24:00	Relative Temperature	Higher	Higher	Similar/ Higher	Similar/ Higher

Table 4.7: Comparison between lounge air and radiant temperatures for the summer sorption isotherm analysis (Scenario 2).

Time	Comparison of Increasing Sorption Isotherm Values	Moisture Content		
		5%	10%	20%
01:00 – 06:00	Relative Temperature	Higher	Higher	Lower/Higher
06:00 – 18:00	Relative Temperature	Higher	Higher	Higher
18:00 – 24:00	Relative Temperature	Higher	Higher	Lower/Higher

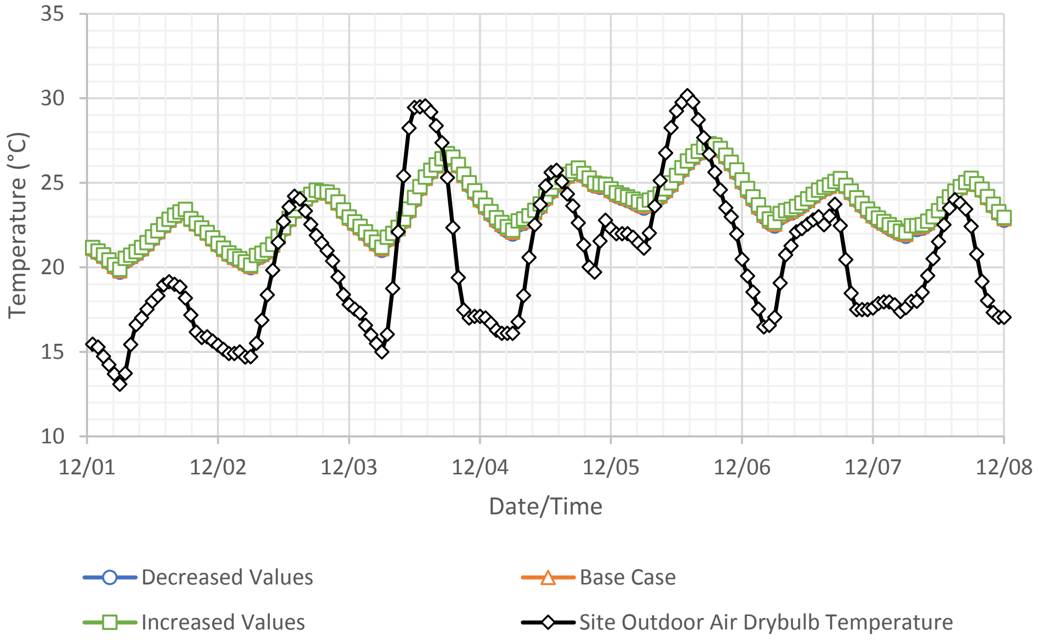
Table 4.8: Comparison between lounge air and radiant temperatures for the winter sorption isotherm analysis (Scenario 2) and summer sorption isotherm analysis (Scenario 3).

Time	Comparison of Increasing Sorption Isotherm Values	Moisture Content		
		5%	10%	20%
01:00 – 24:00	Relative Temperature	Higher	Higher	Similar

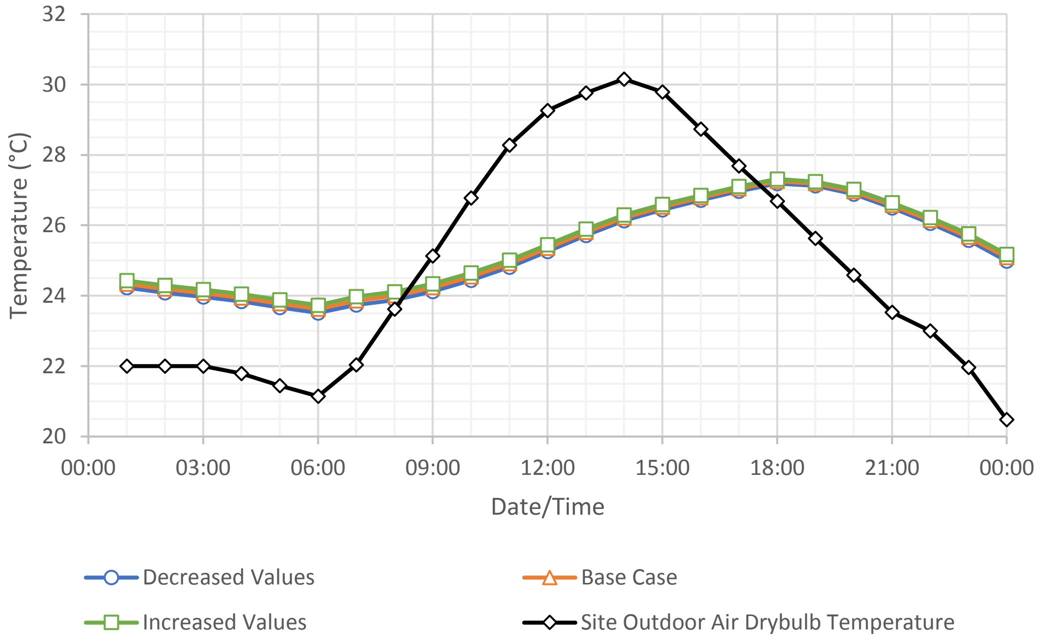
Table 4.9: Comparison between lounge air and radiant temperatures for the winter sorption isotherm analysis (Scenario 3).

Time	Comparison of Increasing Sorption Isotherm Values	Moisture Content		
		5%	10%	20%
01:00 – 24:00	Relative Temperature	Similar/Higher	Similar/Higher	Similar/Higher

Results for the lounge air temperature for the summer week are depicted in Figure 4.5 (a), as well as the progression of lounge air temperature on the fifth day of the summer week in Figure 4.5 (b). The graphs depict the results for Scenario 1 with the initial moisture content set to 0%. Both serve as a visualisation of some of the general observations made in Table 4.6. Results for the HAMT simulation, with decreased sorption isotherm values compared to the base case, are depicted by a blue colour with circular points representing data points. Results for the HAMT simulation, with increased sorption isotherm values compared to the base case are depicted by a green colour, with square points representing data points. An orange colour depicts the base case with triangular points representing data points. The simulated outside dry-bulb temperature is depicted by a black colour with diamond points representing data points. By inspection, the morning period is characterised by higher temperature values when increasing the values of sorption isotherm. The rate of heat loss is similar for this period, however. The period from 06:00 to 18:00 is characterised by higher temperature values when increasing the values of sorption isotherm. The rate of heat gain is initially higher for results associated with higher sorption isotherm values, after which the rate of heat gain is higher for results associated with lower sorption isotherm values. The evening period is also characterised by higher temperature values when increasing the values of sorption isotherm.



(a)



(b)

Figure 4.5: (a) Summer Week for the sorption isotherm analysis with initial moisture content set to 0% (Scenario 1) (b) Day 5 of the Summer Week for the sorption isotherm analysis with initial moisture content set to 0% (Scenario 1).

4.3.1.3 Comparisons Between Different Liquid Transport Coefficient Properties

When increasing the liquid transport coefficient associated with moisture content, comparisons can be made regarding relative temperature values. Although six sets of results are compared, the same observations are made for all of them. Comparisons for the results of the summer and winter liquid transport coefficient analysis are presented in Table 4.10 and Table 4.11.

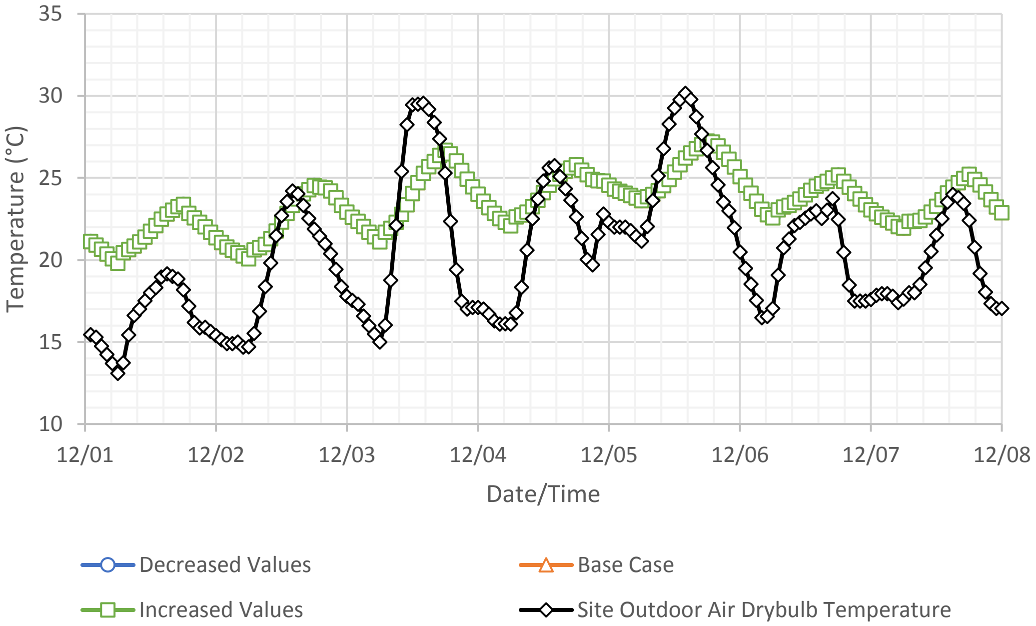
Table 4.10: Comparison between lounge air and radiant temperatures for the summer and winter liquid transport coefficient analysis (Scenario 1).

Time	Comparison of Increasing Liquid Transport Coefficient Values	Moisture Content			
		0%	5%	10%	20%
01:00 – 24:00	Relative Temperature	Similar	Similar	Similar	Similar

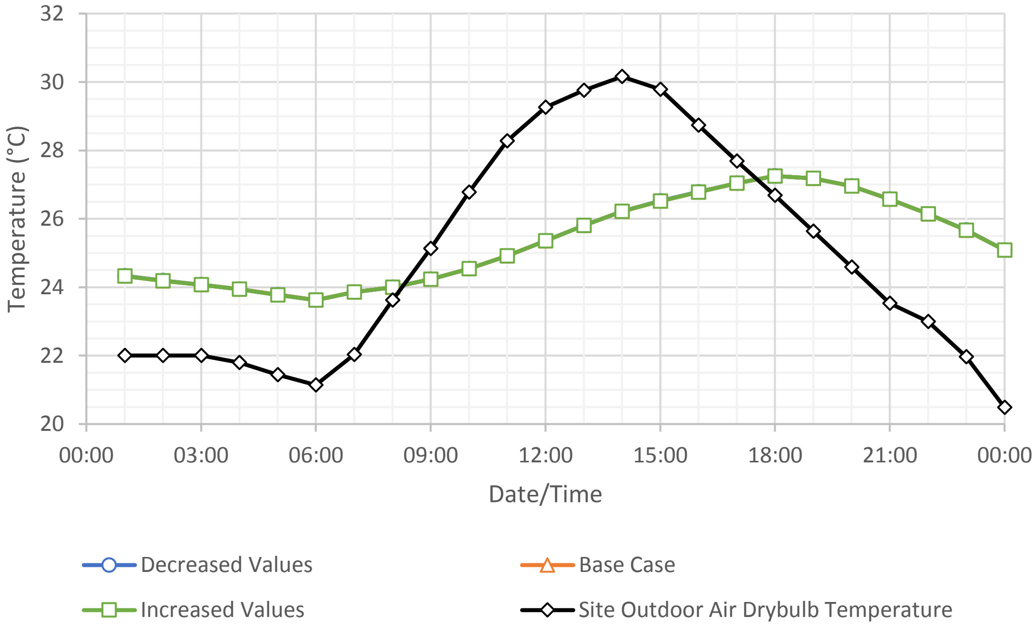
Table 4.11: Comparison between lounge air and radiant temperatures for the summer and liquid transport coefficient analysis (Scenario 2 and Scenario 3).

Time	Comparison of Increasing Liquid Transport Coefficient Values	Moisture Content		
		5%	10%	20%
01:00 – 24:00	Relative Temperature	Similar	Similar	Similar

A depiction of the lounge air temperature progression for the summer week and fifth day of the summer week is presented in Figures 4.6 (a) and (b). The graphs depict the results for Scenario 1 with the initial moisture content set to 0%. The graphs reflects some of the findings summarised in Table 4.10. It is observed that changing the liquid transport coefficient values does not influence temperature values.



(a)



(b)

Figure 4.6: (a) Summer Week for the liquid transport coefficient analysis with initial moisture content set to 0% (Scenario 1) (b) Day 5 of the Summer Week for the liquid transport coefficient analysis with initial moisture content set to 0% (Scenario 1)

4.3.1.4 Comparisons Between Different Vapour Diffusion Resistance Properties

When increasing the vapour diffusion resistance factor associated with relative humidity, comparisons can be made regarding relative temperature values. Six sets of results are compared, with two sets of results being similar. Comparisons for the results of the summer vapour diffusion resistance factor analysis are presented in Table 4.12, Table 4.14, and Table 4.16. Comparisons for the results of the winter vapour diffusion resistance factor analysis are presented in Table 4.13, Table 4.15, and Table 4.16.

Table 4.12: Comparison between lounge air and radiant temperatures for the summer vapour diffusion resistance factor analysis (Scenario 1).

Time	Comparison of Increasing Vapour Diffusion Resistance Factor Values	Moisture Content			
		0%	5%	10%	20%
01:00 – 24:00	Relative Temperature	Lower/ Similar	Similar	Similar	Lower/ Higher

Table 4.13: Comparison between lounge air and radiant temperatures for the winter vapour diffusion resistance factor analysis (Scenario 1).

Time	Comparison of Increasing Vapour Diffusion Resistance Factor Values	Moisture Content			
		0%	5%	10%	20%
01:00 – 24:00	Relative Temperature	Similar	Similar/ Higher	Similar/ Higher	Higher

Table 4.14: Comparison between lounge air and radiant temperatures for the summer vapour diffusion resistance factor analysis (Scenario 2).

Time	Comparison of Increasing Vapour Diffusion Resistance Factor Values	Moisture Content		
		5%	10%	20%
01:00 – 06:00	Relative Temperature	Similar	Similar	Lower/Higher
06:00 – 18:00	Relative Temperature	Similar	Similar	Higher
18:00 – 24:00	Relative Temperature	Similar	Similar	Higher

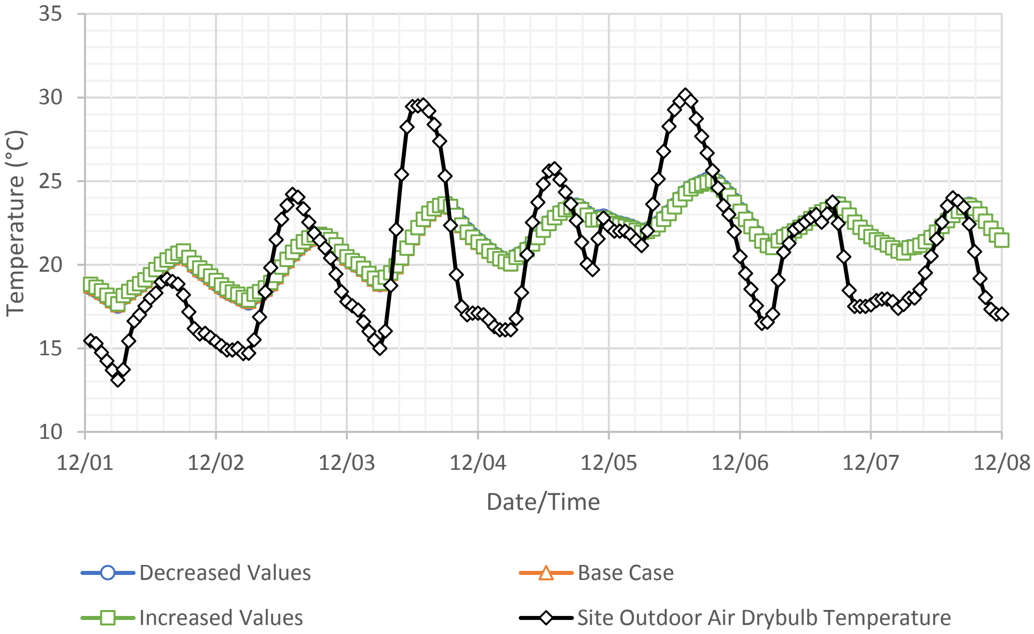
Table 4.15: Comparison between lounge air and radiant temperatures for the winter vapour diffusion resistance factor analysis (Scenario 2).

Time	Comparison of Increasing Vapour Diffusion Resistance Factor Values	Moisture Content		
		5%	10%	20%
01:00 – 24:00	Relative Temperature	Similar	Similar	Higher

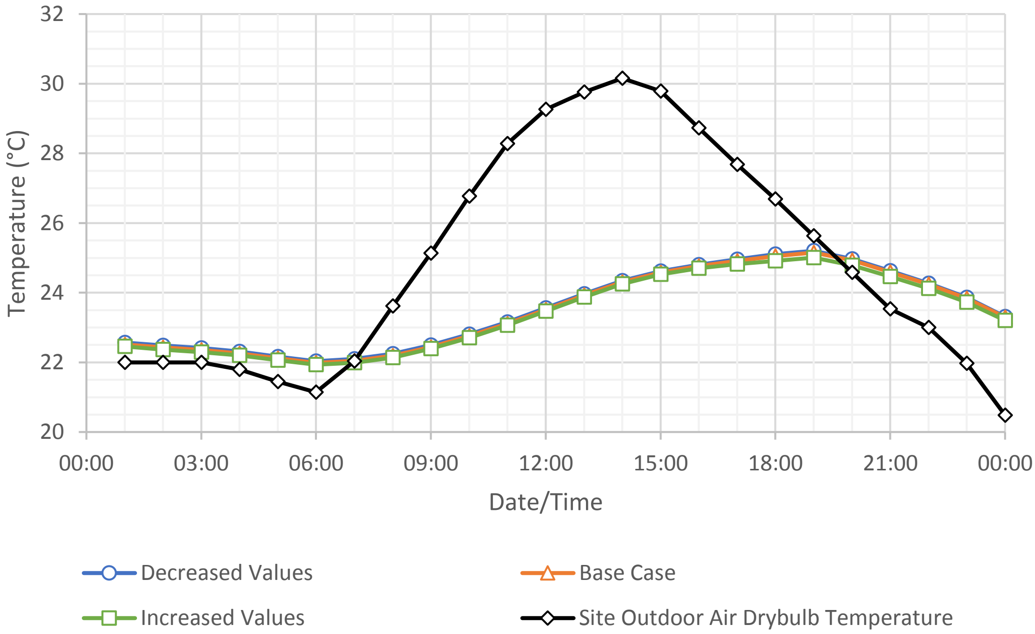
Table 4.16: Comparison between lounge air and radiant temperatures for the summer and winter vapour diffusion resistance factor analysis (Scenario 3).

Time	Comparison of Increasing Vapour Diffusion Resistance Factor Values	Moisture Content		
		5%	10%	20%
01:00 – 24:00	Relative Temperature	Similar	Similar	Similar

A depiction of the lounge air temperature progression for the summer week and fifth day of the summer week is presented in Figures 4.7 (a) and (b). The graphs depict the results for Scenario 1 with the initial moisture content set to 20%, illustrating some of the observations made in Table 4.12. Inspecting the fifth day of the summer week, the morning period is characterised by lower temperature values when increasing the vapour diffusion resistance factor values. The rate of heat loss for increased vapour diffusion resistance factor values is similar during this period. The period from 06:00 to 18:00 is characterised by lower temperature values when increasing vapour diffusion resistance factor values. The rate of heat gain is initially similar, but the rate of heat gain is lower with increased vapour diffusion resistance factor values near the end of the period. The evening period is also characterised by lower temperature values when increasing the vapour diffusion resistance factor values. However, near the end of the fifth day, the rate of heat loss is lower with increased vapour diffusion resistance factor values.



(a)



(b)

Figure 4.7: (a) Summer Week for the vapour diffusion resistance factor analysis with initial moisture content set to 20% (Scenario 1) (b) Day 5 of the Summer Week for the vapour diffusion resistance factor analysis with initial moisture content set to 20% (Scenario 1)

4.3.1.5 Comparisons Between Different Moisture Dependent Thermal Conductivity Properties

When increasing the thermal conductivity associated with moisture content, comparisons are made regarding the initial relative temperature, heat gain/heat loss rate, and the final relative temperature. Six sets of results are compared, with two sets of results being similar. Comparisons for the results of the summer vapour diffusion resistance factor analysis are presented in Table 4.17, Table 4.19, and Table 4.20. Comparisons for the results of the winter vapour diffusion resistance factor analysis are presented in Table 4.18 and Table 4.21.

Table 4.17: Comparison between lounge air and radiant temperatures for the summer moisture dependent thermal conductivity analysis (Scenario 1).

Time	Comparison of Increasing Thermal Conductivity Values	Moisture Content			
		0%	5%	10%	20%
01:00 – 06:00	Initial Temperature	Lower/Higher	Lower/Higher	Lower/Higher	Lower/Higher
	Rate of Heat Loss	Higher	Higher	Higher	Higher
	Final Temperature	Lower	Lower	Lower	Lower
06:00 – 18:00	Initial Temperature	Lower	Lower	Lower	Lower
	Rate of Heat Gain	Higher	Higher	Higher	Higher
	Final Temperature	Higher	Higher	Higher	Higher
18:00 – 24:00	Initial Temperature	Higher	Higher	Higher	Higher
	Rate of Heat loss	Higher	Higher	Higher	Higher
	Final Temperature	Lower/Higher	Lower/Higher	Lower/Higher	Lower/Higher

Table 4.18: Comparison between lounge air and radiant temperatures for the winter moisture dependent thermal conductivity analysis (Scenario 1 and Scenario 2).

Time	Comparison of Increasing Thermal Conductivity Values	Moisture Content			
		0%	5%	10%	20%
01:00 – 06:00	Initial Temperature	Lower/Higher	Lower/Higher	Lower/Higher	Lower/Higher
	Rate of Heat Loss	Higher	Higher	Higher	Higher
	Final Temperature	Lower	Lower	Lower	Lower
06:00 – 18:00	Initial Temperature	Lower	Lower	Lower	Lower
	Rate of Heat Gain	Higher	Higher	Higher	Higher
	Final Temperature	Lower/Higher	Lower/Higher	Lower/Higher	Lower/Higher
18:00 – 24:00	Initial Temperature	Lower/Higher	Lower/Higher	Lower/Higher	Lower/Higher
	Rate of Heat loss	Higher	Higher	Higher	Higher
	Final Temperature	Lower/Higher	Lower/Higher	Lower/Higher	Lower/Higher

Table 4.19: Comparison between lounge air and radiant temperatures for the summer moisture dependent thermal conductivity analysis (Scenario 2).

Time	Comparison of Increasing Thermal Conductivity Values	Moisture Content		
		5%	10%	20%
01:00 – 06:00	Initial Temperature	Lower	Lower	Lower/Higher
	Rate of Heat Loss	Higher	Higher	Higher
	Final Temperature	Lower/Higher	Lower/Higher	Lower/Higher
06:00 – 18:00	Initial Temperature	Lower/Higher	Lower/Higher	Lower/Higher
	Rate of Heat Gain	Higher	Higher	Higher
	Final Temperature	Higher	Higher	Higher
18:00 – 24:00	Initial Temperature	Higher	Higher	Higher
	Rate of Heat loss	Higher	Higher	Higher
	Final Temperature	Lower	Lower	Lower/Higher

Table 4.20: Comparison between lounge air and radiant temperatures for the summer moisture dependent thermal conductivity analysis (Scenario 3).

Time	Comparison of Increasing Thermal Conductivity Values	Moisture Content		
		5%	10%	20%
01:00 – 06:00	Initial Temperature	Lower/Higher	Lower/Higher	Lower/Higher
	Rate of Heat Loss	Lower	Lower	Lower
	Final Temperature	Higher	Higher	Higher
06:00 – 18:00	Initial Temperature	Higher	Higher	Higher
	Rate of Heat Gain	Lower	Lower	Lower
	Final Temperature	Lower	Lower	Lower
18:00 – 24:00	Initial Temperature	Lower	Lower	Lower
	Rate of Heat loss	Lower	Lower	Lower
	Final Temperature	Lower/Higher	Lower/Higher	Lower/Higher

Table 4.21: Comparison between lounge air and radiant temperatures for the winter moisture dependent thermal conductivity analysis (Scenario 3).

Time	Comparison of Increasing Thermal Conductivity Values	Moisture Content		
		5%	10%	20%
01:00 – 06:00	Initial Temperature	Varies	Similar/Lower	Similar/Lower
	Rate of Heat Loss	Lower	Lower	Lower
	Final Temperature	Higher	Higher	Higher
06:00 – 18:00	Initial Temperature	Higher	Higher	Higher
	Rate of Heat Gain	Lower	Lower	Lower
	Final Temperature	Lower	Lower	Lower
18:00 – 24:00	Initial Temperature	Lower	Lower	Lower
	Rate of Heat loss	Lower	Lower	Lower
	Final Temperature	Varies	Similar/Lower	Similar/Lower

As with the previous sets of comparisons, the conclusions drawn from Tables 4.18 to 4.21 are based on the graphs created from the simulation output. The summer week and fifth day of the summer week for the moisture dependent thermal conductivity analysis, is presented in Figures 4.8 (a) and (b). The graphs depict the results for Scenario 1 with the initial moisture content set to 0%, illustrating some of the findings made in Table 4.17. The morning period is characterised by higher temperature values when increasing the moisture dependent thermal conductivity values. However, the rate of heat loss with increased moisture dependent thermal conductivity values is also higher. The period from 06:00 to 18:00 is also characterised by higher temperature values when increasing the moisture dependent thermal conductivity values. Although the rate of heat gain is initially similar, the rate of heat gain associated with increased moisture dependent thermal conductivity values becomes higher compared to decreased moisture dependent thermal conductivity values. The evening period is also characterised by higher temperature values when increasing the moisture dependent thermal conductivity values. Because of the heat loss associated with increased moisture dependent thermal conductivity values, lounge air temperature values are similar by the end of the evening period.

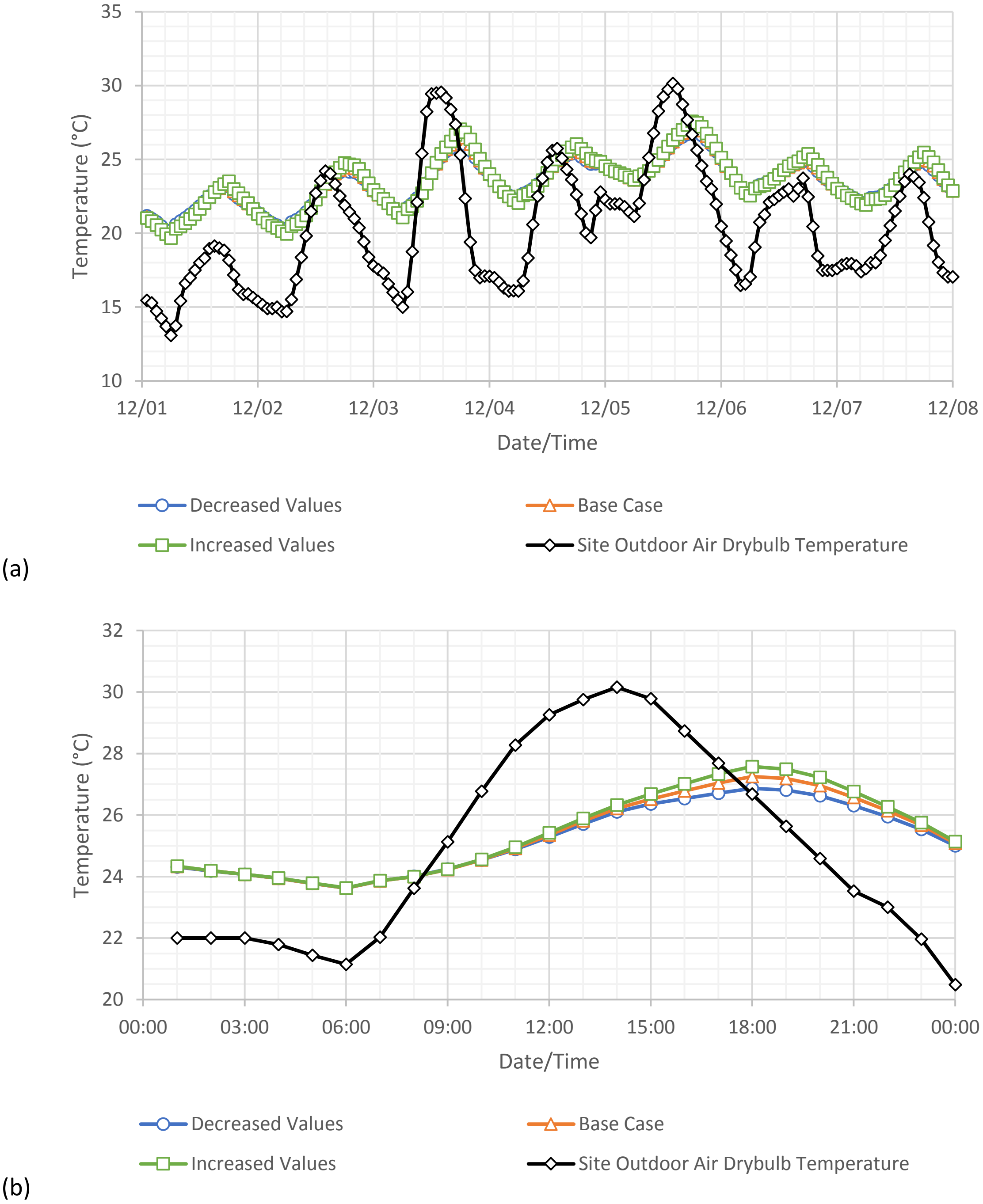


Figure 4.8: (a) Summer Week for the moisture dependent thermal conductivity analysis with initial moisture content set to 0% (Scenario 1) (b) Day 5 of the Summer Week for the moisture dependent thermal conductivity analysis with initial moisture content set to 0% (Scenario 1)

4.3.2 Parametric Analysis of Initial Moisture Content

4.3.2.1 Scenario 1

The second set of comparisons focuses on the change in lounge radiant and air temperature when increasing the initial moisture content of a material while keeping all other material properties the same. In addition, comparisons are made to CTF results. The first analysis of this type focuses on the results for the HAMT solution method applied to the external and internal walls. A summary of the analysis is provided in Table 4.22 and Table 4.23. Although these tables capture general trends, the relative rate of heat gain and heat loss between the CTF and HAMT results vary based on the set of hygrothermal properties used.

Table 4.22: Comparison between lounge air and radiant temperatures with varying initial moisture content values (Scenario 1).

Time	Comparison of increased initial moisture content	Season	
		Summer	Winter
01:00 – 06:00	Relative Temperature	Lower	Lower
	Rate of Heat Loss	Lower	Lower
06:00 – 18:00	Relative Temperature	Lower	Lower
	Rate of Heat Gain	Lower	Lower
18:00 – 24:00	Relative Temperature	Lower	Lower
	Rate of Heat loss	Lower	Lower

Table 4.23: Comparison between lounge air and radiant temperatures for Scenario 1 and Scenario 4.

Time Period	Comparison of HAMT to CTF	Season	
		Summer	Winter
01:00 – 06:00	Rate of Heat Loss	Lower	Lower
06:00 – 18:00	Rate of Heat Gain	Lower	Lower
18:00 – 24:00	Rate of Heat loss	Lower	Lower

Similarly to Sections 4.3.1.1 to 4.3.1.5, observations were based on graphs created from the simulation results. Examples are presented in Figures 4.9 (a) and (b), depicting the lounge air temperature for the summer week and fifth day of the summer week. The graphs serve to illustrate some of the findings made in Table 4.22. The graphs contain the CTF solution and HAMT solution for the base case with increasing initial moisture content values. Comparing the CTF to the HAMT solution, trends during each period can be observed. First, the rate of heat loss associated with the CTF solution can be large enough during the morning and evening period to result in CTF temperature values dropping below specific HAMT solutions. During the day, the rate of heat gain can be large enough to result in CTF temperature values climbing above specific HAMT solutions.

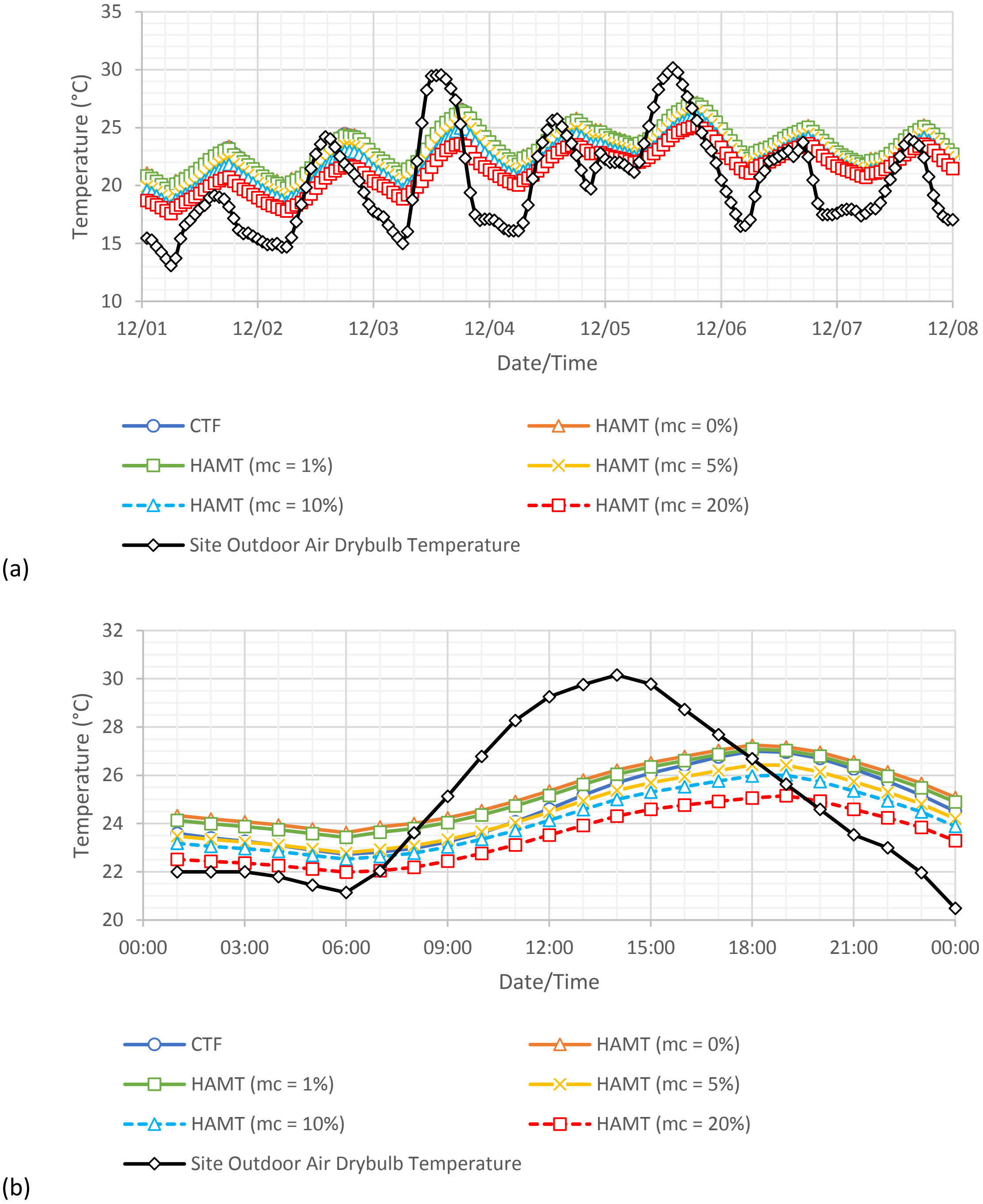


Figure 4.9: (a) Summer Week for increasing moisture content levels for the base case (b) Day 5 of the Summer Week for increasing moisture content levels for the base case.

4.3.2.2 Scenario 2

This section focuses on the results for the HAMT solution method applied to only the external walls. A summary of the analysis is provided in Table 4.24 and Table 4.25. Similarly to the first analysis, focusing on external and internal walls subject to hygrothermal analysis, these tables capture general trends. However, the relative rate of heat gain and heat loss between the CTF and HAMT results vary based on the set of hygrothermal properties used.

Table 4.24: Comparison between lounge air and radiant temperatures with varying initial moisture content values (Scenario 2).

Time	Comparison of increased initial moisture content	Season	
		Summer	Winter
01:00 – 06:00	Relative Temperature	Lower	Lower
	Rate of Heat Loss	Lower	Lower
06:00 – 18:00	Relative Temperature	Lower	Lower
	Rate of Heat Gain	Lower	Lower
18:00 – 24:00	Relative Temperature	Lower	Lower
	Rate of Heat loss	Lower	Lower

Table 4.25: Comparison between lounge air and radiant temperatures for Scenario 2 and Scenario 4.

Time	Comparison of HAMT to CTF	Season	
		Summer	Winter
01:00 – 06:00	Rate of Heat Loss	Lower	Lower
06:00 – 18:00	Rate of Heat Gain	Lower	Lower
18:00 – 24:00	Rate of Heat loss	Lower	Lower

4.3.2.3 Scenario 3

The final analysis focuses on the HAMT solution method applied to only the internal walls. A summary of the analysis is provided in Table 4.26 and Table 4.27. These tables capture the general trends observed for results associated with the internal wall subject to hygrothermal analysis. As with the previous analysis sets, the relative rate of heat gain and heat loss between the CTF and HAMT results vary based on the set of hygrothermal properties used. Although general trends remain, exceptions are observed for initial moisture content levels of 10% and 20%. With specific material property configurations, lounge temperatures for initial moisture contents of 10% are lower at certain time intervals than lounge temperatures with an initial moisture content of 20%. This is observed during the first and second period during summer and for all periods during winter.

Table 4.26: Comparison between lounge air and radiant temperatures with varying initial moisture content values (Scenario 3).

Time	Comparison of increased initial moisture content	Season	
		Summer	Winter
01:00 – 06:00	Relative Temperature	Lower	Lower
	Rate of Heat Loss	Lower	Lower
06:00 – 18:00	Relative Temperature	Lower	Lower
	Rate of Heat Gain	Lower	Lower
18:00 – 24:00	Relative Temperature	Lower	Lower
	Rate of Heat loss	Lower	Lower

Table 4.27: Comparison between lounge air and radiant temperatures for Scenario 3 and Scenario 4.

Time	Comparison of HAMT to CTF	Season	
		Summer	Winter
01:00 – 06:00	Rate of Heat Loss	Lower	Lower
06:00 – 18:00	Rate of Heat Gain	Lower	Lower
18:00 – 24:00	Rate of Heat loss	Lower	Lower

4.4 Results Discussion

Comparing the CTF and HAMT solution method, observations remain the same regardless of the modelling scenario. During cooldown periods, the CTF solution experiences larger heat flux, resulting in cooler temperatures simulated for the CTF solution for certain periods. However, during warmup periods, the CTF solution reflects larger heat flux, resulting in warmer temperatures simulated for the CTF solution for certain periods. Even when the initial moisture content of building walls is 0%, the CTF solution simulates warmer temperatures for certain periods. These large heat fluxes also result in the CTF solution computing larger temperature swings than the HAMT solution method.

Comparisons between different sorption isotherms reveal that although similar observations can be made for the first and third scenario, differences are seen for the second scenario at higher initial moisture content levels. In general, however, higher temperatures are simulated when increasing the values of the sorption isotherm. In addition, the heat flux decreases when increasing the values of the sorption isotherm. When the initial moisture content of building walls increases, the effect of changes to simulation output decreases. This results in similar temperatures being simulated at higher moisture content levels, regardless of sorption isotherm used.

Changes made to liquid transport coefficient values does not influence simulated temperature. This observation is made for all three scenarios.

Regarding the parametric analysis on the vapour diffusion resistance factor, similar observations can be made for the three scenarios, but slight dissimilarities exist. For the first and second scenario, increasing vapour diffusion resistance factor values do not influence results at lower initial moisture content values. However, the simulated temperature increases at higher initial moisture content values. For the third scenario, increasing vapour diffusion resistance factor values do not influence the simulated temperature.

Comparing the results for the moisture dependent thermal conductivity parametric analysis, dissimilarities between the first and second scenario, and the third scenario exist. Regarding the first and second scenario, increasing thermal conductivity values will decrease simulated temperatures during the morning and late evening period. Due to the increased heat flux associated with increased thermal conductivity values, simulated temperatures will increase peak simulated temperatures during the afternoon. In contrast, the simulated temperature for the third scenario reveals an increase during the morning period with increased thermal conductivity values. In addition, heat flux decreases with an increase in thermal conductivity values.

The final set of comparisons focuses on the change in lounge temperature when changing the initial moisture content of the building walls. Analysing the results for the first and second scenarios reveals that increasing the initial moisture content decreases simulated temperature. Also, heat flux decreases when increasing the initial moisture content. Consequently, the daily temperature swing decreases with an increase in moisture content. Regarding the third scenario, although similar observations to first and second scenario are made, dissimilarities exist at higher initial moisture content values. Whereas the first and second scenarios show a decrease in simulated temperature when increasing initial moisture content from 10% to 20%, the third scenario shows an increase at certain times.

4.5 Concluding Summary

This chapter focused on the inclusion of moisture transfer and storage in hygroscopic materials in building energy analysis. A single storey, 40 m^2 house was analysed to study the effects of moisture transfer and storage on heat transfer and storage. Effects were analysed by performing parametric analysis on six hygroscopic material properties: initial moisture content, the sorption isotherm of the material, suction and redistribution liquid transport coefficients, vapour diffusion resistance factor values, and the thermal conductivity of materials as a function of moisture content. Performing building energy analysis without moisture transfer and storage in hygroscopic materials is referred to as CTF analysis. Including the effects of moisture transfer and storage in hygroscopic materials is referred to as HAMT analysis.

In addition to the parametric analysis, three scenarios are created in which materials are modelled, including hygroscopic effects. The first scenario entails analysing the exterior and interior building walls with moisture transfer and storage. The second scenario entails analysing only the exterior building walls with the effects of moisture transfer and storage. The third scenario entails analysing only the interior building walls with the effects of moisture transfer and storage.

Results reveal that the CTF solution method simulates cooler temperatures during the morning and evening, but warmer temperatures during the afternoon. Also, the heat flux associated with the CTF solution is larger compared to the HAMT solution. When adjusting the hygrothermal properties of the building walls, changes to the simulated temperature can be observed for changes made to the sorption isotherm and moisture dependent relative conductivity. Although changes to simulated temperature is observed for changes to the vapour diffusion resistance factor at higher initial moisture content, results remain similar at low initial moisture content.

Regarding the three analysed scenarios, results for the first and second scenarios are similar regarding observations made when adjusting hygrothermal properties. Dissimilarities exist when compared to the third scenario. This is not only observed when adjusting hygrothermal properties, but also when adjusting the initial moisture content. Simulated temperature for the first and second scenario decrease when increasing the initial moisture content. At higher initial moisture content, an increase is observed for the third scenario.

The results from the simulation reveal that hygrothermal analysis influence the average simulated temperature, as well as the simulated temperature range. The influence of the hygrothermal analysis on simulated temperature is dependent on the accuracy of the specific hygrothermal properties, initial moisture content, and the selected building constructions subject to hygrothermal analysis.

The influence of the hygrothermal processes on simulation output indicates a need to analyse structures with moisture buffering potential with the HAMT solution algorithm. However, due to the sensitivity of this solution algorithm, material properties and expected initial moisture content must be accurately presented if accurate results are desired.

Regarding housing in Cape Town, as wet winters are typically experienced, it can be reasonable to expect building materials to contain a significant amount of moisture content. This implies buildings in the Cape Town region with moisture buffering potential will experience cooler indoor conditions during the summer, but discomfort during wet and cold winter months.

In Chapter 5, an actual case is considered. Measured performance is not available for a house in the Cape Town Region. Instead, an instrumented house in the Eastern Cape is studied, which is also a coastal region, but roughly 1000 km north-east of Cape Town, in the East London region of South Africa.

Chapter 5 Validating the modelled thermal and hygral performance of a low-income house

5.1 Introduction

To aid individuals with a low income in owning a house, the South African government created a subsidy program. Low-income residents may apply for the government to build a house they may occupy when construction has finished. As of 2018, 13.6% of South African residents occupy subsidised housing (Statistics South Africa, 2019). These houses are built according to provincial regulations, the 2009 National Housing Code of South Africa, and the National Building Regulations.

The houses have been found to be exposed to harsh environmental conditions. Naicker et al. (2017) recorded indoor temperatures during 2014 of up to 45.4 °C during February and 6.1 °C during April for subsidised housing located in Johannesburg. This is in addition to Matandirotya et al. (2019) recording indoor temperatures reaching up to -1 °C and 39 °C for housing located in Mpumalanga, a northern province in South Africa, during 2017. Indoor temperatures for houses in the North West Province of -2 °C and 36 °C were reached during 2016. Adesina et al. (2020) found the average indoor temperature to reach 8.6 °C during the winter and 32.5 °C during the summer for housing in Mpumalanga. Recent studies focusing on the thermal and solar performance of housing located in the Eastern Cape have been started at University of Fort Hare. Initial studies focused on monitoring environmental conditions with recorded internal temperatures reaching 33 °C in the summer and 9.9 °C in the winter during 2012 (Kelvin et al., 2017). It can be seen that houses built according to housing programs are exposed to severe environmental conditions.

If the thermal properties, climatic conditions and occupational use of a structure are known, the thermal performance of the building can be modelled. DesignBuilder (DesignBuilder Software Ltd, 2020) is currently approved by the South African government for thermal analysis of structures. This can be used to reproduce measured data and identify and mitigate sources of heat loss and heat gain if deemed unfavourable.

In light of the conclusions and observations of Chapter 4, this chapter is dedicated to validating the modelled thermal and hygral performance of a low-income house. Subsequently, this chapter addresses Aim 3 of this study. It provides a hygrothermal analysis of a low-income house using the collected data of a subsidised, low-income house monitored by the University of Fort Hare in a previous study (Kelvin et al., 2017). In addition, parametric analysis is performed on assumed air leakage, floor thickness, appliance usage, hygral properties, and the opening of windows and doors. The analysis results provide insight into the thermal performance of the monitored house and the sensitivity of results when changing inputs.

The chapter is divided into four sections. Section 5.1 presents a discussion of the background for the chapter and a breakdown of the structure of the chapter. Section 5.2 describes the building selected for analysis, model parameters, and a description of the parametric analysis. Section 5.3 presents computational results stemming from the parametric analysis. Five sets of results are discussed. First, the computational results with different sets of air leakage values are presented. This is followed by the computational results for two floor thicknesses, due to uncertainty of the actual, as-built floor thickness. The third and fourth sets of results present the computational results for different internal heat gains and different values of initial moisture content. The final set of results presents the computational results for the closure of all ventilation opening components.

Section 5.4. presents a discussion on the hygrothermal analysis of the low-income house. The results indicate improved accuracy when modelling low-income with the HAMT solution method. Increasing the expected air leakage does not noticeably change simulated temperature but decreases relative humidity. Due to the roof being the largest source of heat gain and heat loss, changes to floor thickness have minimal impact on simulated temperature. However, due to increased moisture storage with increased floor thickness, relative humidity is decreased during periods where ventilation components are closed. Decreasing the internal heat loads influences both the simulated temperature and relative humidity, indicating an overestimation of expected internal loads. Changes to the initial moisture content do not significantly influence simulated temperature but greatly influence simulated relative humidity during periods where ventilation components are closed. Closing ventilation components increases simulated temperature and relative humidity during periods where ventilation components were previously closed.

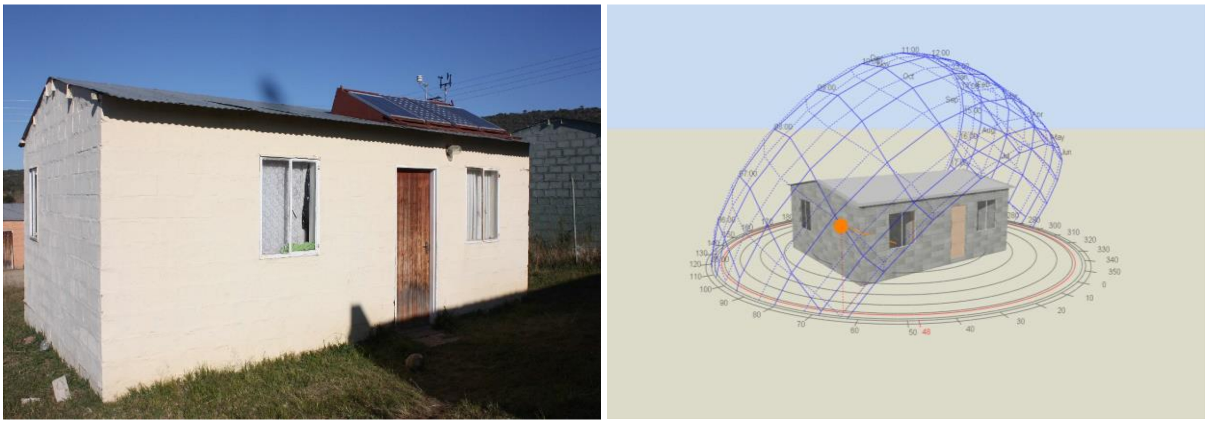
5.2 Model Description

To study the thermal performance of a low-income house, the inputs of the thermal model must be obtained from either the site, specialised software, or literature. Required model data are composed of the site data, building design, material thermal properties, material hygric properties, internal heat gains, ventilation properties, and heat balance solution method.

5.2.1 Site Data

The building under investigation is located in Alice, Eastern Cape. The model coordinates from the weather file are 32.79°S and 26.85°E. The building is orientated 16° east of north. Weather and site data were captured from 22 February to 26 December 2012. The region is classified as Cfb (oceanic climate) under the Köppen climate classification. The identified summer months are from September to May. The winter months are from June to August. An image of the house used for the analysis is presented in Figure 5.1 (a). A model image with a sun path diagram is presented in Figure 5.1 (b). A floor plan diagram of the house is presented in Figure 5.2.

The weather input file for the location was created by first obtaining the Meteonorm (Meteotest AG, 2020) weather file. Meteonorm data was then replaced with recorded data where possible. Recorded data were obtained for the dry-bulb temperature, relative humidity, wind speed, wind direction, and global horizontal irradiation (GHI). Due to the software requiring direct normal irradiation (DNI) and direct horizontal irradiation (DHI), the measured GHI was split according to the DNI and DHI components of the Meteonorm weather file.



(a) (b)

Figure 5.1 (a) External View of the Studied House (Kelvin et al., 2017) (b) Image Model of the Studied House

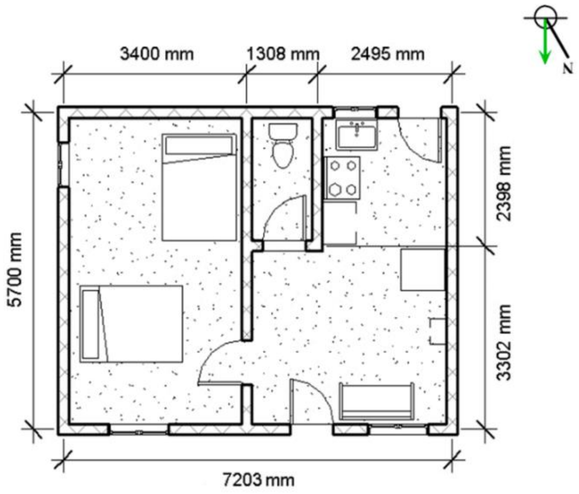


Figure 5.2: Floor Plan Diagram of the Studied House (Kelvin et al., 2017)

5.2.2 Building Design and Condition

The design of the building can be found in a previously published article (Kelvin et al., 2017). For the window frame, the thickness of the frame was modelled as 8 mm. The roof overhang is assumed to be 250 mm on the north and south and 200 mm on the east and west. Kelvin et al., (2017) identified openings and cracks on the building envelope as leakage paths. Some of the identified leakage paths are presented in Figure 5.3. Leakage (L) is modelled using Equation 5.1.

$$L = K \cdot \Delta P^{n} \qquad 5.1$$

where K is the flow coefficient, ΔP is the pressure difference across a building component, and n is the flow exponent. Three sets of flow coefficients and flow exponents are defined for each building component. These three are considered building components with 'very poor' airtightness, 'poor' airtightness, and 'medium' airtightness.

(a) (b)

(c) (d)

Figure 5.3: Sources of Air Leakage at the Studied House (Kelvin et al., 2017) (a) Cracks at the Outside Roof Perimeter (b) Cracks at the Sill of the Door (c) Cracks at the Inside Roof Perimeter (d) Loose Fitted Window Frame

5.2.3 Material Thermal Properties

Thermal properties for building components that are considered dry were obtained from CIBSE Guide A (Butcher and Craig, 2015). In addition to the thermal properties, the hygric properties of concrete and wood must also be obtained. The hygric properties of concrete were obtained from IEA Annex 24 (Kumaran, 1996). The hygric properties of the wood were obtained from IEA Annex 24 (Kumaran, 1996), except for the moisture dependent thermal conductivity, which was based on the thermal conductivity data of pine recorded in a study by Kol (2009).

The thermal bulk properties of materials are summarised in Table 5.1.

Table 5.1: Thermal Bulk Properties of Materials

Material	Thermal Conductivity (W/(m.K))	Density (kg/m^3)	Specific Heat Capacity (J/(kg.K))
Medium-Weight Concrete (Dry)	0.84	1650	840
Block, Hollow, Medium-Weight, 150 mm	0.62	1040	840
Pine, Pitch Pine (Dry)	0.17	650	2120
Steel	45	7800	480

5.2.4 Hygric Properties

Hygric properties are comprised of the initial moisture content, porosity, sorption isotherm, suction and redistribution liquid transport coefficient, and moisture diffusivity.

5.2.4.1 Concrete

The initial moisture content of the concrete materials is assumed to be 5% by weight based on recommendations of CIBSE Guide A (Butcher and Craig, 2015). The porosity of concrete for the walls was assumed to be 0.15 m^3/m^3 and the floor 0.33 m^3/m^3 (Kumaran, 1996). The sorption isotherm is defined by Equation 5.2.

$$w_c = 147.5 \cdot \left(1 - \frac{ln\,\phi_c}{0.0453}\right)^{-\frac{1}{1.67}} \tag{5.2}$$

where w_c is the concrete moisture content (mass per volume), ϕ_c is the relative humidity expressed as a fraction. The vapour resistance factor is defined by Equation 5.3.

$$\mu_c = \frac{1}{0.0084 + 0.079 \cdot (\phi_c)^{11}} \tag{5.3}$$

The moisture diffusivity is defined by Equation 5.4.

$$D_{Wc} = 1.8 \cdot 10^{-11} \cdot e^{0.0582 \cdot w_c} \tag{5.4}$$

The dry thermal conductivity of concrete increases by 4% of the dry thermal conductivity per percentage increase in weight.

5.2.4.2 Wood

The initial moisture content of the pine doors is assumed to be 8% by weight. The porosity of pine is assumed to be 0.8 m^3/m^3. The sorption isotherm is defined by Equation 5.5.

$$w_w = \frac{\phi_w}{-0.0026 \cdot {\phi_w}^2 + 0.02687 \cdot \phi_w + 0.8949} \tag{5.5}$$

where ϕ_w is the wood relative humidity expressed as a percentage. The vapour resistance factor is defined by Equation 5.6.

$$\mu_w = \frac{1}{0.0021 \cdot e^{0.0396 \cdot \phi_w}} \tag{5.6}$$

The wood moisture diffusivity is assumed constant, with value $D_{Ww} = 2.3 \cdot 10^{-11}$ m^2/s.

5.2.5 Internal Heat Gains

5.2.5.1 Occupancy

Occupancy was monitored in a previous study (Kelvin et al., 2017). From the observations, an occupancy profile was made for the bedroom and living room. Observations on the use of electronics and appliances were also made.

Three occupants were present in the study: an adult female, a female child, and a toddler. During school hours, assumed to be from 08:00 to 15:00, the female child was assumed to be absent. At all other times, all the occupants occupied the house. The lounge occupation hours ranged from 07:00 to 21:00 and the bedroom occupation hours ranged from 00:00 to 07:00 and 21:00 to 24:00. A metabolic heat rate of 75 W is chosen based on recommendations of SANS 10400-XA:2011 (South African Bureau of Standards, 2011b). A metabolic adjustment factor of 0.85 was chosen for the adult female, and an adjustment factor of 0.75 was chosen for the child and toddler, based on recommendations of CIBSE Guide A (Butcher and Craig, 2015).

5.2.5.2 Electronics and Appliances

Notable electronics and appliances observed for the study were a cathode-ray tube (CRT) TV and DVD player, an electric kettle, as well as an electric cooker. These items were modelled in the living room and kitchen zone. The CRT TV and DVD player were assumed to be on from 07:00 to 21:00. The electric kettle was assumed to be used between 07:00 and 07:30 and between 15:00 and 15:30. The electric cooker was assumed to be used between 17:00 and 18:00.

The heat gains for the CRT TV and DVD player were assumed to be 22 W and 5 W, respectively, based on recommendations of CIBSE Guide A (Butcher and Craig, 2015). The heat gain for the electric kettle was assumed to be 11 W per use. The heat fraction for the CRT TV, DVD player, and electric kettle was assumed to be 90% sensible and 10% radiant. The heat gain for the electric cooker was obtained by multiplying a usage factor of 0.5 with the nameplate rating, 2000 W, for South African electric cookers. The heat fraction of the electric cooker was assumed to be 33% latent and 66% sensible.

5.2.5.3 Lighting

11 W compact fluorescent lamp (CFL) lights were observed in the bedroom and living room. Both lights were observed as switched on between 19:00 and 21:00 during the summer and between 17:00 and 21:00 during the winter. Both lights were modelled as surface mounts resulting in heat fractions of 0.72 radiant, 0.18 visible, and 0.1 convective.

5.2.6 Ventilation

Ventilation is achieved through the opening and closing of building components monitored in a previous study (Kelvin et al., 2017). From the observations, a schedule was created for doors and windows.

It was observed that windows were opened halfway between 08:00 and 18:00 during the summer months and closed during the winter months. For windows to be opened in the summer, a rule was set that the air temperature of a zone must be warmer than 20 °C and that the outside temperature is cooler than the air temperature of a zone.

It was observed that external doors were opened for 6 and 3 hours between 08:00 and 18:00 in the summer and winter, respectively. For summer, the 6 coolest hours in the summer were identified and the 3 warmest hours in the winter. These times were then used to schedule the opening of the external doors. The bathroom door was always assumed to be closed. The bedroom door was assumed to be open during summer and closed during winter.

5.2.7 Scenarios Investigated

The analysis investigates a reference case, using the weather data, building materials and thermal properties, heat sources and occupancy, as well as leakage described in Sections 5.2.1 to 5.2.6. Both CTF and HAMT solution methods are used, but the HAMT solution is denoted as the reference numerical solution. The CTF solution addresses the secondary objective to study its accuracy in future analysis of building thermal performance, given its simpler solution and parameter characterisation. Subsequently, five likely scenarios are investigated, given the uncertainty in actual construction condition and detail, moisture content, and occupant behaviour. Scenario 1 investigates two lower leakage levels, denoted medium and low leakage, respectively, as opposed to the high level of leakage considered in the reference case. Scenario 2 entails a ground floor thickness of 75 mm, instead of the assumed more general reference thickness of 100 mm. The third scenario omits the electric cooker as a source of heat gain. Scenario 4 considers the initial moisture content of materials to be 0%. Scenario 5 assumes the doors and windows to be closed at all times. These five scenarios, which each deviates from the reference model only in the stated variation, are analysed to investigate likely causes of difference between measured and computed thermal performances.

A single summer week and a single winter week was chosen to be analysed. These two weeks correspond with weeks in which there was no interruption in data capture. The summer week was from 23 to 29 February and the winter week from 25 to 31 August.

5.3 Results

Measured and computed hourly averaged results for the reference and five different scenarios are compared in this section. This reference model is analysed with high leakage, and the electric cooker enabled, the floor thickness of 100 mm, material moisture content listed in Section 5.2.4 and ventilation possible. Section 5.3.1 compares the reference model to the measured results and Scenario 1 of medium and low air leakage. Sections 5.3.2 to 5.3.5 compare the reference and measured results to Scenarios 2 to 5, namely of a smaller floor thickness, no cooker, building materials containing no moisture and no ventilation by opening windows and doors.

Figure 5.4 to Figure 5.8 compare weekly and selected daily temperatures and relative humidity of computed reference and scenario cases with the actual measured indoor conditions. They also show the external temperatures and relative humidity obtained from weather data and used in the analyses.

Table 5.2 captures the maximum difference in the measured and calculated air temperatures and RH at the measured daily peak and the measured daily minimum values. Regarding the decreased air leakage of Scenario 1, only the values calculated for the least amount of air leakage are compared to the measured values. T_{max} is the largest calculated difference for the warmest temperature during a week and T_{min} is the largest calculated difference for the coldest temperature measured during a week. RH_{max} is the largest calculated difference for measured relative humidity during a week. Table 5.3 repeats this data for the selected summer and winter days. Significant underestimation of living and bedroom peak summer temperatures by 5 and 7 °C respectively are seen in Table 5.2, and overestimation of minimum winter temperatures by 1.5 and 3 °C respectively. Relative humidity in the living room is overestimated by more than 20% in summer and underestimated by more than 20% in winter. These large deviations underline uncertainty in actual weather data and model parameters, and are further discussed in Sections 5.3.1 to 5.3.5. The sensitivity to the scenario parameter study is shown in Figure 5.4 (c) and (d) to Figure 5.8 (c) and (d) for the selected summer and winter days reflected in Table 5.3. These closer observations of a single day cycle improve visual interpretation.

Table 5.2. Maximum differences between calculated and measured values

Scenario	Summer week						Winter week					
	T_{max} (°C)		T_{min} (°C)		RH_{max} (%)	RH_{min} (%)	T_{max} (°C)		T_{min} (°C)		RH_{max} (%)	RH_{min} (%)
	Living Room	Bed-room	Living Room	Living Room	Living Room	Living Room	Living Room	Living Room	Living Room	Bed-room	Living Room	Living Room
Reference Case - (HAMT)	-4.81	-7.41	-3.69	-4.19	19.3	14.9	-3.70	2.36	1.51	2.91	-16.2	9.8
Scenario1 - Low leakage	-4.73	-7.34	-3.65	-4.15	24.6	16.6	-3.72	2.73	1.83	3.22	14.0	20.0
Scenario 2 - 75 mm floor	-4.86	-7.47	-3.71	-4.23	24.1	16.8	-3.75	2.12	1.52	2.97	-13.9	11.0
Scenario 3 - No cooker	-4.81	-7.41	-3.69	-4.19	19.3	14.9	-3.70	2.36	1.49	2.90	-16.7	9.6
Scenario 4 - No moisture	-4.71	-7.30	-3.72	-4.21	14.5	7.0	-3.68	2.44	1.49	2.88	-17.3	9.2
Scenario 5 - No ventilation	2.69	-4.51	-2.48	-3.29	23.1	20.2	1.90	2.62	1.57	2.94	-15.1	15.1
Reference Case - (CTF)	-4.51	-7.13	-3.95	-4.68	21.7	23.5	-3.52	3.17	-2.06	2.38	-24.5	8.2

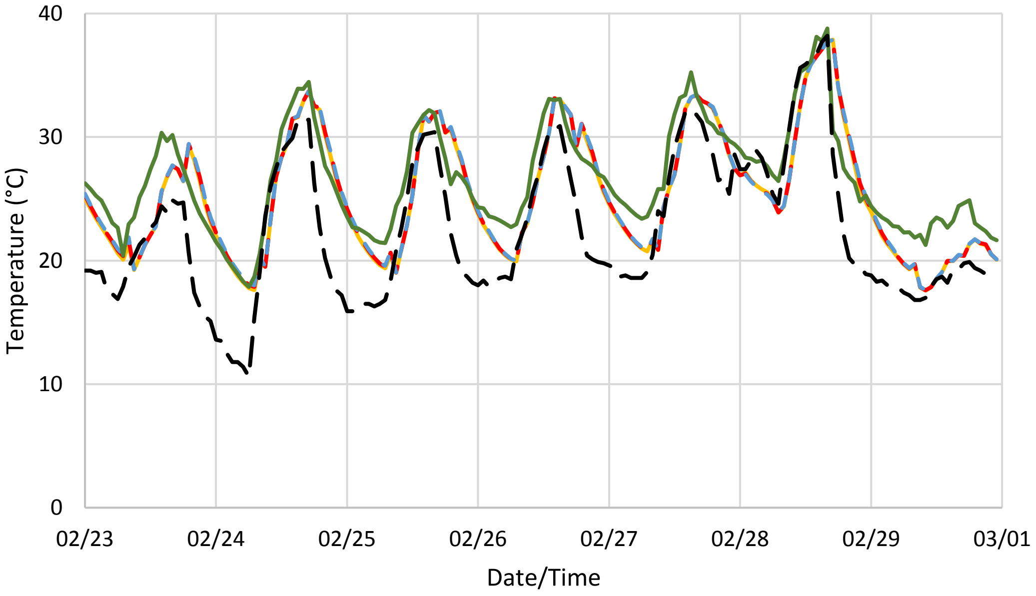
Table 5.3. Differences between calculated and measured values for a summer and winter day

Scenario	Summer day 24/2						Winter day 28/8					
	T_{max} (°C)		T_{min} (°C)		RH_{max} (%)	RH_{min} (%)	T_{max} (°C)		T_{min} (°C)		RH_{max} (%)	RH_{min} (%)
	Living Room	Bed-room	Living Room	Living Room	Living Room	Living Room	Living Room	Living Room	Living Room	Bed-room	Living Room	Living Room
Reference Case - (HAMT)	-0.78	-5.58	-0.09	-0.41	19.3	3.5	2.45	1.21	1.49	2.91	-2.9	-0.6
Scenario1 - Low leakage	-0.74	-5.46	0.28	-0.05	24.6	3.8	2.42	1.15	1.83	3.22	6.2	1.2
Scenario 2 - 75 mm floor	-1.03	-5.75	-0.16	-0.46	24.1	4.2	2.40	1.03	1.52	2.97	0.6	-0.1
Scenario 3 - No cooker	-0.78	-5.58	-0.10	-0.41	19.3	3.5	2.45	1.22	1.47	2.90	-3.5	-0.6
Scenario 4 - No moisture	-0.41	-5.38	-0.21	-0.50	3.6	2.1	2.48	1.34	1.45	2.88	-4.0	-0.8
Scenario 5 - No ventilation	1.41	-2.30	0.11	-0.17	23.1	19.3	1.23	1.18	1.55	2.94	-1.1	14.7
Reference Case - (CTF)	0.23	-4.83	-0.75	-0.95	12.4	0.8	2.79	2.34	0.73	2.38	-2.5	-3.2

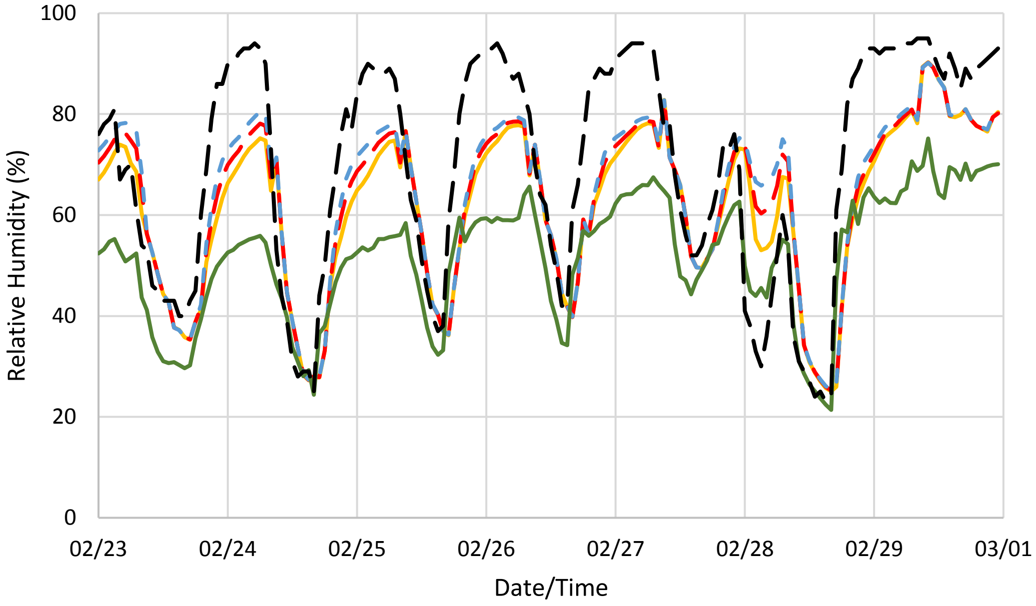
5.3.1 Scenario 1, Reduced Air Leakage

Varied air leakage does not influence room temperatures by a considerable amount, yet reduces the temperature differences at peak. It can still be observed that the room air temperatures decrease due to the incoming air being cooler than the room air temperature. This infiltration is, however, offset by conduction heat gains and heat losses through the building envelope, as well as heat gains and heat losses through ventilation. Results for the summer week and selected day are presented in Figure 5.4 (a) and (c), respectively. Due to the time staggering approach used for solutions, air infiltrating the building will assume the environmental conditions of the air at the current time step to calculate the outputs of the next time step. This can result in internal temperatures being colder than its exposed environment if a large increase in environmental temperature is recorded, as observed for 09:00 on the 24th of February.

Increasing air leakage results in decreased relative humidity during mornings and evenings but has no influence during the afternoon and when openings in the building envelope are open. Increased building leakage results in a decrease in relative humidity. This is due to the moisture content of air infiltrating the living room being less than the moisture content of the air of living room. The influence of air leakage falls away as the outside and inside air temperature increases, resulting in a simultaneous decrease in relative humidity. It can be noticed that introducing morning air can result in a sudden increase in relative humidity due to the increased water vapour of the outside air. This is observed for both the summer and winter week. Results for the summer week and selected day are presented in Figure 5.4 (b) and (d).



(a)



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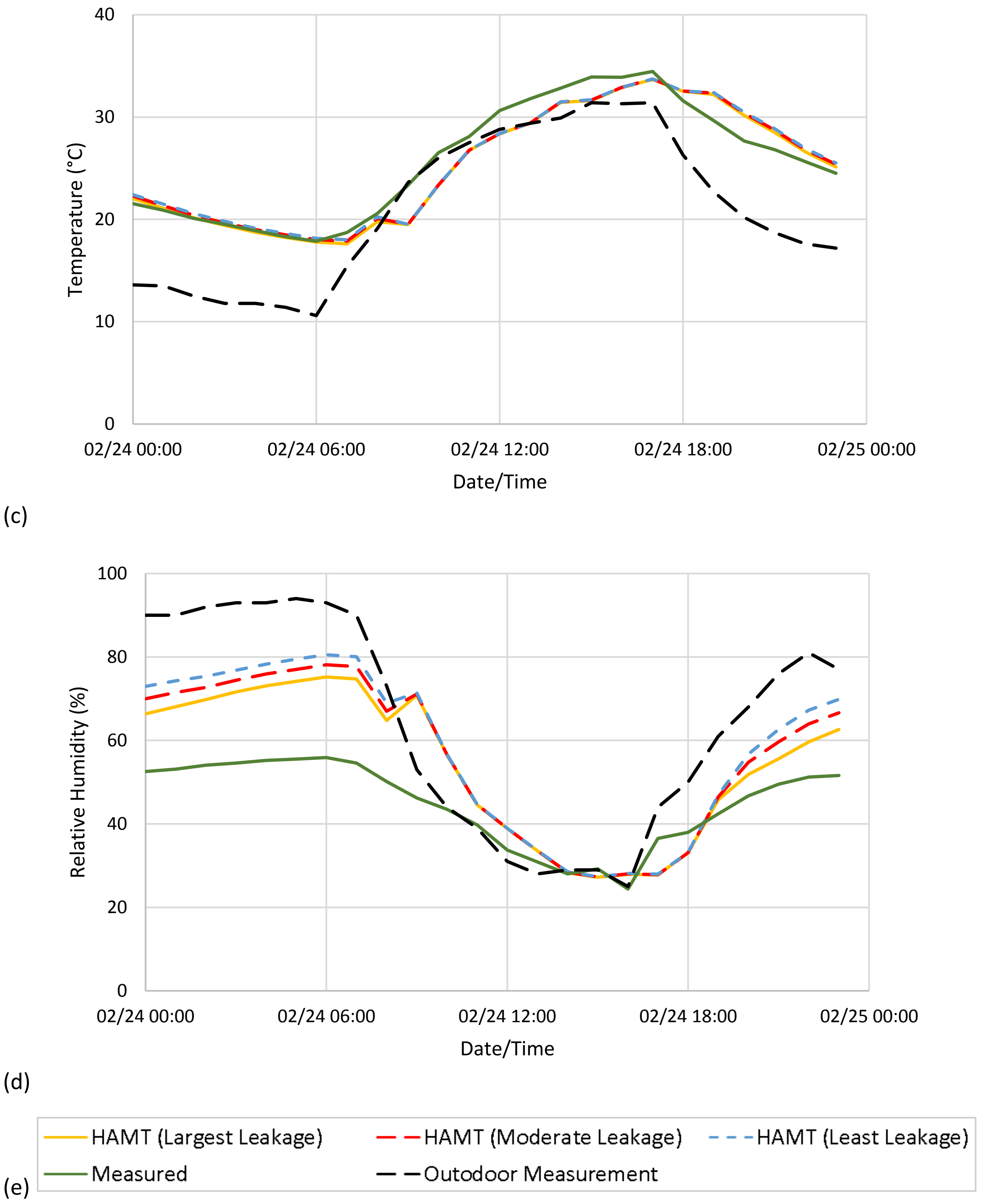
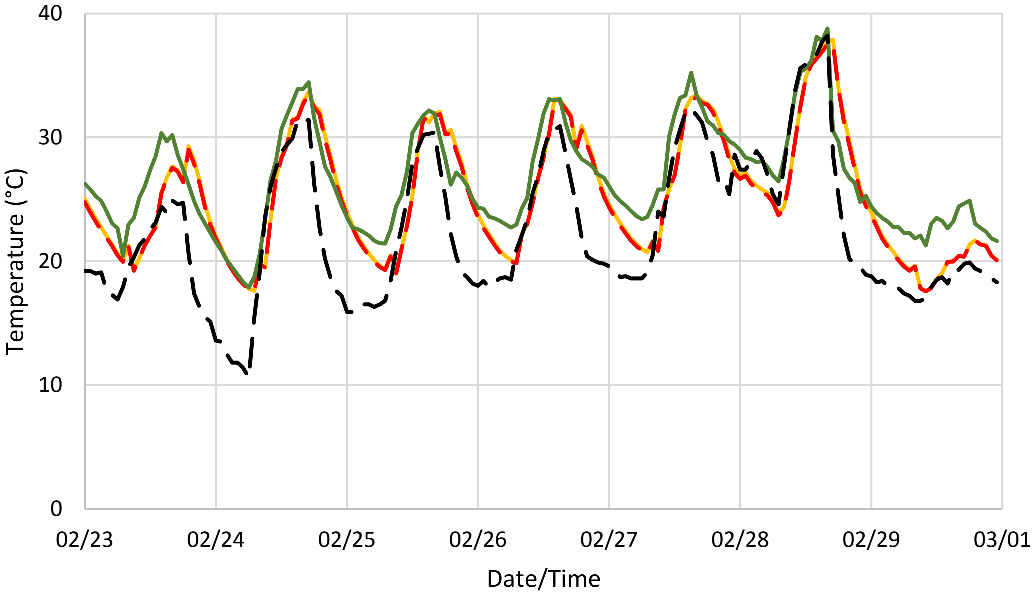


Figure 5.4: Comparison between the reference model and reduced air leakage (a) Weekly air temperature of the living room (Summer) (b) Weekly relative humidity of the living room (Summer) (c) Daily air temperature of the living room (Summer) (d) Daily relative humidity of the living room (Summer) (e) Graph legend

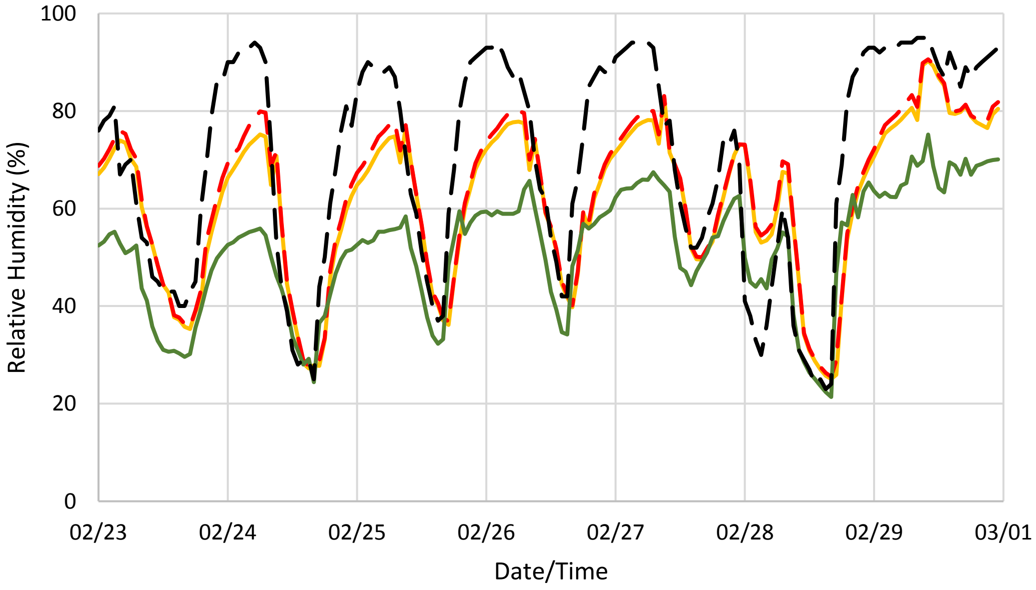
5.3.2 Scenario 2, Increased Floor Thickness

Room air temperature is insensitive to the floor thickness reduction from 100 mm to 75 mm, although a slight increase can be observed for the summer and winter week. Although the floor surface temperature increases, the room air temperature is dominated by conduction through the roof and convection through ventilation. Results for a summer week and selected day are presented in Figure 5.5 (a) and (c).

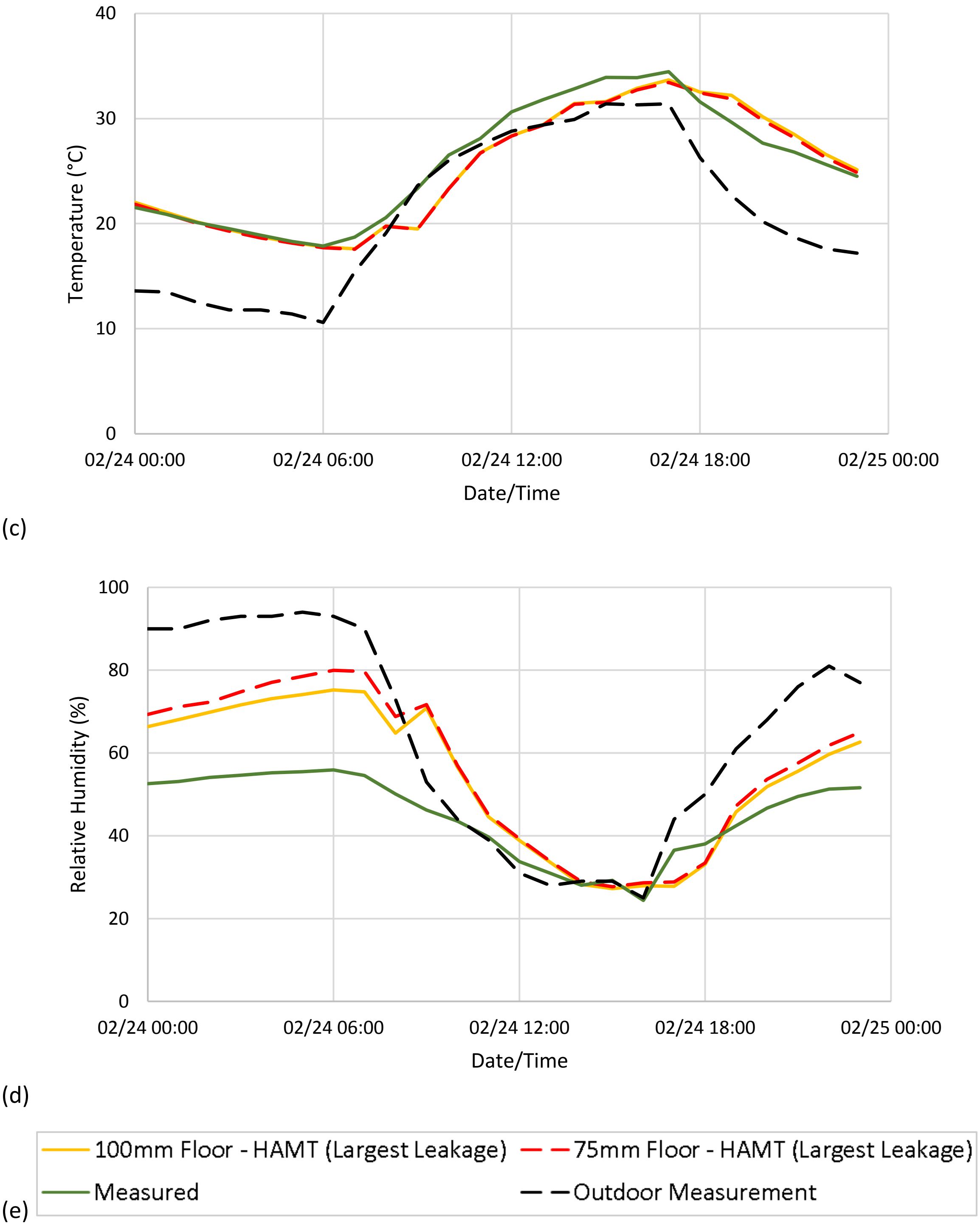
An increase in floor thickness results in decreased room relative humidity during the morning and evening due to increased moisture storage but has no influence during the afternoon or when openings in the building envelope are open. This can be observed for the summer and winter week. Results for a summer week and day are shown in Figure 5.5 (b) and (d).



(a)



(b)



(c)

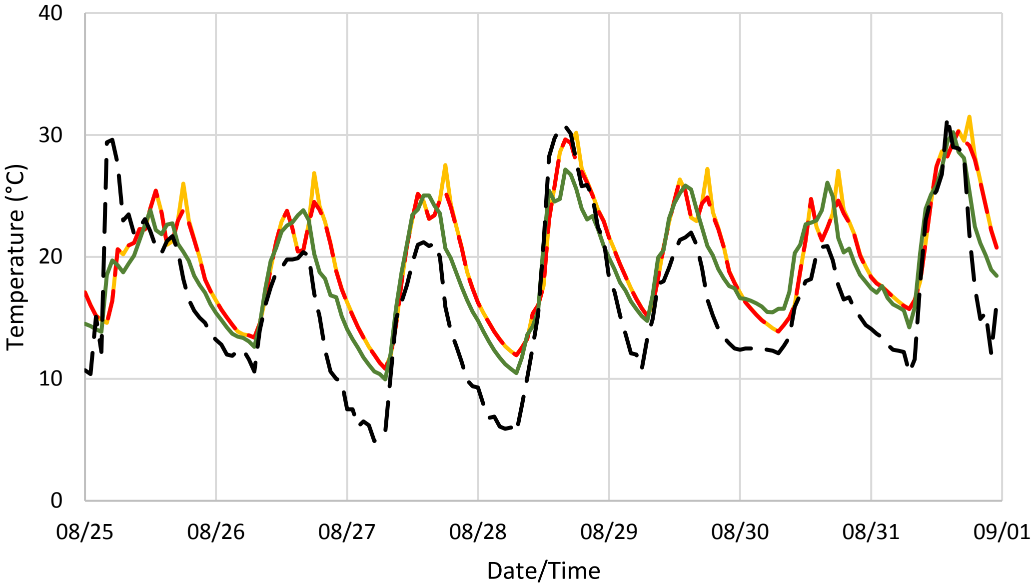
(d)

(e)

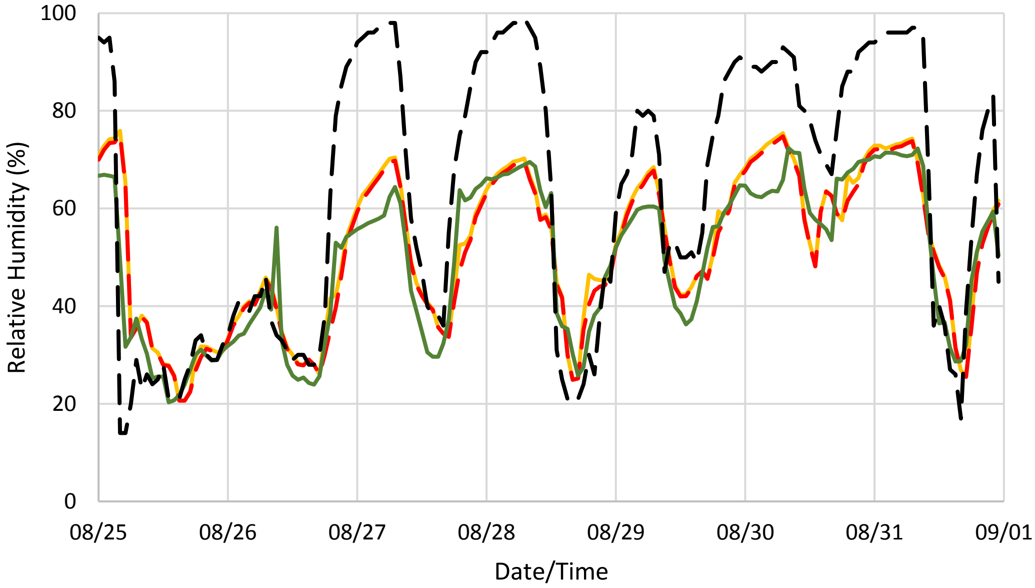
Figure 5.5: Comparison between the reference model and reduced floor thickness (a) Weekly air temperature of the living room (Summer) (b) Weekly relative humidity of the living room (Summer) (c) Daily air temperature of the living room (Summer) (d) Daily relative humidity of the living room (Summer) (e) Graph legend

5.3.3 Scenario 3, Absence of Electric Cooker

Although not as noticeable during summer compared to winter, deactivating the electric cooker results in a decrease in room temperature between 17:00 and 18:00, when the electric cooker is scheduled to be on. Results for a winter week and selected day are presented in Figure 5.6 (a) and (c). Removal of that spike suggests that the cooker is used less than thought, as it improves agreement with the measured temperature. For the winter week, a decrease in room relative humidity can also be observed after 18:00 due to the removed latent heat. No considerable difference in relative humidity can be observed at all other times – see Figure 5.6 (b) and (d).



(a)



(b)

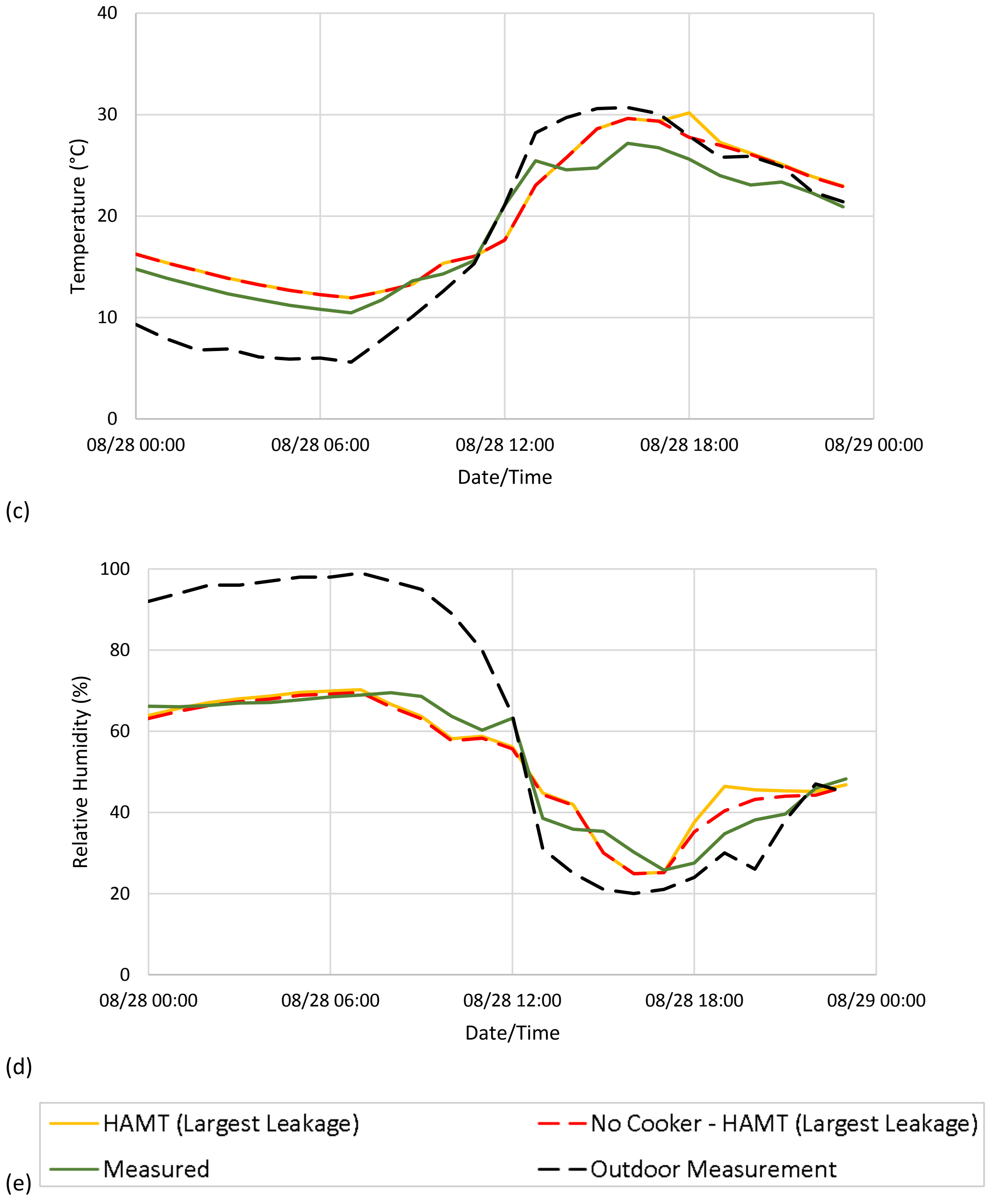
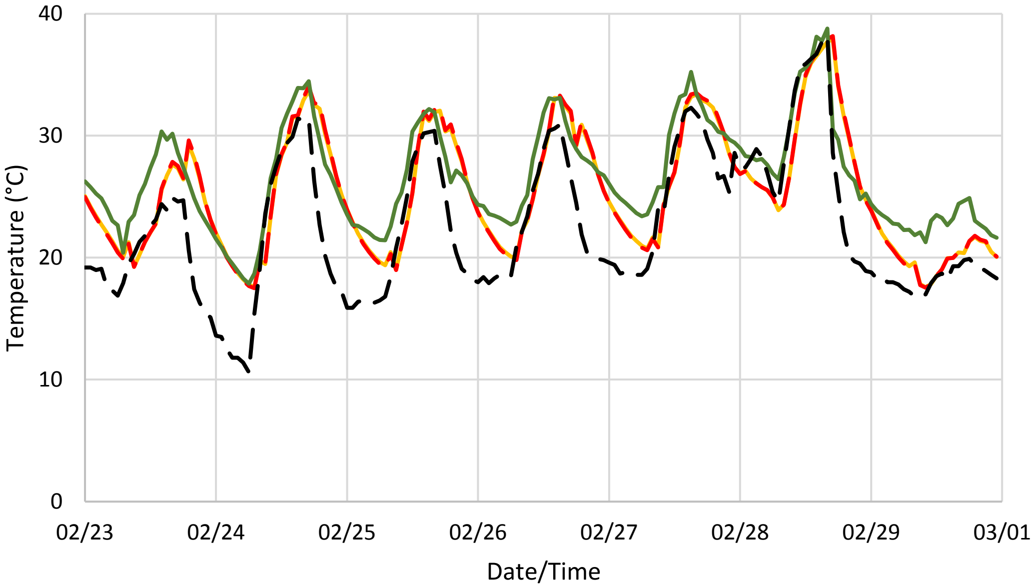


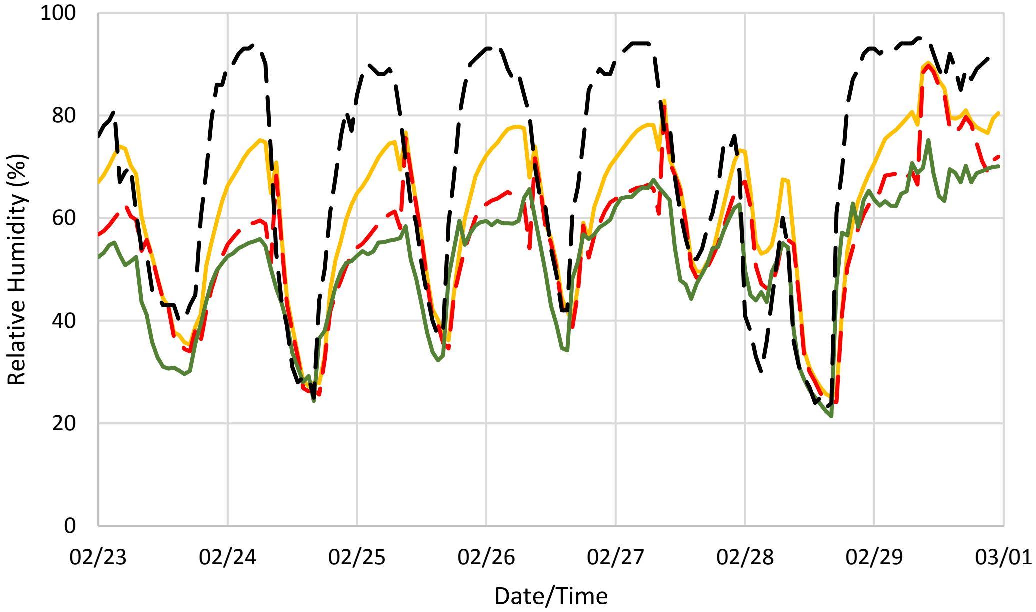
Figure 5.6: Comparison between the reference model and the removal of the electric cooker (a) Weekly air temperature of the living room (Winter) (b) Weekly relative humidity of the living room (Winter) (c) Daily air temperature of the living room (Winter) (d) Daily relative humidity of the living room (Winter) (e) Graph legend

5.3.4 Scenario 4, Change of Initial Moisture Content

Changing the initial moisture content does not significantly influence the room air temperature during the summer and winter weeks. Although a large amount of heat is transferred by conduction through the walls, room air temperature is dominated by conduction through the roof and convection through ventilation. Results for a summer week and selected day are shown in Figure 5.7 (a) and (c). Decreasing the initial moisture content results in a large decrease in room relative humidity during the morning and evening for the summer and winter weeks but insignificantly affects afternoons or when openings in the building envelope are open. This indicates a decrease in convective vapour transfer. Figure 5.7 (b) and (d) show results for a summer week and day. The initial moisture content of the material not only affects the thermal properties of a material but greatly influences the moisture balance of zones.



(a)



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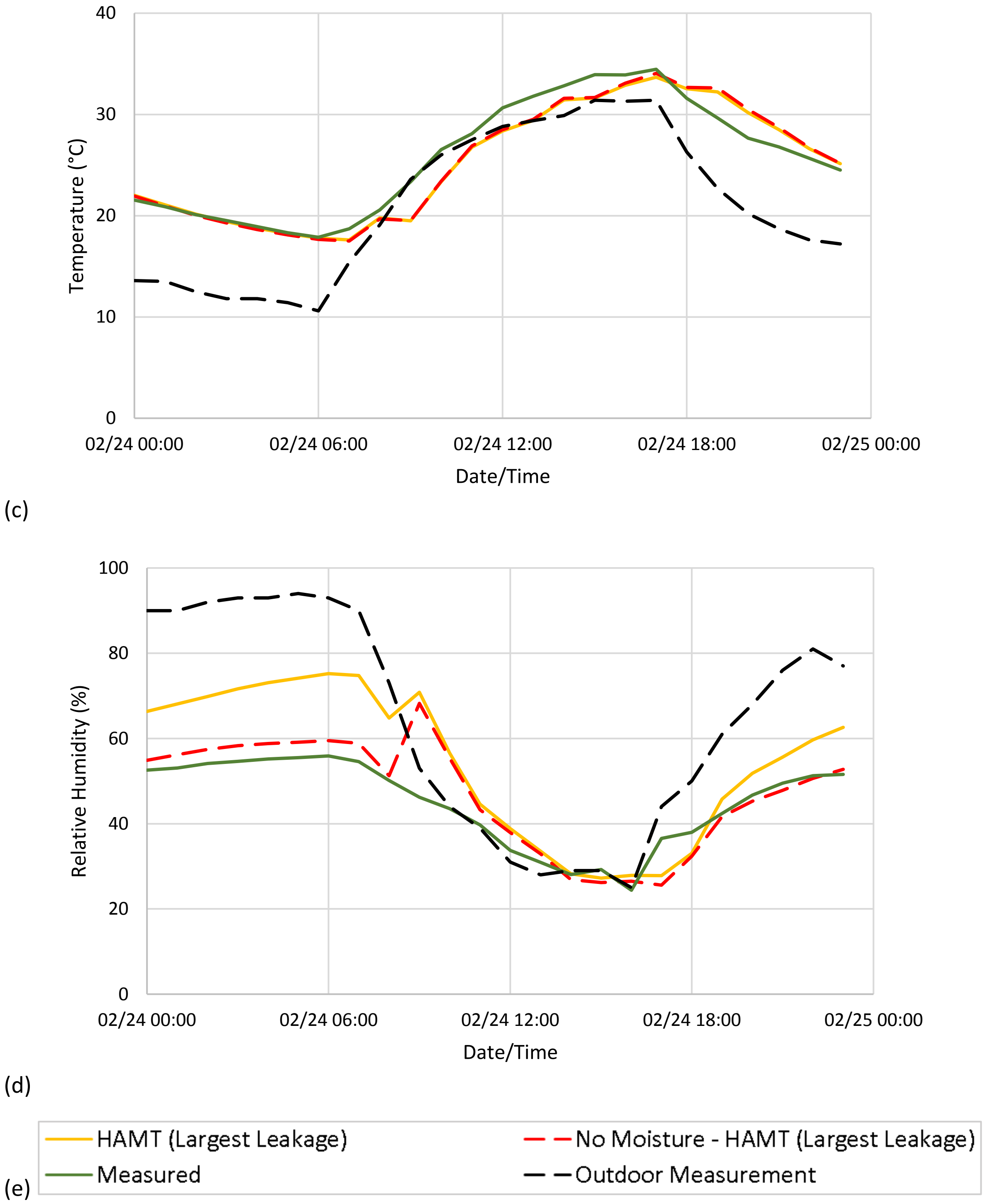
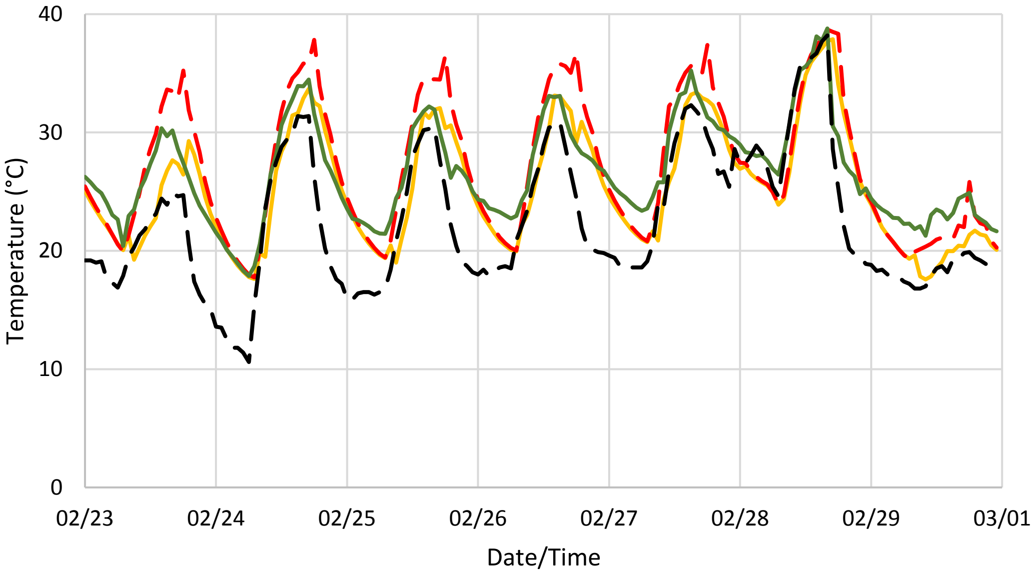


Figure 5.7: Comparison between the reference model and reduced initial moisture content of building materials (a) Weekly air temperature of the living room (Summer) (b) Weekly relative humidity of the living room (Summer) (c) Daily air temperature of the living room (Summer) (d) Daily relative humidity of the living room (Summer) (e) Graph legend

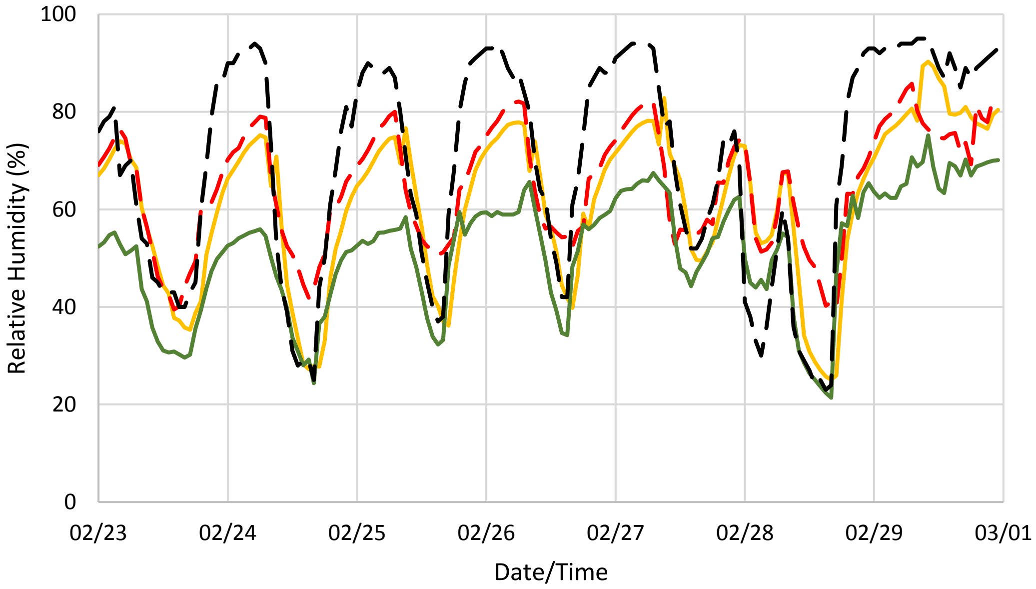
5.3.5 Scenario 5, Closing of All Openings

Closing all the openings of the building results in an increase in room air temperature during the afternoon when openings are scheduled to be open. This is observed for the winter and summer weeks. Figure 5.8 (a) and (c) show the results for a summer week and day.

Closing all the openings of the building results in an increase in relative humidity during the evenings and the afternoon for the summer and winter week. This is due to moist air not being allowed to escape. Results for a summer week and selected day are presented in Figure 5.8 (b) and (d).



(a)



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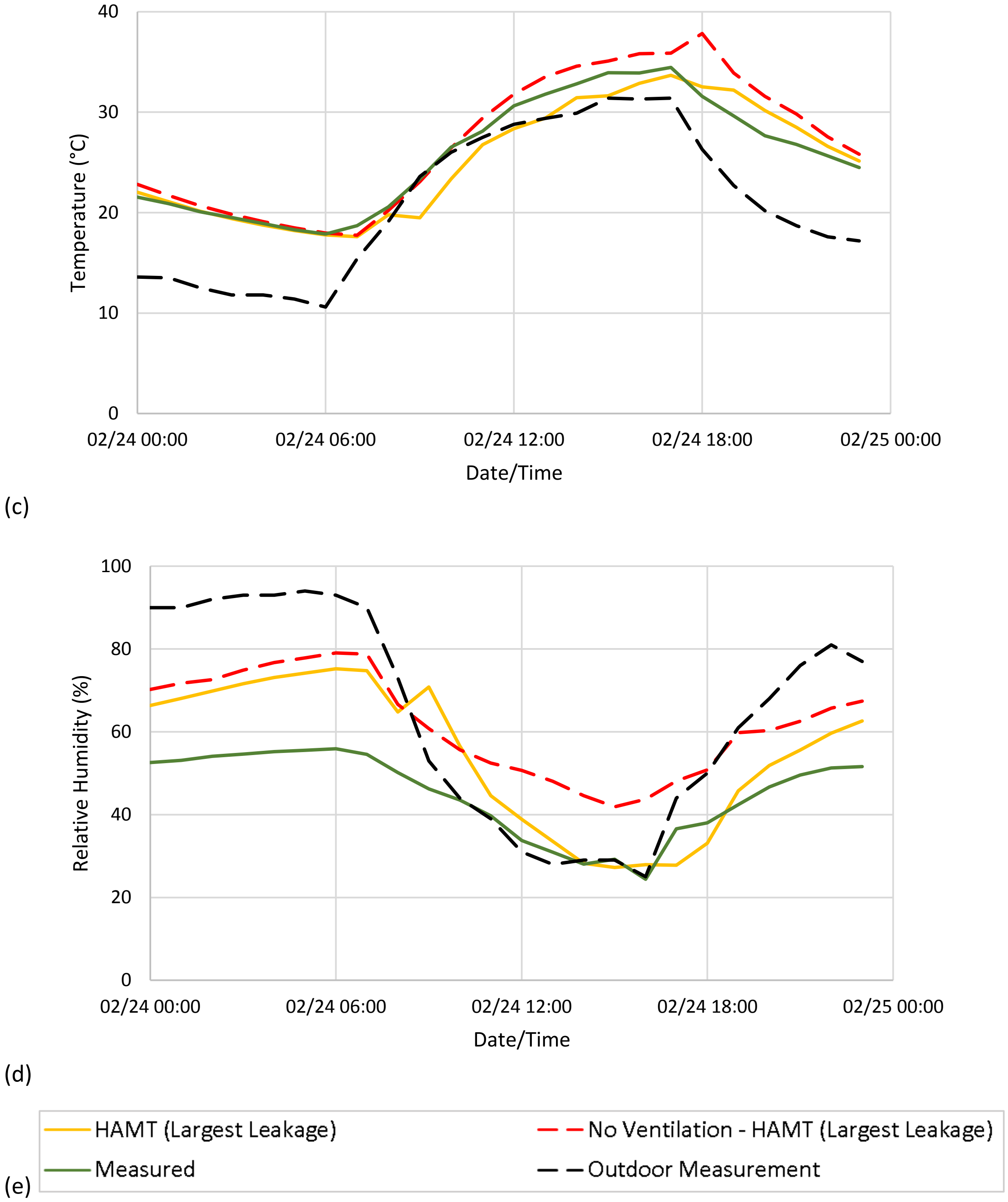


Figure 5.8: Comparison between the reference model and closed ventilation components (a) Weekly air temperature of the living room (Summer) (b) Weekly relative humidity of the living room (Summer) (c) Daily air temperature of the living room (Summer) (d) Daily relative humidity of the living room (Summer) (e) Graph legend

5.3.6 Validation of Results

Nine validation metrics proposed by Huerto-Cardenas *et al.* (2020) were chosen for the validation analysis. The metrics chosen for validation, introduced in Section 2.8.3, are the MBE, MAE, RMSE, NMBE, CVRMSE, NRMSE, Pearson correlation coefficient, coefficient of determination, and IC. A summary of the descriptions of the validation metrics is presented in Table 5.4, including threshold values detailed by Huerto-Cardenas *et al.* (2020) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14 (ANSI/ASHRAE, 2014). Regarding the threshold values of the NRMSE, although no threshold value is suggested, a lower NRMSE value is desired. The threshold values of the MAE and RMSE are based on the air temperature and relative humidity.

Table 5.4: Descriptions and threshold values of validation metrics used for the validation of hygrothermal simulation models

Index	Description	Threshold Value	
MBE	The average value of error between the measured and simulated values		
MAE	The average value of absolute error between the measured and simulated values	Higher accuracy Lower accuracy	< 1 °C < 5% < 2 °C < 10%
RMSE	The standard deviation of model errors		
NMBE	Normalised MBE using the mean of the measured values	±10%	
CVRMSE	Normalised RMSE using the mean of the measured values	±30%	
NRMSE	Normalised RMSE using the range of the measured values		
r	Represents the linear relationship between measured and simulated values	> 0.5	
R^2	Represents the correlation between measured and simulated values	> 0.75	
IC	Indication of how well two different time series compare	< 0.25	

In addition, the validation analysis was performed for six sample sizes. The first validation analysis is the traditional method, considering the entire simulation sample size and producing statistical indices for a single set of values. The second validation analysis is weekly-based, considering each week of an entire set of series ($24 \leq n \leq 168$), producing statistical indices for a maximum of 53 sets of values and a minimum of 1 set of values. The third validation analysis is day-based, considering each day of an entire set of results ($n=24$), producing statistical indices for a maximum of 365 sets of values and a minimum of 1 set of values. The fourth and final validation analysis is hourly-based, considering each hour of an entire set of results ($24 \leq n \leq 8760$), producing statistical indices for 24 sets of values. The hourly-based analysis was performed using three different sample sizes: the summer week, the winter week, and the summer and winter week combined. Due to the amount of data produced using different sample sizes, only a selection of the results is presented, with the remainder of the results found in Appendix E.6.

5.3.6.1 Living Room Air Temperature

A summary of the validation analysis metrics of the living room air temperature for the entire sample size is summarised in Table 5.5. The cells of the table are coloured according to the value they contain. If the compared value surpassed the threshold value detailed in Table 5.4, it would be assigned a light red colour. If the value were within the limits of the threshold value, it would be assigned a light blue colour. However, validation metrics without a threshold value were assigned a light grey colour.

From Table 5.5, it can be observed that although the MBE is less than ±1 °C for all cases, the MAE is less than 2 °C for only the reference HAMT case, as well as Scenarios 3 and 4. The RMSE for all cases lies above 2 °C, indicating that the model contains outliers. In all cases, the NMBE and CVRMSE are well below the 10% and 30% limits imposed by ASHRAE Guideline 14 (ANSI/ASHRAE, 2014). Regarding the normalised RMSE value, Scenario 3 performs the best, with the CTF model performing the worst. Although the r, R^2, and IC values for all cases are deemed satisfactory compared to the threshold values proposed by Huerto-Cardenas *et al.* (2020), the CTF case performs worse or is equal to the other cases.

Table 5.5: Validation metrics for the living room air temperature for the summer and winter week combined

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.21	2.13	2.68	0.93	11.74	9.29	0.90	0.79	0.06
Reference Case (HAMT)	0.16	1.97	2.44	0.69	10.70	8.47	0.91	0.82	0.05
Scenario 1 - Low leakage	-0.03	2.04	2.53	-0.12	11.09	8.78	0.90	0.81	0.05
Scenario 2 - 75 mm floor	0.28	1.95	2.41	1.23	10.56	8.36	0.91	0.83	0.05
Scenario 3 - No cooker	0.24	1.90	2.33	1.04	10.20	8.08	0.92	0.84	0.05
Scenario 4 - No moisture	0.14	1.99	2.47	0.61	10.82	8.57	0.91	0.82	0.05
Scenario 5 - No ventilation	-0.99	2.01	2.57	-4.35	11.28	8.93	0.93	0.80	0.05

A summary of the validation analysis metrics of the living room air temperature for the summer and winter week sample size is summarised in Table 5.6 and Table 5.7. The summer week shows decreased accuracy compared to the winter week, with the MAE and RMSE being above 2 °C for the summer week. It is again observed that the CTF case performs worse than the reference HAMT case. In addition, it can be noticed that the MBE leads to error cancellation due to underprediction experienced during the summer week but overestimation during the winter week. Regarding the r and R^2 values, both values deteriorate with a decrease in sample size.

Table 5.6: Validation metrics for the living room air temperature for the summer week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.33	2.38	2.81	4.99	10.56	13.42	0.89	0.57	0.05
Reference Case (HAMT)	1.29	2.10	2.55	4.85	9.59	12.20	0.90	0.65	0.05
Scenario 1 - Low leakage	1.15	2.09	2.55	4.32	9.57	12.17	0.89	0.65	0.05
Scenario 2 - 75 mm floor	1.44	2.14	2.57	5.39	9.68	12.31	0.90	0.64	0.05
Scenario 3 - No cooker	1.32	2.10	2.55	4.95	9.59	12.20	0.90	0.65	0.05
Scenario 4 - No moisture	1.26	2.15	2.59	4.72	9.75	12.40	0.90	0.63	0.05
Scenario 5 - No ventilation	-0.52	2.04	2.65	-1.94	9.95	12.65	0.91	0.62	0.05

Table 5.7: Validation metrics for the living room air temperature for the winter week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.90	1.88	2.54	-4.74	13.36	12.55	0.89	0.68	0.06
Reference Case (HAMT)	-0.97	1.83	2.33	-5.12	12.22	11.48	0.90	0.73	0.06
Scenario 1 - Low leakage	-1.20	1.98	2.51	-6.33	13.21	12.40	0.89	0.69	0.06
Scenario 2 - 75 mm floor	-0.87	1.75	2.23	-4.60	11.73	11.02	0.90	0.75	0.06
Scenario 3 - No cooker	-0.84	1.71	2.08	-4.44	10.93	10.27	0.91	0.78	0.05
Scenario 4 - No moisture	-0.98	1.83	2.34	-5.13	12.29	11.54	0.90	0.73	0.06
Scenario 5 - No ventilation	-1.47	1.99	2.50	-7.71	13.12	12.32	0.92	0.69	0.06

Although a summary of the day- and hourly-based validation analyses of the living room air temperature is presented in Appendix E.6.1, notable observations include:

- Validation metrics for the 29th of February, see Table E.10, indicate large uncertainty for this day. This large level of uncertainty can be explained by Figure 5.4 (a), which indicates that the data captured for this day was compromised.
- Table E.84 indicates the heat gain from the electric cooker needs to be adjusted as the MAE of the reference HAMT case is 5.93 °C compared to an MAE of 3.61 °C for Scenario 3.
- Table E.51 to Table E.55 indicate that allowing the house to be closed during the morning hours results in immediate improvement for the summer week between 09:00 and 13:00.

5.3.6.2 Living Room Relative Humidity

A summary of the validation analysis metrics of the living room relative humidity for the entire sample size is summarised in Table 5.8. The MBE is less than ±10% for all cases, except for Scenario 1. In contrast, the MAE and RMSE is less than 10% for only the reference HAMT case, Scenario 3, and Scenario 4. Regarding the NMBE and CVRMSE limits, only Scenario 4 falls below both limits. Scenario 4 is also observed to perform the best when using NRMSE as a validation metric. Although the r and IC value for all cases are deemed satisfactory compared to the threshold values proposed by Huerto-Cardenas et al. (2020), the R^2 value for Scenario 4 is the only case that comes close to the 0.75 threshold value proposed by Huerto-Cardenas et al. (2020). It is clear from Table 5.8 that Scenario 1 is the worst performing model for simulating relative humidity.

Table 5.8: Validation metrics for the living room relative humidity for the summer and winter week combined

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-5.21	8.81	11.34	-10.26	22.31	20.66	0.88	0.36	0.10
Reference Case (HAMT)	-6.06	7.94	9.85	-11.93	19.39	17.96	0.88	0.51	0.09
Scenario 1 - Low leakage	-11.41	12.37	14.19	-22.45	27.92	25.86	0.86	-0.01	0.12
Scenario 2 - 75 mm floor	-7.63	9.05	10.99	-15.01	21.62	20.02	0.88	0.40	0.10
Scenario 3 - No cooker	-5.69	7.90	9.82	-11.19	19.33	17.90	0.87	0.52	0.09
Scenario 4 - No moisture	-2.70	5.29	7.21	-5.30	14.19	13.14	0.89	0.74	0.07
Scenario 5 - No ventilation	-8.80	9.71	11.74	-17.32	23.10	21.40	0.85	0.31	0.10

A summary of the validation analysis metrics of the living room relative humidity for the summer and winter week sample size is summarised in Table 5.9 and Table 5.10. The summer week shows decreased accuracy compared to the winter week, with a decrease in the MAE and RMSE observed for all cases. It is again observed that the CTF case performs worse than the reference HAMT case. When comparing the R^2 value, only the reference HAMT case, Scenario 3, and Scenario 4 for the winter week are deemed satisfactory compared to the threshold values proposed by Huerto-Cardenas et al. (2020). In contrast, the r and IC values for all cases are deemed satisfactory compared to the threshold values proposed by Huerto-Cardenas et al. (2020).

Table 5.9: Validation metrics for the living room relative humidity for the summer week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-9.00	11.15	13.42	-17.35	25.87	24.95	0.87	-0.20	0.11
Reference Case (HAMT)	-9.80	10.98	12.34	-18.88	23.80	22.95	0.89	-0.01	0.11
Scenario 1 - Low leakage	-12.12	13.24	14.89	-23.36	28.72	27.69	0.86	-0.47	0.12
Scenario 2 - 75 mm floor	-11.09	12.14	13.57	-21.37	26.17	25.23	0.88	-0.22	0.11
Scenario 3 - No cooker	-9.83	10.98	12.35	-18.95	23.80	22.95	0.89	-0.01	0.11
Scenario 4 - No moisture	-3.92	6.01	8.13	-7.55	15.67	15.11	0.86	0.56	0.07
Scenario 5 - No ventilation	-13.17	13.43	14.73	-25.39	28.40	27.38	0.85	-0.44	0.12

Table 5.10: Validation metrics for the living room relative humidity for the winter week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.42	6.46	8.77	-2.86	17.64	16.85	0.90	0.69	0.08
Reference Case (HAMT)	-2.33	4.90	6.46	-4.69	12.99	12.41	0.93	0.83	0.06
Scenario 1 - Low leakage	-10.70	11.49	13.45	-21.50	27.03	25.82	0.87	0.27	0.12
Scenario 2 - 75 mm floor	-4.17	5.97	7.56	-8.37	15.19	14.52	0.92	0.77	0.07
Scenario 3 - No cooker	-1.55	4.83	6.37	-3.11	12.81	12.24	0.92	0.84	0.06
Scenario 4 - No moisture	-1.47	4.58	6.15	-2.96	12.37	11.82	0.93	0.85	0.06
Scenario 5 - No ventilation	-4.44	6.00	7.66	-8.92	15.40	14.71	0.92	0.76	0.07

A summary of the day- and hourly-based validation analysis of the living room relative humidity is presented in Appendix E.6.2.

The improved model accuracy in relative humidity associated with Scenario 4 compared to the reference HAMT case can be associated with the time it takes to reach moisture equilibrium. When inspecting the water content of the HAMT cells of the wall on the north side of the living room, it can be observed that the wall dries out when assuming an initial moisture content of 5% but absorbs moisture from the air when assuming an initial moisture content of 0%. This observation is captured in Figure 5.9. Cell 11 represents the HAMT cell closest to the home's inside surface, whereas Cell 7 is closer to the centre of the wall. From the graph, it can be observed that while HAMT cells near the wall's surface are close to moisture equilibrium, the cells near the centre must still reach a state of moisture equilibrium.

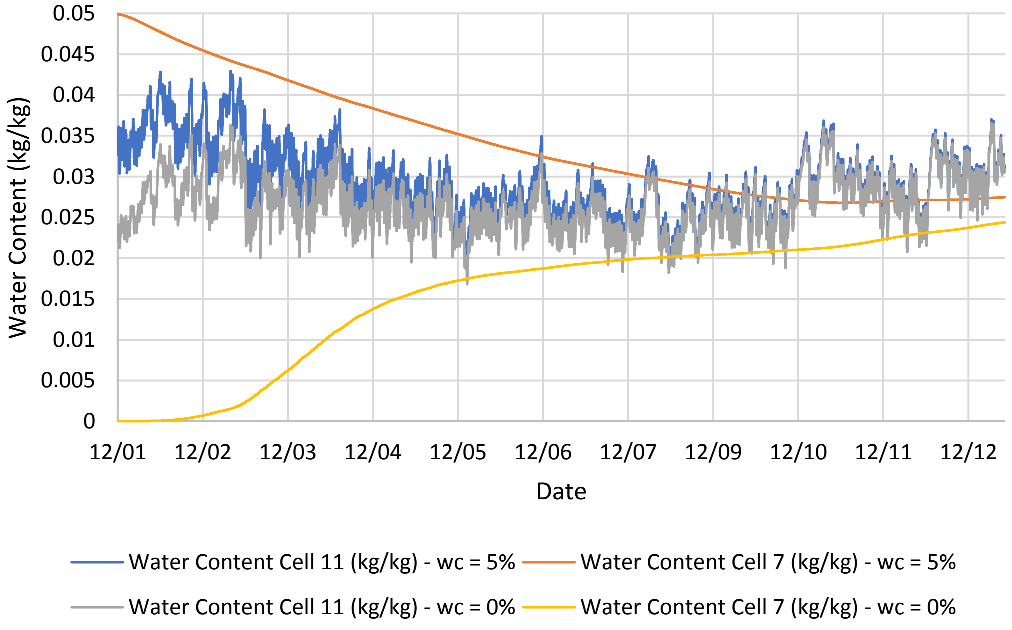


Figure 5.9: Water content in Cells 7 and 11 of north living room wall throughout the year

5.3.6.3 Bedroom Air Temperature

A summary of the validation analysis metrics of the bedroom air temperature for the entire sample size is summarised in Table 5.11. Although the MBE is less than ±2 °C for all cases, the MAE is less than 2 °C for only Scenario 5. In addition, the RMSE for all cases lies above 2 °C. In all cases, the NMBE and CVRMSE are well below the 10% and 30% limits imposed by ASHRAE Guideline 14 (ANSI/ASHRAE, 2014). Regarding the normalised RMSE value, Scenario 5 performs the best, with the CTF model performing the worst. Although the r and R^2 values for all cases are deemed satisfactory compared to the threshold values proposed by Huerto-Cardenas et al. (2020), the CTF case performs worse or is equal to the other cases.

Table 5.11: Validation metrics for the bedroom air temperature for the summer and winter week combined

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.06	2.63	3.20	4.52	13.59	9.54	0.90	0.78	0.07
Reference Case (HAMT)	1.13	2.46	3.08	4.81	13.09	9.19	0.92	0.80	0.06
Scenario 1 - Low leakage	0.96	2.50	3.09	4.10	13.11	9.20	0.91	0.80	0.06
Scenario 2 - 75 mm floor	1.27	2.46	3.11	5.39	13.21	9.27	0.92	0.79	0.07
Scenario 3 - No cooker	1.15	2.45	3.07	4.88	13.06	9.17	0.92	0.80	0.06
Scenario 4 - No moisture	1.10	2.47	3.06	4.66	13.00	9.12	0.92	0.80	0.06
Scenario 5 - No ventilation	0.48	1.93	2.32	2.05	9.87	6.93	0.94	0.88	0.05

A summary of the validation analysis metrics of the bedroom air temperature for the summer and winter week sample size is summarised in Table 5.12 and Table 5.13. The summer week shows decreased accuracy compared to the winter week, with the MAE and RMSE being above 2 °C for the summer week. Again, the CTF case performs worse than the reference HAMT case, with only the CTF case having an RMSE higher than 2 °C. In addition, it can be noticed that the MBE leads to error cancellation due to underprediction experienced during the summer week but overestimation during the winter week. Regarding the r and R^2 values, these metrics, in most cases, improve for the winter week but worsen for the summer week when comparing these values to Table 5.11. However, Scenario 5 shows much higher accuracy than the rest, indicating an overestimation of natural ventilation.

Table 5.12: Validation metrics for the bedroom air temperature for the summer week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.20	3.47	4.01	11.29	14.13	16.29	0.89	0.43	0.07
Reference Case (HAMT)	3.21	3.35	3.97	11.31	13.98	16.12	0.90	0.44	0.07
Scenario 1 - Low leakage	3.07	3.27	3.91	10.80	13.77	15.87	0.89	0.46	0.07
Scenario 2 - 75 mm floor	3.36	3.46	4.06	11.84	14.29	16.47	0.90	0.42	0.07
Scenario 3 - No cooker	3.22	3.36	3.97	11.33	13.99	16.13	0.90	0.44	0.07
Scenario 4 - No moisture	3.16	3.34	3.93	11.12	13.83	15.95	0.90	0.45	0.07
Scenario 5 - No ventilation	2.00	2.21	2.70	7.05	9.49	10.94	0.95	0.74	0.05

Table 5.13: Validation metrics for the bedroom air temperature for the winter week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.08	1.79	2.09	-5.77	11.18	10.82	0.94	0.77	0.05
Reference Case (HAMT)	-0.95	1.57	1.80	-5.06	9.61	9.29	0.94	0.83	0.05
Scenario 1 - Low leakage	-1.14	1.73	1.95	-6.09	10.42	10.07	0.94	0.80	0.05
Scenario 2 - 75 mm floor	-0.83	1.46	1.69	-4.42	9.06	8.76	0.94	0.85	0.04
Scenario 3 - No cooker	-0.92	1.54	1.77	-4.91	9.45	9.14	0.94	0.83	0.04
Scenario 4 - No moisture	-0.96	1.59	1.82	-5.16	9.73	9.41	0.94	0.82	0.05
Scenario 5 - No ventilation	-1.04	1.65	1.88	-5.55	10.07	9.74	0.94	0.81	0.05

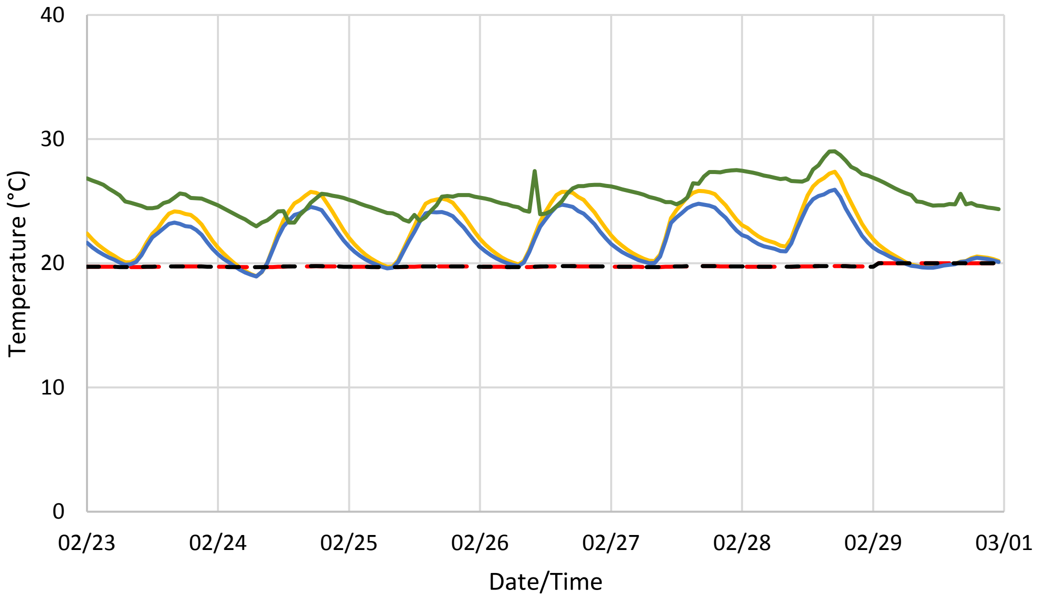
A summary of the day- and hourly-based validation analysis of the bedroom air temperature is presented in Appendix E.6.3.

5.4 Discussion

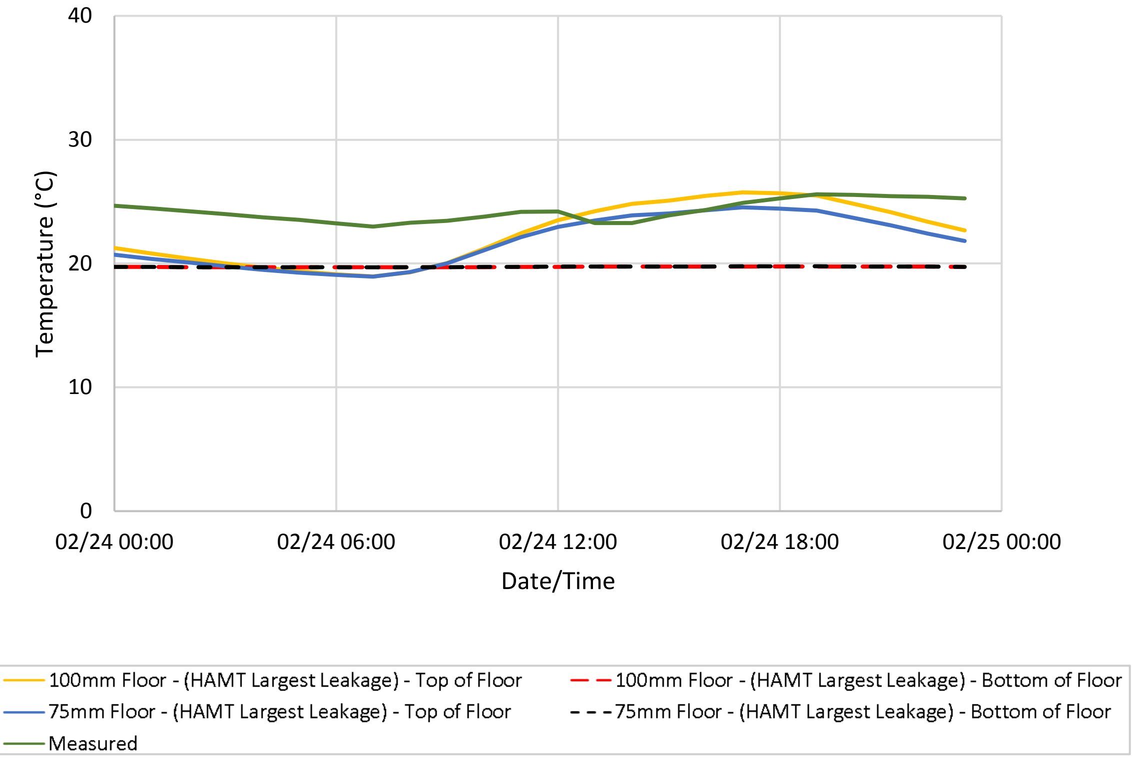
Reasonable agreement is found between modelled and measured trends in temperature and relative humidity in the building considered. Given uncertainties in exact occupant behaviour and conditions in the periods investigated, parameter studies on what are considered significant factors serve to study trends towards improved confidence in the modelling approach. The discussion here draws attention to the trends of the simulation output when compared to the measured data.

The large heat gains through the building envelope and through ventilation point at a demand for improved environmental condition monitoring at higher spatial resolution to improve modelling towards intervention and improvement of housing such as the one investigated, motivated by the extreme conditions occupants are exposed to. No attempt was made at altering weather data, resulting in anomalies appearing in the modelling, e.g. the outside dry-bulb temperature on the 25th of August.

By adjusting the floor thickness, the air temperatures increase at their peak. This is also seen for floor temperatures. Figure 5.10 (a) and (b) show the living room floor surface temperature results for a summer week and day. Although the relative humidity does not show improvement compared to the measured relative humidity, the surface temperature of the model improves during the afternoon. The floor acts as a heat sink. A thicker floor surface provides improved thermal resistance; thus, heat will be transferred at a slower rate compared to a thinner floor.



(a)



(b)

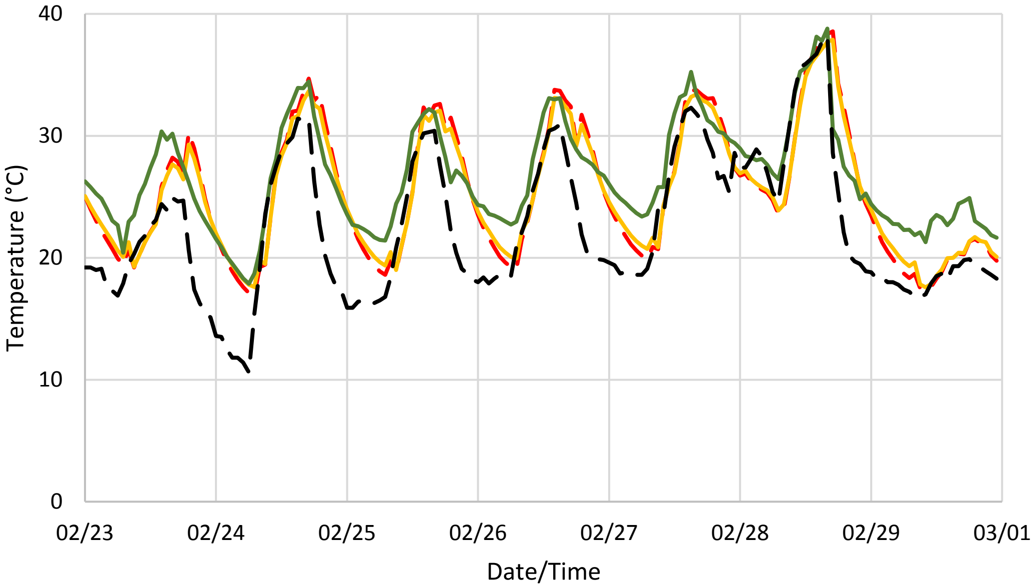
(c)

Figure 5.10: Comparison between the reference model and reduced floor thickness (a) Weekly air temperature of the living room (Summer) (b) Weekly relative humidity of the living room (Summer) (c) Graph legend

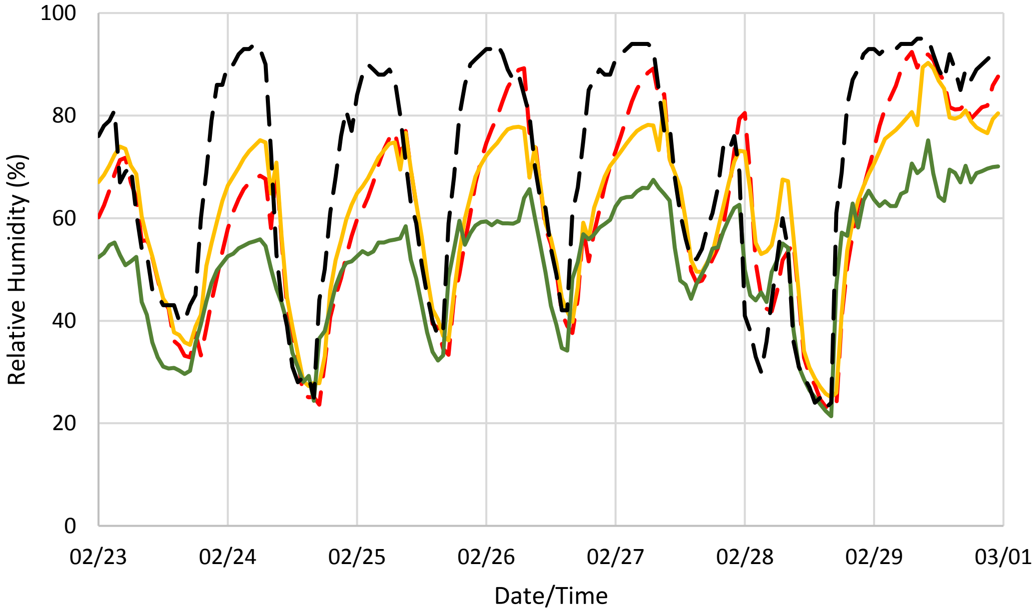
Disabling the electric cooker results in a noticeable decrease in air temperature for both the living room and bedroom when the electric cooker is scheduled to be on. The decrease results in both solution methods following the trend of the measured values more closely. The schedule of significant heat gains should be accounted for and carefully integrated.

When closing all external and internal openings, an improvement can be seen for most mornings when comparing the calculated and measured air temperatures. This indicates a mismatch between when openings are scheduled to be open and when they are scheduled to be closed. Comparing the scenario of all openings closed to all of the openings open at scheduled times, it can be observed that mornings are typically under predicted where openings are scheduled to be open and over predicted in the afternoon where all openings are assumed to be closed.

Comparing the CTF and HAMT solutions, although the difference between room air temperature for the CTF and HAMT solution is small, the CTF solution calculates larger temperatures during the afternoon and smaller temperatures during the mornings. This can be attributed to the increased thermal storage due to moisture and surface cooling resulting from vaporisation. This is observed for the summer and winter week. Figure 5.11 (a) and (b) show the results for a summer week. Results for a selected day are presented in Figure 5.11 (c) and (d). An increase in relative humidity can be observed for the HAMT solution.-This is in comparison to the CTF solution which only transfers moisture through the air. The smaller relative humidity calculated by the CTF solution during the day can be attributed to the warmer temperature calculated by the CTF solution when compared to the HAMT solution. The CTF solution does not account for the interaction of moisture between materials and their surrounding environment. This becomes a larger issue when thermal comfort models consider relative humidity for how humans perceive thermal comfort (Schweiker et al., 2018).


Temperature (°C)
40
30
20
10
0
02/23
02/24
02/25
02/26
02/27
02/28
02/29
03/01
Date/Time

(a)


Relative Humidity (%)
100
80
60
40
20
0
02/23
02/24
02/25
02/26
02/27
02/28
02/29
03/01
Date/Time

(b)

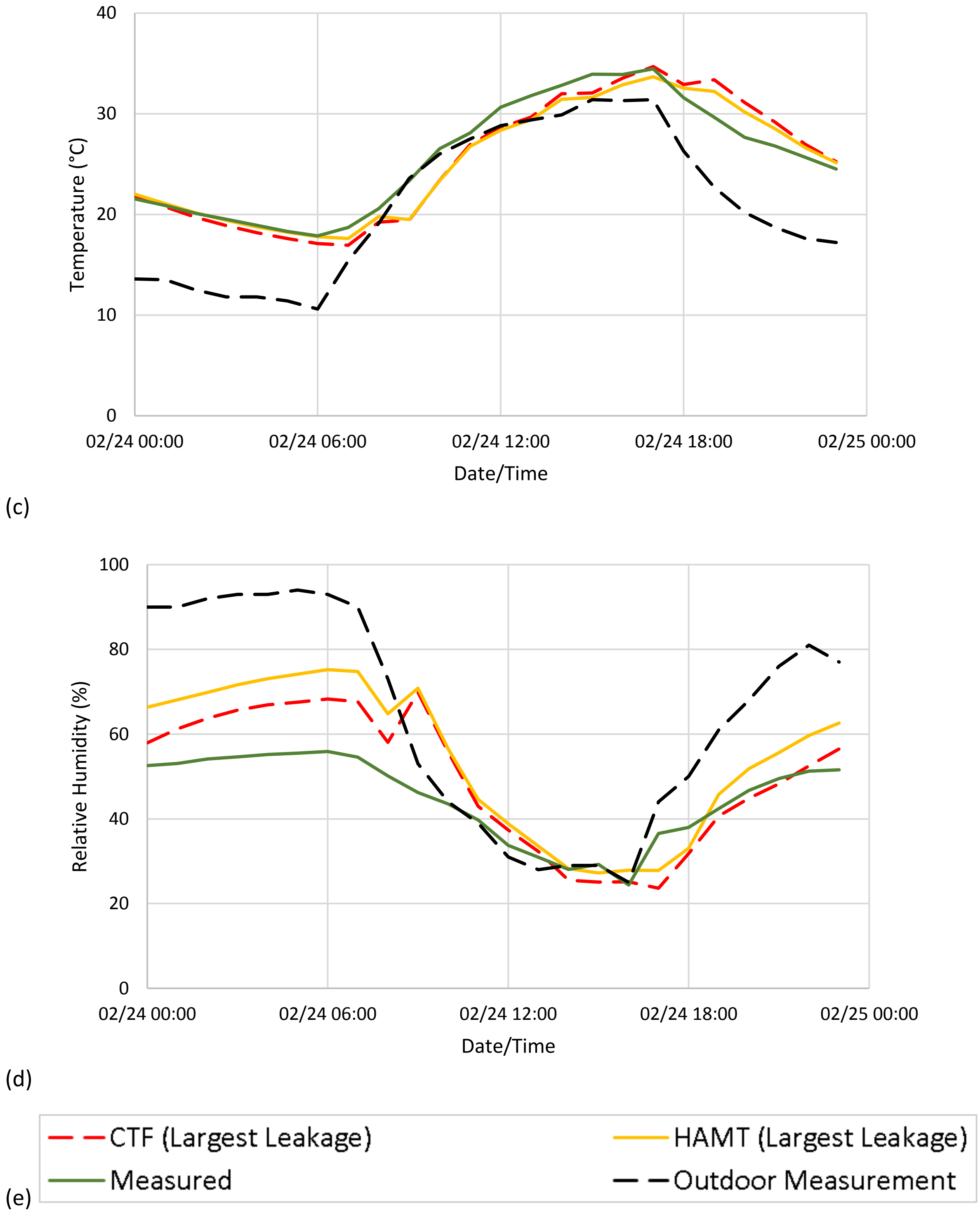


Figure 5.11: Comparison between the reference model and CTF solution method (a) Weekly air temperature of the living room (Summer) (b) Weekly relative humidity of the living room (Summer) (c) Daily air temperature of the living room (Summer) (d) Daily relative humidity of the living room (Summer) (e) Graph legend

It is clear that the relative humidity is more sensitive to changes in the thermal model. This is due to the relative humidity being more sensitive to changes in the air resulting from leakages in building components, vapour diffusion into the wall, surface evaporation, natural ventilation, and the heating and cooling of air. It is shown that the initial moisture content has a large impact on the calculation of relative humidity, providing much better results during the summer. This improvement is offset by introducing outside air, providing an indicator of where further improvement is required. Changes to moisture content are also brought on by latent heat produced by internal sources, as noticed in Scenario 3. This also emphasises the requirement of a thorough analysis of building activity data. The exclusion of latent heat influences air temperature and results in a decrease in moisture content and subsequently relative humidity of the air. Due to occupant activity being the driving factor of ventilation and building activity, closer monitoring of occupant activity should be done for future monitoring studies.

5.5 Conclusion

Studies have shown that subsidised housing in South Africa is exposed to extreme cold and hot weather. This has led to studies investigating possible thermal retrofit measures to improve thermal comfort. Provincial design codes specify that subsidised housing should be built with insulated ceilings, which indicates a deviation from the studied house, which did not have a ceiling. Whereas other studies focused on measuring thermal and environmental conditions, this chapter aimed to reproduce measured results using thermal analysis software.

By supplementing measured data with literature data and data from specialised weather software, it was possible to build a thermal model. By adjusting the inputs, the outputs can be compared to the measured data to see which inputs result in improvements for the thermal model compared to the measured data. Although the purpose of the chapter is not to provide a full parametric analysis of all variables, it does provide insight into which variables require attention if the impact of thermal retrofitting is to be investigated for thermal comfort.

Comparisons show that closer monitoring of occupant behaviour is required for improved agreement between measured and predicted thermal performance. Occupant behaviour determines the usage of internal sources of heat gain and natural ventilation. As shown by the comparisons, assumptions made based on observations proved inadequate. By assuming extremes, e.g. closing all sources of natural ventilation, improvement in predicted performance can be seen at times where the opposite was initially assumed. Closer monitoring is required to decrease the performance gap between predicted and measured internal temperatures. To eliminate the need for literature for material characterisation, further research is required for the thermal and hygric characterisation of South African building materials and components. Accurate hygric characterisation is essential for accurate modelling using the HAMT solution method. Results show that hygric characterisation of building materials are required to improve the performance gap between predicted measured relative humidity. Results also indicate that the performance gap between predicted measured relative humidity is large at low temperatures when moisture transfer through and from building walls and floor hygroscopic materials is ignored.

Characterisation of South African soils must also be developed to use thermal models to characterise ground temperature profiles. Due to the constant temperature being applied to the bottom surface of the ground floor, the ground floor acts as either a heat source or heat sink at all times. Soil characterisation will allow for improved prediction of ground temperatures at the bottom of the ground floor surface.

Chapter 6 Conclusion

The sensitivity of modelled building energy and thermal performance to model input changes regarding the building envelope, internal partitions, and occupant behaviour was investigated through the usage of thermal analysis software. Two building typologies were selected for investigation: Green Star office buildings and low-income residential buildings. The Green Star office building models investigated decisions related to the glazing design and thermal bulk properties of the building envelope. The low-income residential house models investigated the importance of accounting for moisture buffering materials, first for a typical summer and winter week using a base case model, and then for a summer and winter week using captured data.

The importance of moisture buffering materials was accounted for by allocating hygrothermal properties on building materials: initial moisture content, sorption isotherm, liquid transport coefficient, vapour diffusion resistance factor, and moisture dependent thermal conductivity. Model validation of hygrothermal simulation was achieved by comparing model results to collected data from an instrumented house. In addition, the influence of building design and occupancy assumptions were investigated, namely: foundation thickness, air leakage coefficients, absence of internal heat and moisture loads, and closure of ventilation components.

6.1 Findings

Although the assumptions and inputs limit the study, the study shows that the parametric analysis of simulated building performance of South African Green Star buildings can yield insight into how traditional design strategies associated with specific building properties influence simulated building performance. Furthermore, hygrothermal simulation of South African low-income housing reveals that if porous building materials are exposed to South African environmental conditions, the simulated building performance is influenced by the inclusion of moisture transport in the solution method for heat transfer through building constructions. By applying validation metrics over different data sample sizes, it is shown how validation metrics can be used, not only to indicate the accuracy of the simulation output, but also to indicate whether certain simulation input choices are incorrect when considering a specific data sample size.

Research is needed for improved building simulation standardisation in South Africa, as well as improvements to the quantity and quality of simulation input data provided by building standards for South African building performance simulation. Research for when hygrothermal modelling should be considered in the building performance simulation of South African buildings is also needed.

This study aimed to:

- Evaluate the influence of the building envelope on the performance of Green Star buildings when modelling heat-only transfer
- Evaluate the change in building performance when modelling heat-only transfer compared to heat-moisture coupled transfer for a low-income house in South Africa.
- Evaluate the detail of building simulation input provided by South African building standards.

The objectives of the aims were achieved as detailed below.

Aim 1: "Assess the change in energy performance with changes to the thermal performance of the building envelope of South African Green Buildings"

Objective 1.1. Perform parametric analysis of building energy performance of South African Green Star buildings, using the thermal bulk properties and glazing properties of the building envelope as input parameters.

Parametric analysis reveals that high-performance thermal insulation is counterproductive when combined with the large WWRs associated with the evaluated Green Star buildings in South Africa. Due to the introduction of solar heat gains through the glazing, in addition to internal heat gains, increasing the thermal diffusivity with increases to the thermal conductivity of the building envelope lessens the required cooling load to meet setpoint temperatures.

Increases to the WWR reveal that more targeted analysis is required for improved building performance when targeting improvements for Green Star buildings in South Africa through changes to the WWR. Although the results indicate clear trends when increasing the WWR, it only provides limited insight unless inspecting the relationship of heat transfer through all opaque building elements and glazing.

Objective 1.2. Evaluate the change in building energy performance of South African Green Star buildings due to changes in the thermal bulk properties and glazing properties of the building envelope.

Although the relative difference in required heating loads, when changing building envelope properties, tends to be larger compared to the cooling loads, the cooling loads remain dominant when considering combined cooling and heating loads. Thus, changes to combined cooling and heating loads are dictated by the changes in the cooling loads.

Aim 2: "Establish a case for the building performance of a representative low-income house in South Africa to be influenced by moisture buffering materials"

Objective 2.1. Perform parametric analysis of the air temperature of a representative low-income house in South Africa, using different heat transfer solution methods and moisture transfer properties as input parameters.

Analysing a base case South African low-income house for a typical summer and winter week reveals that only changes to the sorption isotherm and moisture dependant thermal conductivity will noticeably influence simulated results. In addition, observations made for the HAMT heat transfer solution method are dependent on not only the accuracy of the hygrothermal properties, but also on the prescribed initial moisture content of porous building materials.

Comparing the CTF and HAMT solution, the CTF solution typically simulates higher temperatures compared to the HAMT solution method. However, at initial moisture content levels of less than 5%, the HAMT solution method simulates higher temperatures compared to the CTF solution method. Thus, the importance of choosing the correct initial moisture content is also important for comparisons between heat transfer solution methods.

Objective 2.2. Evaluate the change in air temperature of a representative low-income house in South Africa due to changes in the heat transfer solution method and moisture transfer properties.

Although initial moisture content levels are exaggerated for the purpose of analysing its influence, results indicate that exposed porous building materials will influence simulated results when simulating typical summer or winter South African weather conditions for a week. However, it is up to user discretion if HAMT analysis is needed. This will depend on the amount of porous building materials exposed to the environment, the hygrothermal properties of the exposed building materials, as well as the environmental conditions of the environment.

Aim 3: "Evaluate the influence of moisture presence and changes in simulation assumptions regarding occupant behaviour and building design on the environmental parameters for a low-income house in South Africa"

Objective 3.1. Perform parametric analysis of the air temperature and relative humidity of a low-income house in South Africa, using different heat transfer solution methods as input parameters.

Although simulated temperatures are similar when comparing the results of the CTF and HAMT solution method, the hygrothermal material properties dampens the influence of the introduction of outside air on the simulated relative humidity. As a result, the daily swing in simulated relative humidity observed for the CTF solution method is larger compared to the HAMT solution method.

Objective 3.2. Evaluate the difference in simulated and captured environmental parameters of a low-income house in South Africa due to changes in the assumptions of occupant behaviour and building design.

Although many forms of validation for building simulation exist, a set of validation metrics was chosen to also act as a guide of how future building modelling can be improved. The chosen validation metrics reveal that the HAMT solution method improves upon the simulated relative humidity, especially when considering an initial moisture content of 0%. The improvement in simulated relative humidity associated with an initial moisture content of 0% can be attributed to an overestimation of initial moisture content for the base case.

Applying the validation metrics over smaller data samples reveal that assumptions related to the scheduling of natural ventilation and additional internal heat gains can be improved. Although validation metrics do not improve when considering the entire sample size, applying validation metrics over the periods associated with input choices reveal improvements to the validation metrics.

Aim 4: "Assess the need for South African building simulation guidelines to include requirements for hygrothermal simulation"

Objective 4.1. Determine whether simulation results in South Africa, compared to captured environmental data, provide improved simulation results when performing hygrothermal analysis compared to thermal analysis.

Results from Chapters 4 and 5 reveals that when porous building materials are exposed to South African weather, the simulated temperature and relative humidity are influenced by the heat transfer solution method chosen for analysis. In the case of Chapter 5, the HAMT solution method provides improved simulation results. Thus, future iterations to South African building standards related to building simulation should include requirements for hygrothermal simulation.

6.2 Summary of Contributions

The contributions of the study are summarised below.

- The study serves as the 1st hygrothermal study in South Africa.
- The study serves as the 1st study using temperature and relative humidity validation in South Africa.
- The study serves as the 1st study to perform hygrothermal analysis on low-income housing in South Africa.
- The study presents an evolution of several validation methods for hygrothermal analysis and how existing validation methods can be used to improve model accuracy.

6.3 Future Research

Future iterations of the SANS 10400-XA building standard requires improvement if improved building performance modelling in South Africa is desired. Research to improve upon the SANS 10400-XA building standard must focus on two areas: hygrothermal modelling, and the provision of simulation input data. The following two sections discuss the need for research in the two identified research areas, as well as the specifics of the research required.

6.3.1 Hygrothermal Modelling

Although research indicate hygroscopic building materials are capable of influencing the building environment, the interaction of exposed hygroscopic building materials with its surroundings is not addressed by SANS 10400-XA. Research into when hygrothermal modelling should be implemented, as well as how hypothermal modelling should be implemented, is required.

Research into hygrothermal modelling for South African building simulation must address three questions: 1. When should hygrothermal modelling be considered in building simulation of South African buildings?; 2. How should hygrothermal modelling be performed to allow for replicability irrespective of the modeller?; and 3. What level of detail is needed in the specification of hygroscopic building material data?

6.3.2 Provision of Simulation Input Data

The input data for building simulation provided by SANS 10400-XA:2011 is lacking in terms of quantity and quality. Research into supplementing future iterations of SANS 10400-XA must address the following questions: 1. What are the inputs which influences simulated building performance in South Africa?; 2. What level of detail is required for the inputs which influences simulated building performance?; 3. Are the inputs identified which influences simulated building performance in South Africa covered by SANS 10400-XA to an acceptable level of detail?; and 4. Is the simulation input realistic for the building typology, climate, and occupancy class?

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Appendices

Appendix A: Simplified Model Validation of DesignBuilder

To supplement Chapters 3 to 5, and instil confidence into the simulated results of DesignBuilder, simplified model validation was performed by analysing a simplified ASHRAE 140 – 2020 (ASHRAE, 2021) test case and comparing results with numerical models produced in Abaqus, a finite element analysis software package. Although this does not follow the procedures specified in ASHRAE 140, test cases specified in ASHRAE 140 have already been performed in South Africa to obtain certification for the usage of DesignBuilder in South Africa (Agrément South Africa, 2018).

The test case chosen for validation was case 600 (ASHRAE, 2021). Simplifications were made with regard to the building construction, surface properties, internal heat gains, and the weather file. An additional model was also created with the purpose to eliminate the influence of outside longwave thermal radiation by creating two zones separated by a single wall, and all exterior surfaces defined adiabatic.

A.1 Non-Adiabatic Model Description

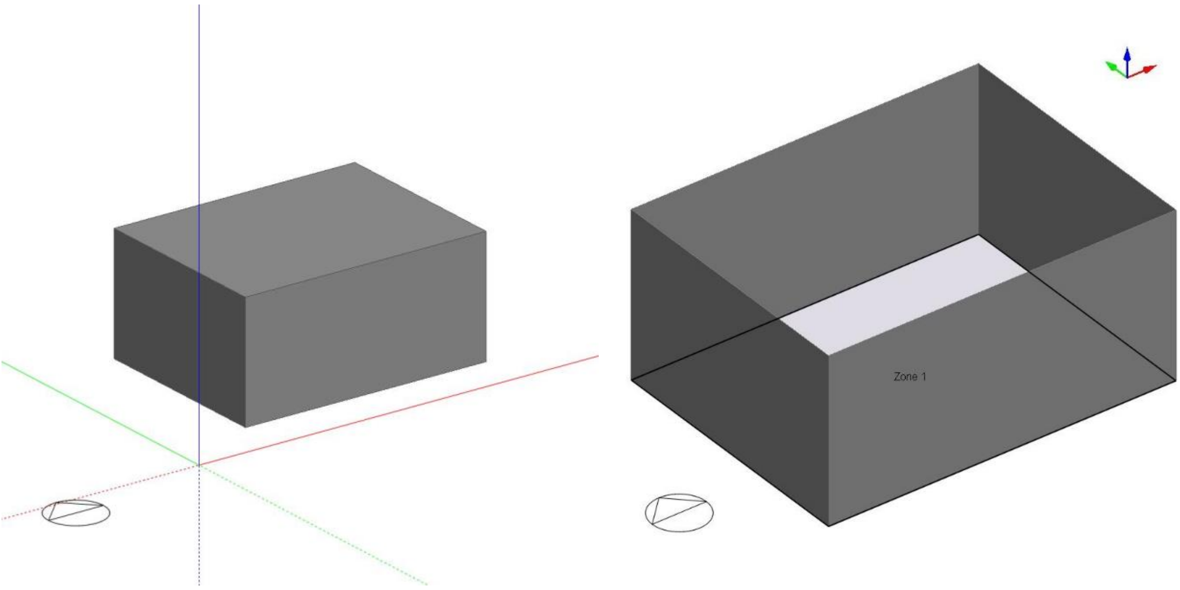
A.1.1 DesignBuilder Model Description

The case 600 building consists of a single zone with a raised floor and exterior dimensions of 8.174 m x 6.174 m x 3.869 m. Two 3 m x 2 m windows are located on the south face of the building.

The first simplification made to the model is the replacement of the windows with opaque wall elements. With regard to the building construction, changes were made to the thermal properties of the building materials. The thermal properties of the building elements were made to that of the innermost material of the exterior wall for case 600. This change was made to simplify all building materials from a multi-layered construction to a single layer construction with the same thermal bulk properties. A summary of the thermal bulk and surface properties of the building are summarised in Table A.1. A visual depiction of the DesignBuilder model is presented in Figure A.1.

Table A.1: Thermal bulk properties of the test case building walls, floor, and roof

k (W/(m.K))	Thickness (m)	ρ (kg/m^3)	c (J/(kg.K))
0.16	0.087	950	840



(a) (b)

Figure A.1: (a) Building viewed at building level in DesignBuilder (b) Building viewed at block level in DesignBuilder for non-adiabatic case

For the surface convection coefficients, an exterior convection surface coefficient of 11.9 W/(m^2.K) and interior convection surface coefficient of 2.2 W/(m^2.K) were selected.

Regarding the surface properties, the thermal, solar, and visible absorptance of materials were changed from 0.9, 0.6, and 0.6 to 10 x 10^{-7}, 0, and 0 to negate the influence of heat transfer due to radiation. The specification of surface properties was made to allow for time-dependent solar radiation heat gains to be ignored from the thermal model. Because solar radiation heat-gains are time-dependent due to the angle of incidence changing, the solar radiation heat-gains will change even if constant direct and diffuse solar radiation values are used in the weather file, resulting in changes to the exterior surface temperature.

Regarding the weather file, changes were made to the temperature. In addition, the solar radiation values was set to 0 Wh/m^2. The temperature of the weather file was changed to a constant 15 °C for the first 24 hours, followed by a constant 10 °C for the next 48 hours. The first temperature is to allow DesignBuilder to perform its warm-up routine at the start of the analysis, which iterates to determine the wall temperature from its standard initial setting of 23 °C. By this first step, the wall temperature is allowed to reach 15 °C, as set in the Abaqus analysis in Section A.1.2.

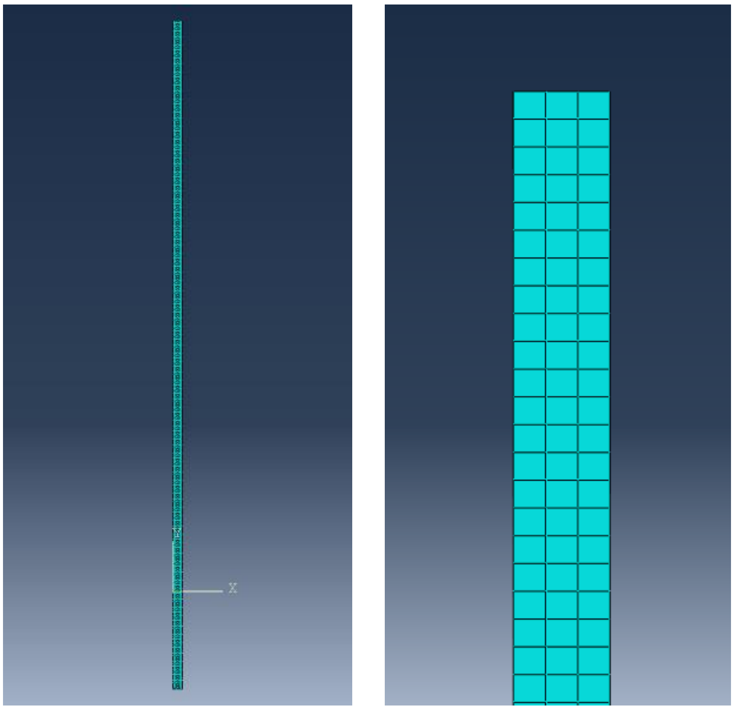
The final simplification of the model was to assume that internal heat gains were absent and that no model infiltration was present.

Regarding the conditioning of the internal zone, the temperature in the zone is set to 15 °C for the first 24 hours, for the warm-up phase in DesignBuilder, followed by a temperature of 20 °C over the subsequent 48 hours. An initial temperature for building elements was not prescribed as DesignBuilder automatically prescribes initial temperatures during the warm-up routine at the start of each simulation.

The time step of the simulation was chosen as six time steps per hour, i.e. time increments of 10 minutes.

A.1.2 Abaqus Model

To replicate the DesignBuilder model in Abaqus, the west wall was modelled in Abaqus. A 0.087 m x 6.174 m section was created in Abaqus with 4-node linear heat transfer quadrilateral elements chosen for the finite element mesh. An element size of 0.029 m x 0.025 m was chosen, resulting in a total of 741 elements. The section was given the same properties as the DesignBuilder walls as summarised in Table A.1. For the surface convection coefficients, an exterior convection surface coefficient of 11.9 W/(m^2.K) and interior convection surface coefficient of 2.2 W/(m^2.K) were used, the same as the DesignBuilder model. The left face was chosen as the outside face. The sink temperature of the outside face was 9.99718 °C whereas the sink temperature for the inside face was 20 °C. Because DesignBuilder calculates the outside air temperature based on the height of each surface centroid, the outdoor air temperature for the surface of the eastern face of the building calculated by DesignBuilder was used rather than the outdoor dry-bulb air temperature. In addition, an initial temperature of 15 °C was used as the initial temperature for all nodes at the start of the analysis. A visual depiction of the Abaqus model is presented in Figure A.2.



(a) (b)

Figure A.2: (a) Abaqus model mesh (b) Magnified view of Abaqus model mesh

For the analysis, uncoupled transient heat transfer analysis was performed, i.e. only heat transfer due to conduction, convection, and radiation is considered. A time period of 172800 s was chosen, with an initial and maximum time increment of 600 s.

A.2 Adiabatic Model Description

A.2.1 DesignBuilder Model Description

The second DesignBuilder model follows the same design as the first DesignBuilder model with the exception that the zone is divided into two zones by a central wall with the surface facing east/west. The thickness of the wall is 0.087 m, the same as the exterior walls, roof, and floor. To eliminate the influence of outside longwave radiation exchange, the building exterior surface was made adiabatic. To replicate the environmental conditions of the first DesignBuilder model, both the eastern zone and western zone was conditioned to a constant 15 °C for the first 24 hours, followed by a constant 10 °C for the western zone and 20 °C for the eastern zone for the next 48 hours. Because the western zone was cooled, the inside surface of this zone was assigned the convection surface coefficient of 11.9 W/(m^2.K) by the software. A convection surface coefficient of 2.2 W/(m^2.K) was assigned to the inside surface of the eastern zone. All other variables were kept the same as the first DesignBuilder model. A visual depiction of the DesignBuilder model is presented in Figure A.3. Only the model viewed at block level is provided as the model looks the same as the first model when viewed at building level.

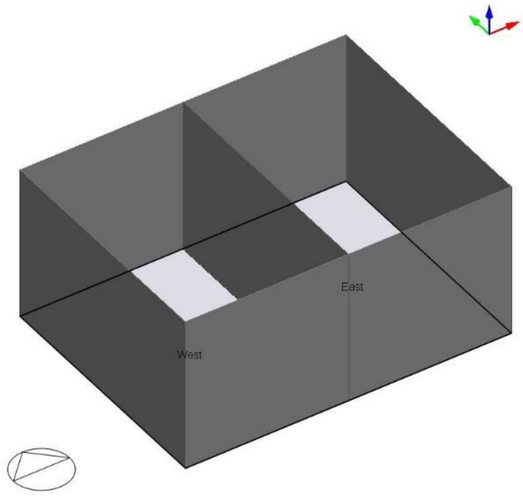


Figure A.3: Building viewed at block level in DesignBuilder for adiabatic case

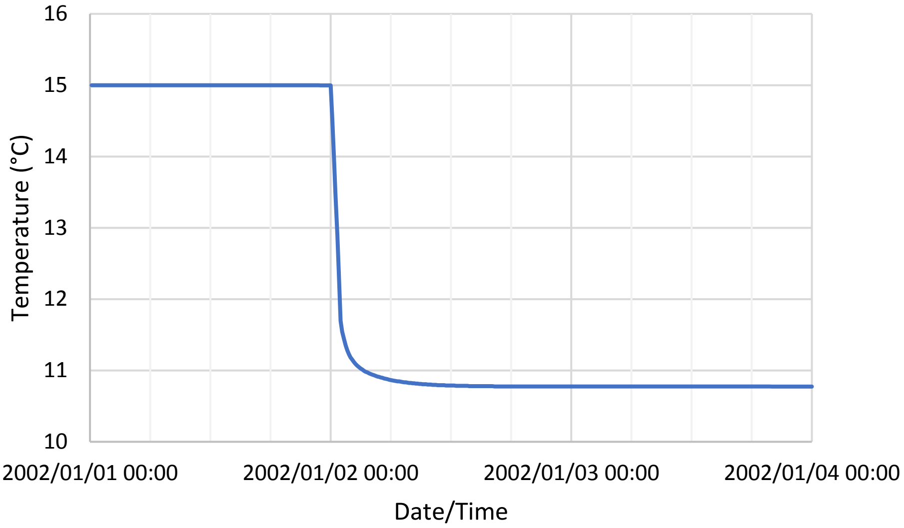
A.2.2 Abaqus Model Description

For the second Abaqus model, a single change to the boundary conditions of the outer surface of the model was made. The sink temperature of the outside surface was changed to 10 °C as the variable used by DesignBuilder was the zone mean air temperature. Because only a single aspect was changed, the visual depiction of the first Abaqus model remains the same for the second Abaqus model.

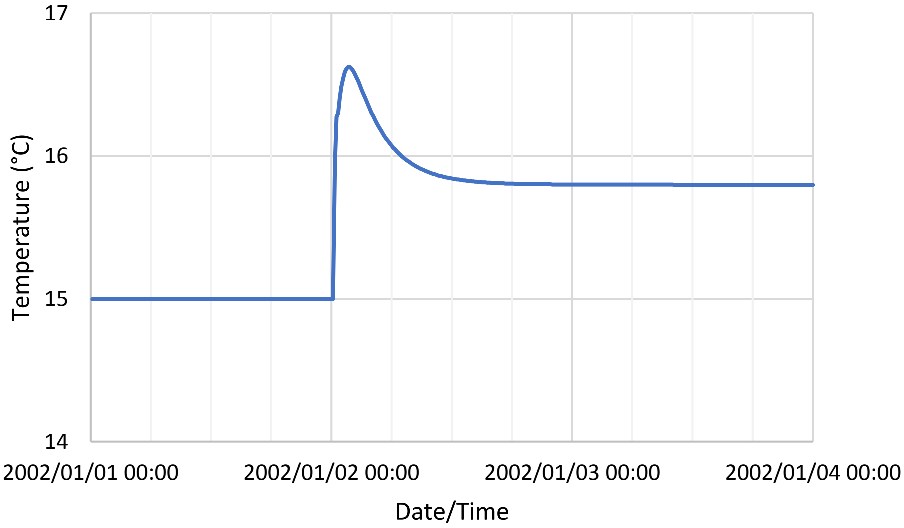
A.3 Model Results

A.3.1 Results from Non-Adiabatic Model

From the DesignBuilder model, five variables were requested for the west wall: surface temperature, air temperature (used for convection heat flux calculations), conduction heat flux near the surface, convection heat flux, and thermal radiation heat flux. From the conduction, convection, and thermal radiation, the heat balance for each surface was calculated (i.e. sum of conduction, convection, and radiation heat flux). To allow for easier comparisons with Abaqus, the reported values from DesignBuilder is expressed as W/m^2. A summary of the results for the non-adiabatic model in DesignBuilder is presented in Table A.2, showing the values of each variable for the two faces of the west wall at the end of 72 hours. In addition, the simulated outside and inside surface temperature of the west wall of the DesignBuilder model is presented in Figure A.4.



(a)



(b)

Figure A.4: (a) Outside surface temperature of the west wall for the non-adiabatic case in DesignBuilder (b) Inside surface temperature of the west wall for the non-adiabatic case in DesignBuilder

Table A.2: Results of the non-adiabatic DesignBuilder model for the west wall

Reported Value	Exposed Air Temperature (°C)	Surface Temperature (°C)	Conduction Heat Flux (W/m^2)	Convection Heat Flux (W/m^2)	Thermal Radiation Heat Flux (W/m^2)	Heat Balance (W/m^2)
Outside Surface	9.99718	10.77381	9.24195	-9.24192	-0.00003	0.00000
Inside Surface	20.00000	15.79912	-9.24194	9.24194	0.00000	0.00000

From the Abaqus model, two variables were requested: nodal temperature and heat flux magnitude at integration points. Results for the non-adiabatic case are visualised in Figures A.5 to A.8. At the inside surface (right face), the analysis stabilises at an average nodal temperature of 15.79909 °C and average heat flux magnitude of 9.24186 W/m^2. At the outside surface (left surface), the analysis stabilises at an average nodal temperature of 10.77383 °C and average heat flux magnitude of 9.24186 W/m^2.

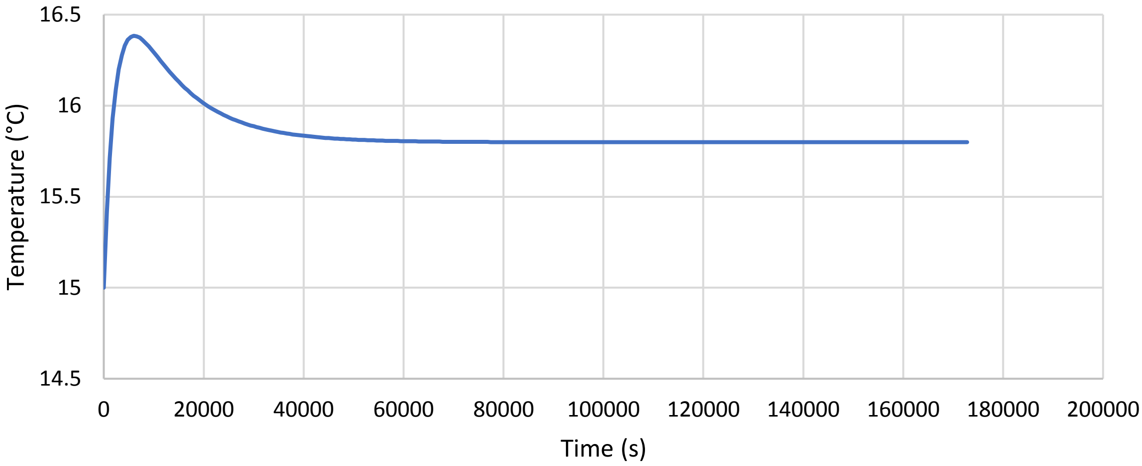


Figure A.5: Average nodal temperature of inside surface nodes for the non-adiabatic case in Abaqus

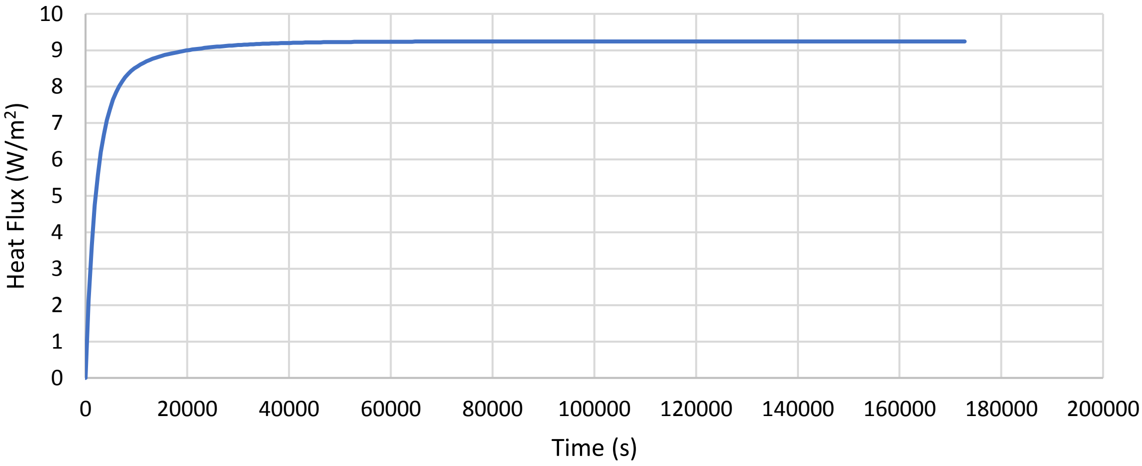


Figure A.6: Average Heat flux magnitude of elements at the inside surface for the non-adiabatic case in Abaqus

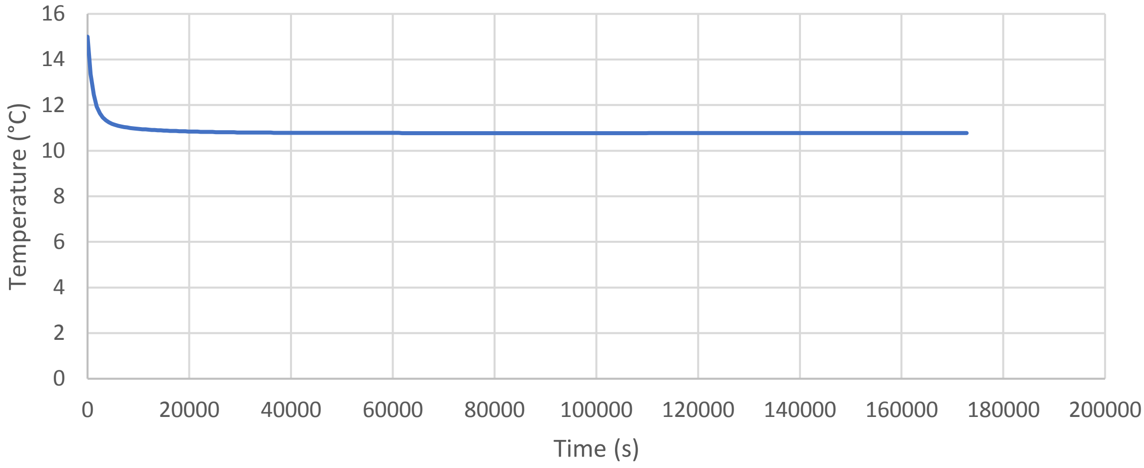


Figure A.7: Average nodal temperature of outside surface nodes for the non-adiabatic case in Abaqus

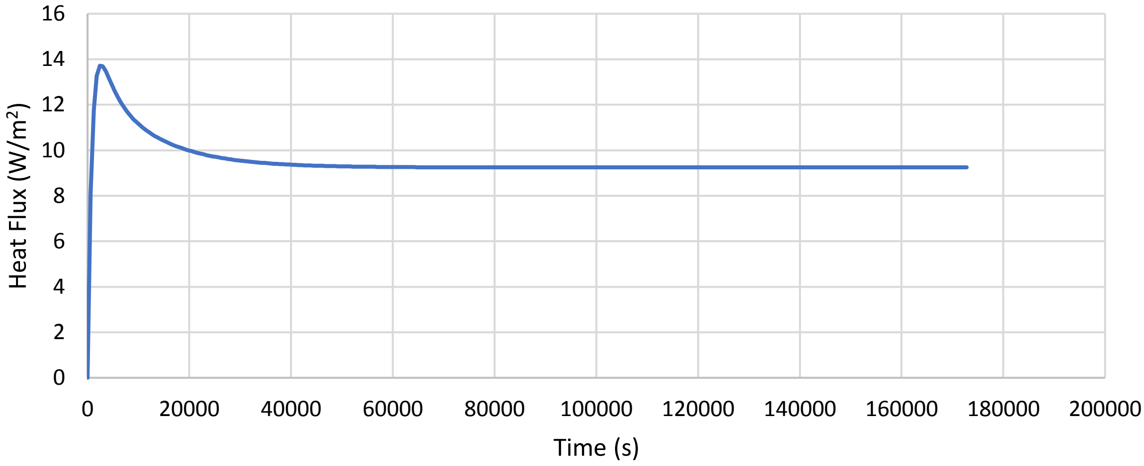
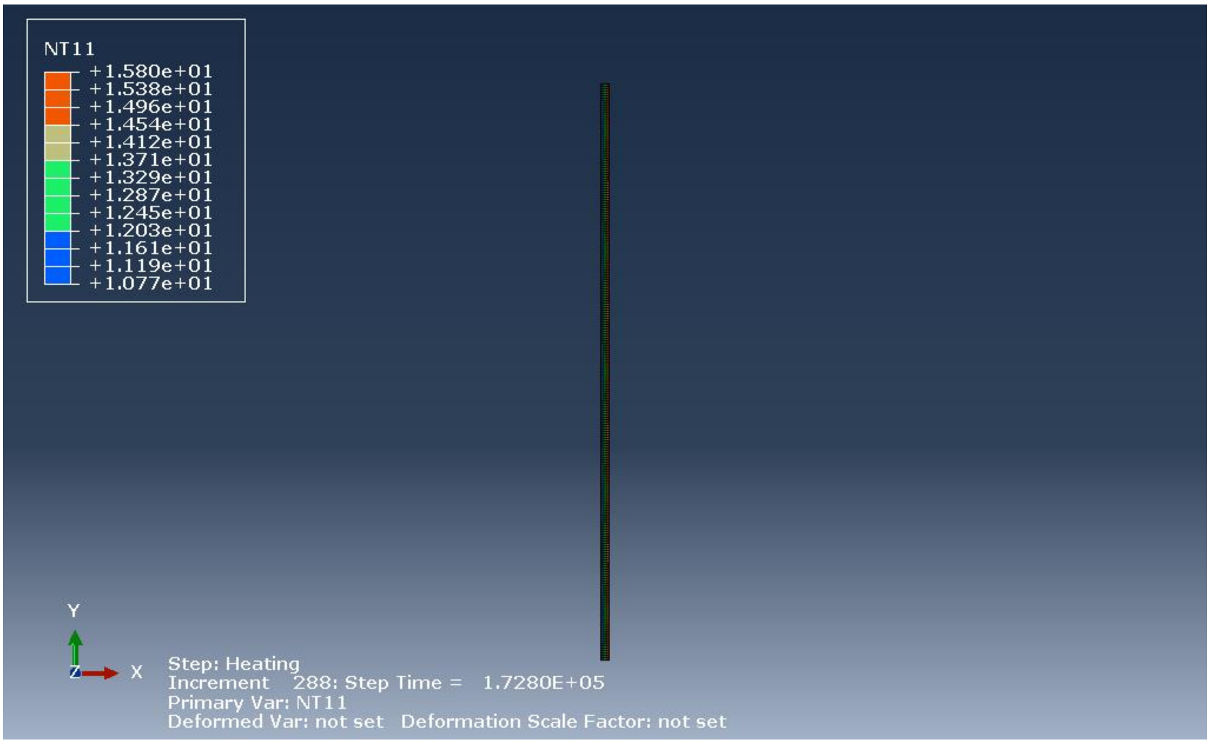


Figure A.8: Average Heat flux magnitude of elements at the outside surface for the non-adiabatic case in Abaqus

A visual depiction of the results on the section at the end of the simulation is presented in Figure A.9.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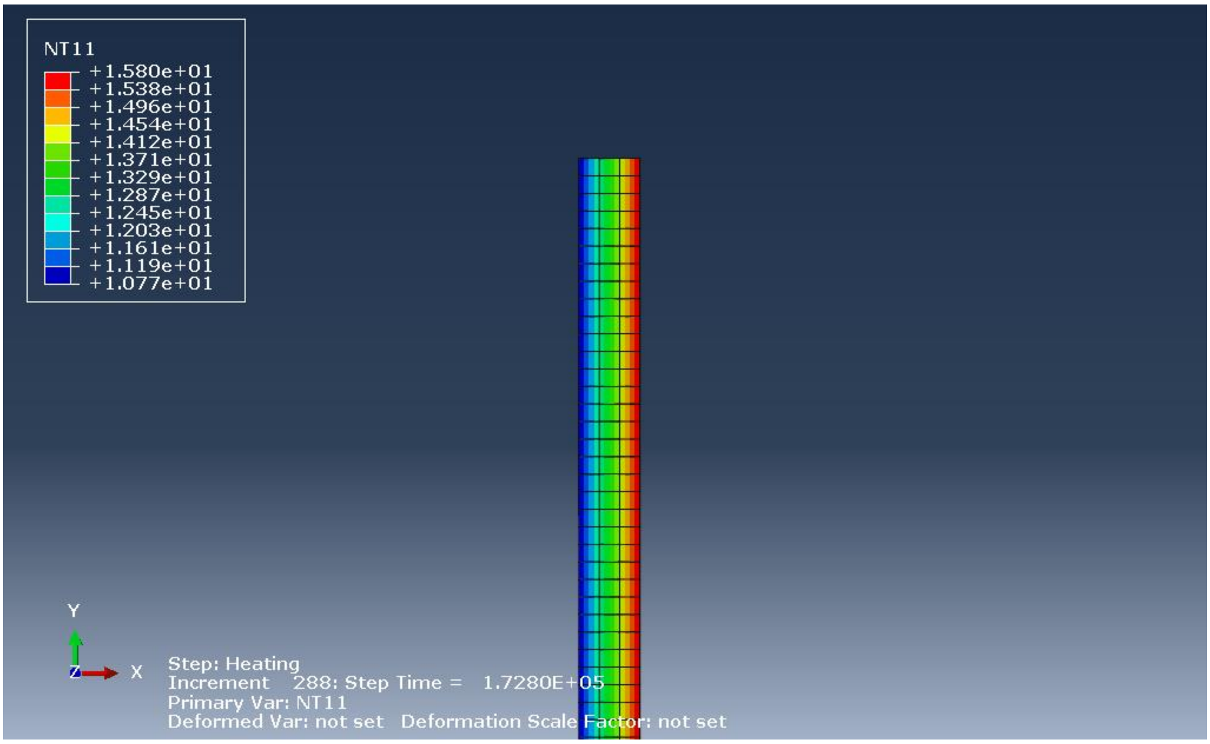
+1.329e+01
+1.287e+01
+1.245e+01
+1.203e+01
+1.161e+01
+1.119e+01
+1.077e+01
Y
X
Z
Step: Heating
Increment 288: Step Time = 1.7280E+05
Primary Var: NT11
Deformed Var: not set Deformation Scale Factor: not set

(a)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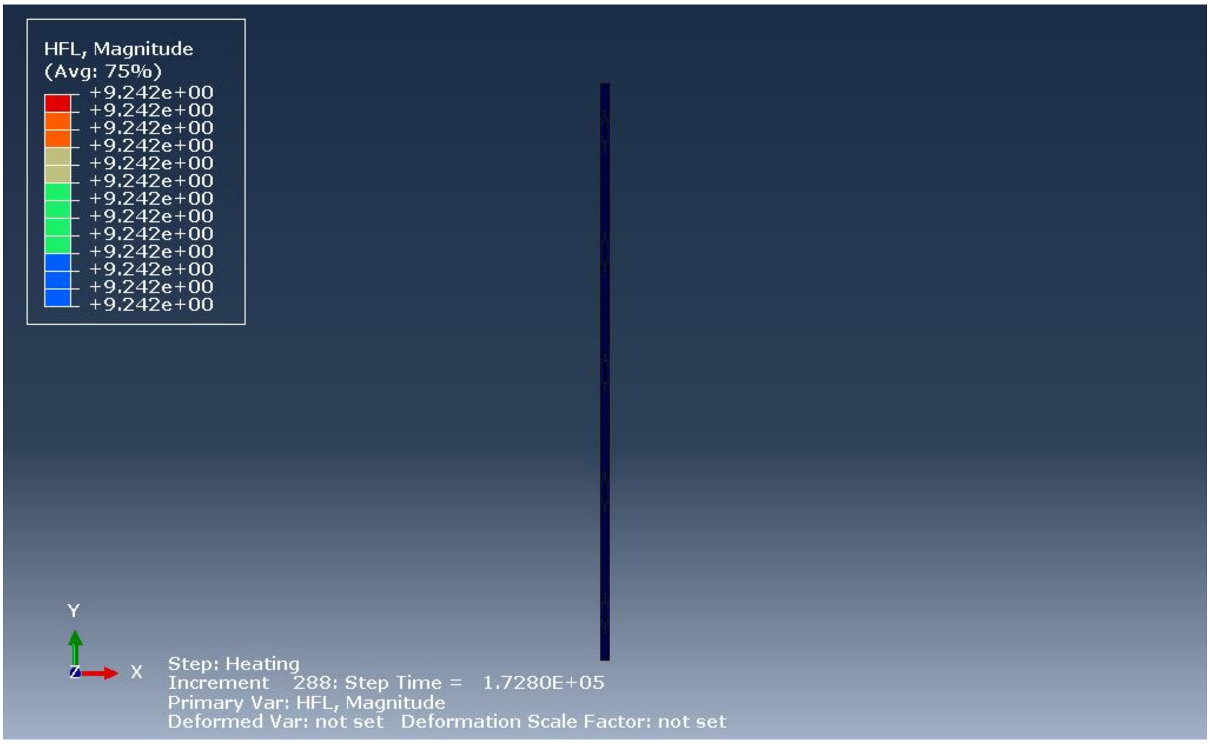
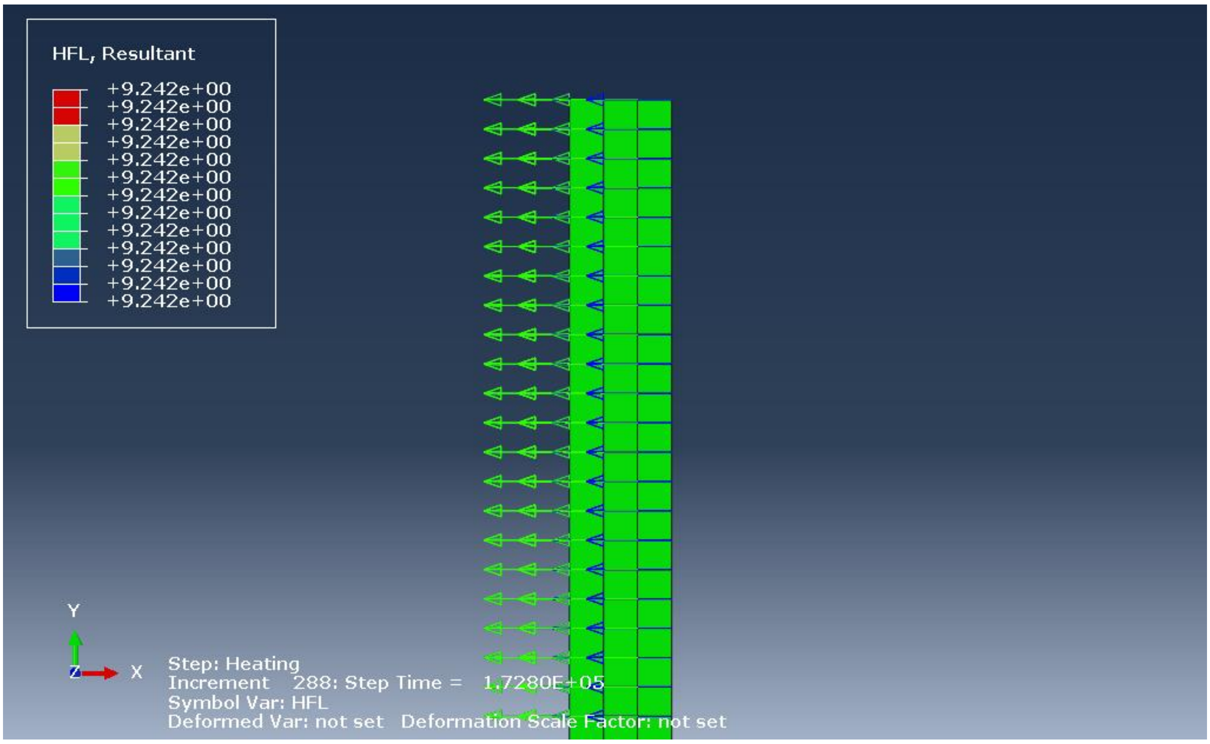
+1.245e+01
+1.203e+01
+1.161e+01
+1.119e+01
+1.077e+01
Y
X
Z
Step: Heating
Increment 288: Step Time = 1.7280E+05
Primary Var: NT11
Deformed Var: not set Deformation Scale Factor: not set

(b)



(c)



(d)

Figure A.9: (a) Nodal temperatures of the wall section at t = 172800 s for the non-adiabatic case in Abaqus (b) Magnified nodal temperatures of the wall section at t = 172800 s for the non-adiabatic case in Abaqus (c) Heat flux magnitude of the wall section at t = 172800 s for the non-adiabatic case in Abaqus (d) Magnified heat flux magnitude vectors of the wall section at t = 172800 s for the non-adiabatic case in Abaqus

A.3.2 Results from Adiabatic Model

A summary of the results for the adiabatic model in DesignBuilder is presented in Table A.3.

Table A.3: Results of the adiabatic DesignBuilder model for the internal partition

Reported Value	Exposed Air Temperature (°C)	Surface Temperature (°C)	Conduction Heat Flux (W/m^2)	Convection Heat Flux (W/m^2)	Thermal Radiation Heat Flux (W/m^2)	Heat Balance (W/m^2)
West Surface	10.00000	10.77642	9.23936	-9.23935	-0.00001	0.00000
East Surface	20.00000	15.80031	-9.23935	9.23931	0.00004	0.00000

For the Abaqus model, nodal temperatures and heat flux magnitude at integration points was again requested. Results for the adiabatic case are visualised in Figures A.10 to A.13. At the inside surface (right face), the analysis stabilises at an average nodal temperature of 15.80029 °C and average heat flux magnitude of 9.23928 W/m^2. At the outside surface (left surface), the analysis stabilises at an average nodal temperature of 10.77639 °C and average heat flux magnitude of 9.23928 W/m^2.

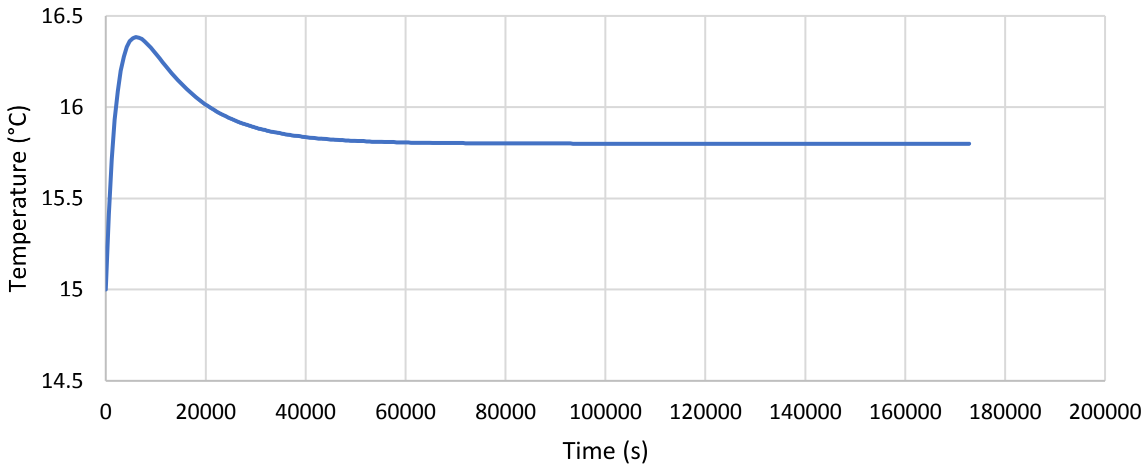


Figure A.10: Average nodal temperature of inside surface nodes for the adiabatic case in Abaqus

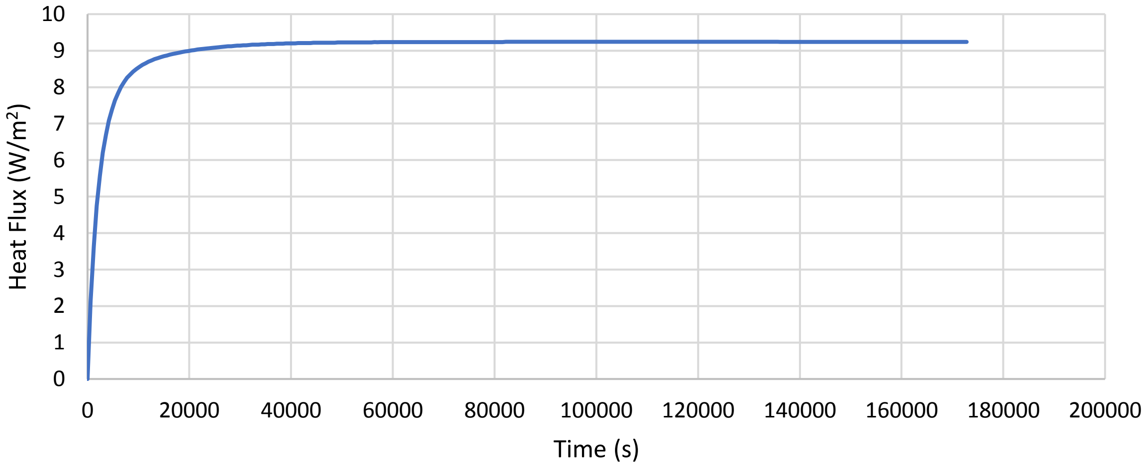


Figure A.11: Average Heat flux magnitude of elements at the inside surface for the adiabatic case in Abaqus

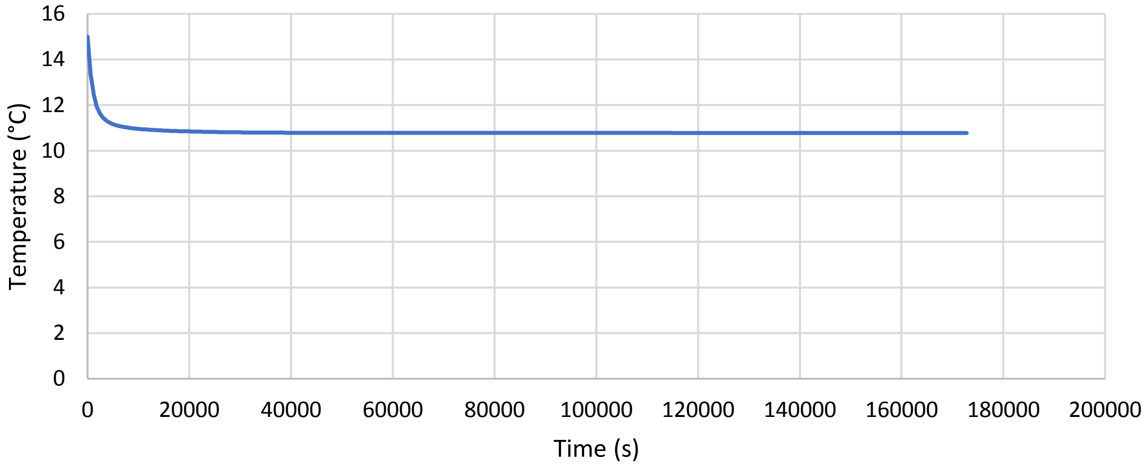


Figure A.12: Average nodal temperature of outside surface nodes for the adiabatic case in Abaqus

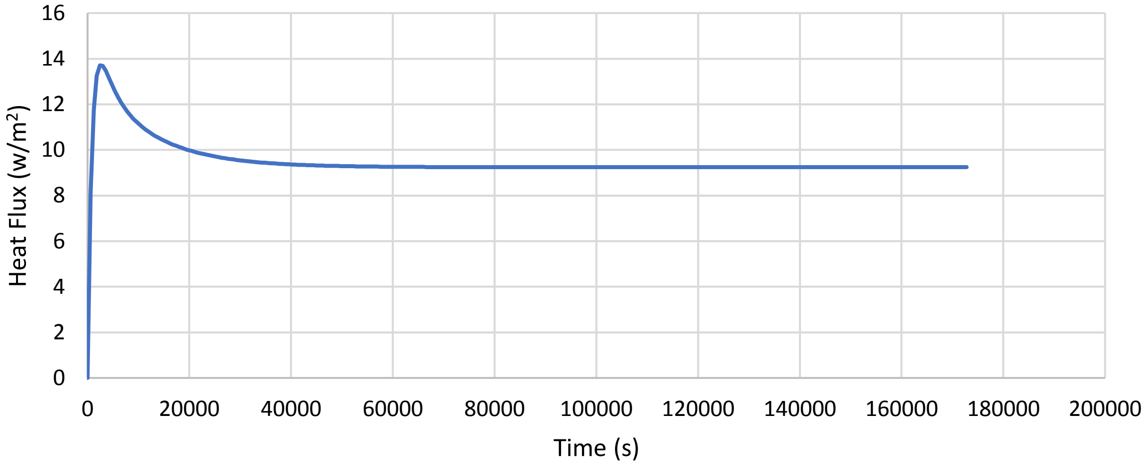
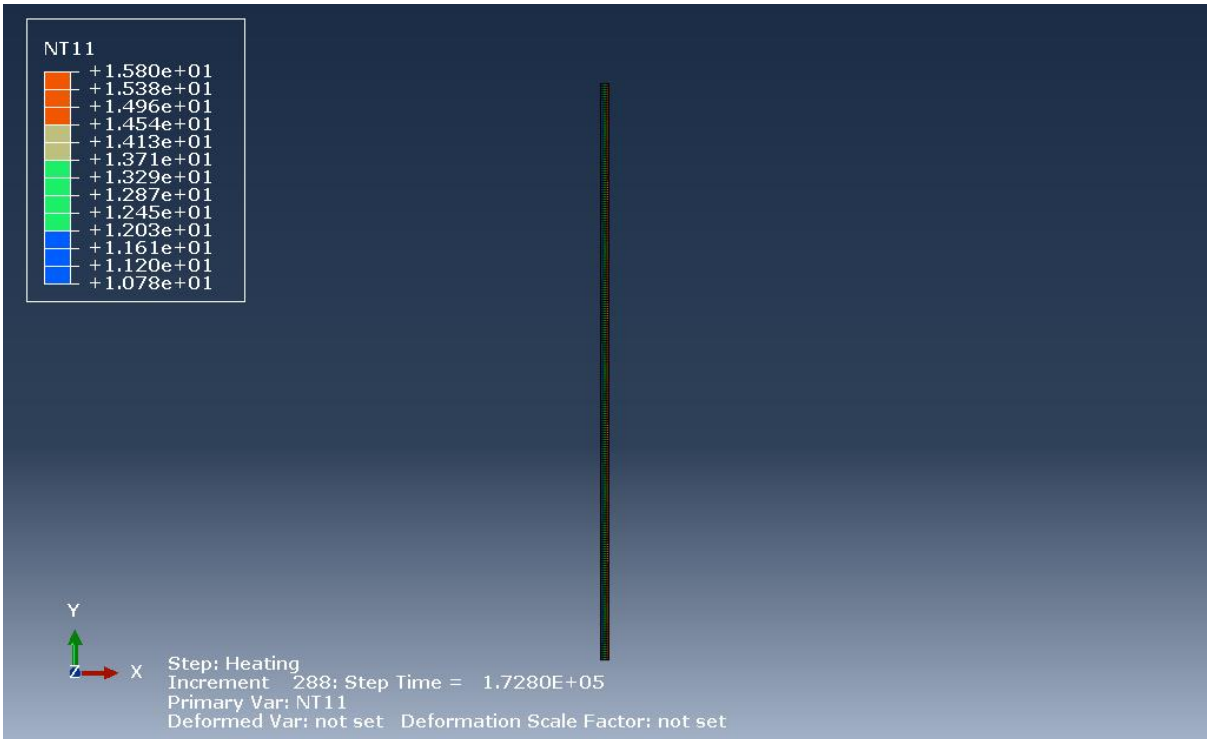


Figure A.13: Average Heat flux magnitude of elements at the outside surface for the adiabatic case in Abaqus

A visual depiction of the results on the section at the end of the simulation is presented in Figure A.14.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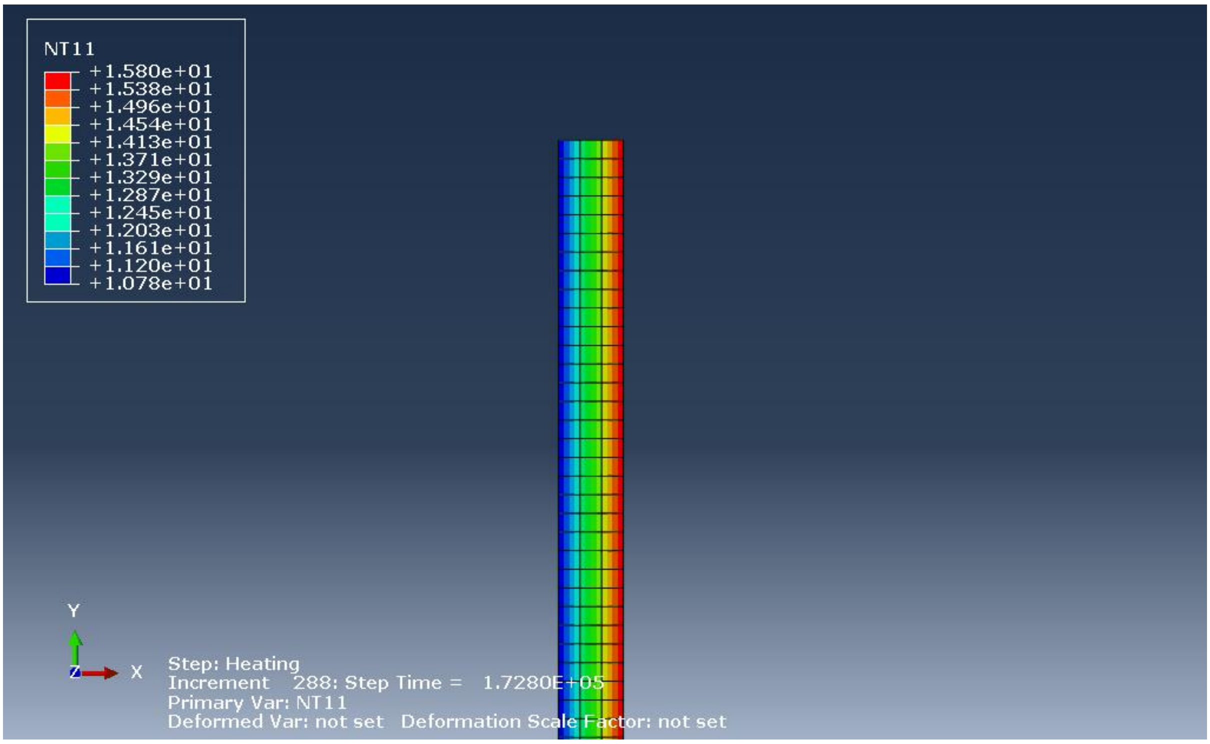
+1.287e+01
+1.245e+01
+1.203e+01
+1.161e+01
+1.120e+01
+1.078e+01
Y
Z
X
Step: Heating
Increment 288: Step Time = 1.7280E+05
Primary Var: NT11
Deformed Var: not set Deformation Scale Factor: not set

(a)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+1.120e+01
+1.078e+01
Y
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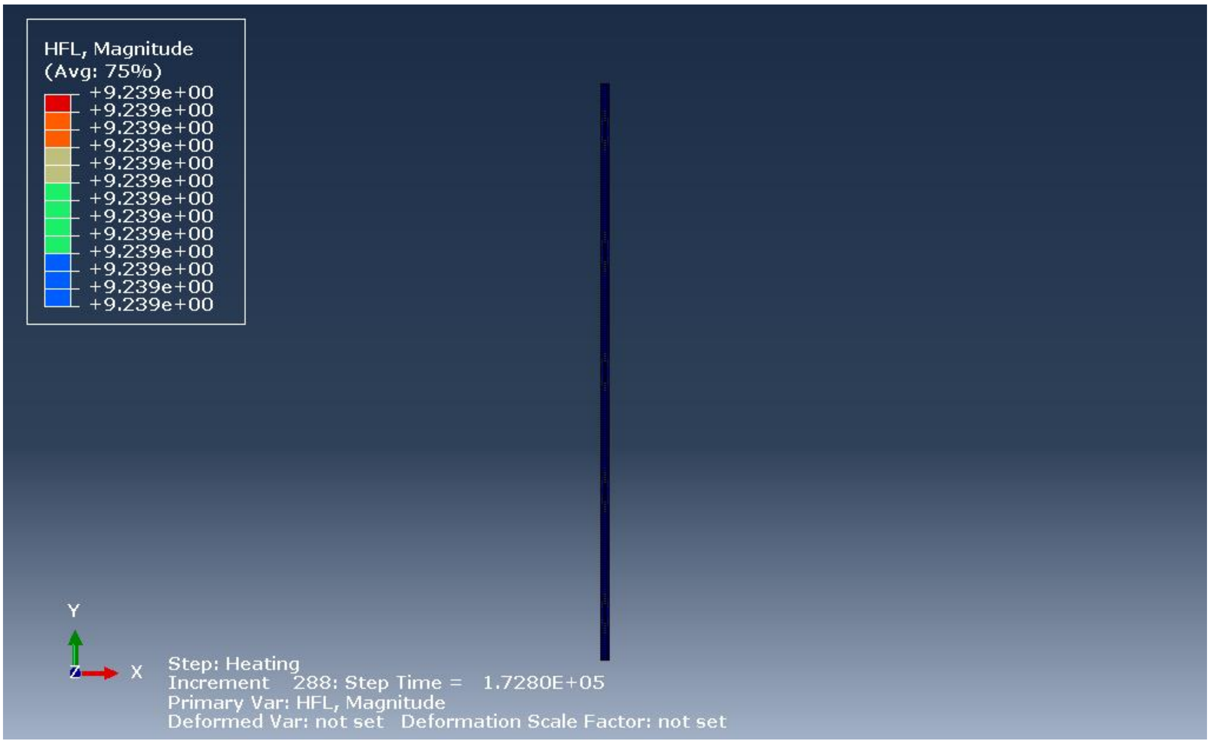
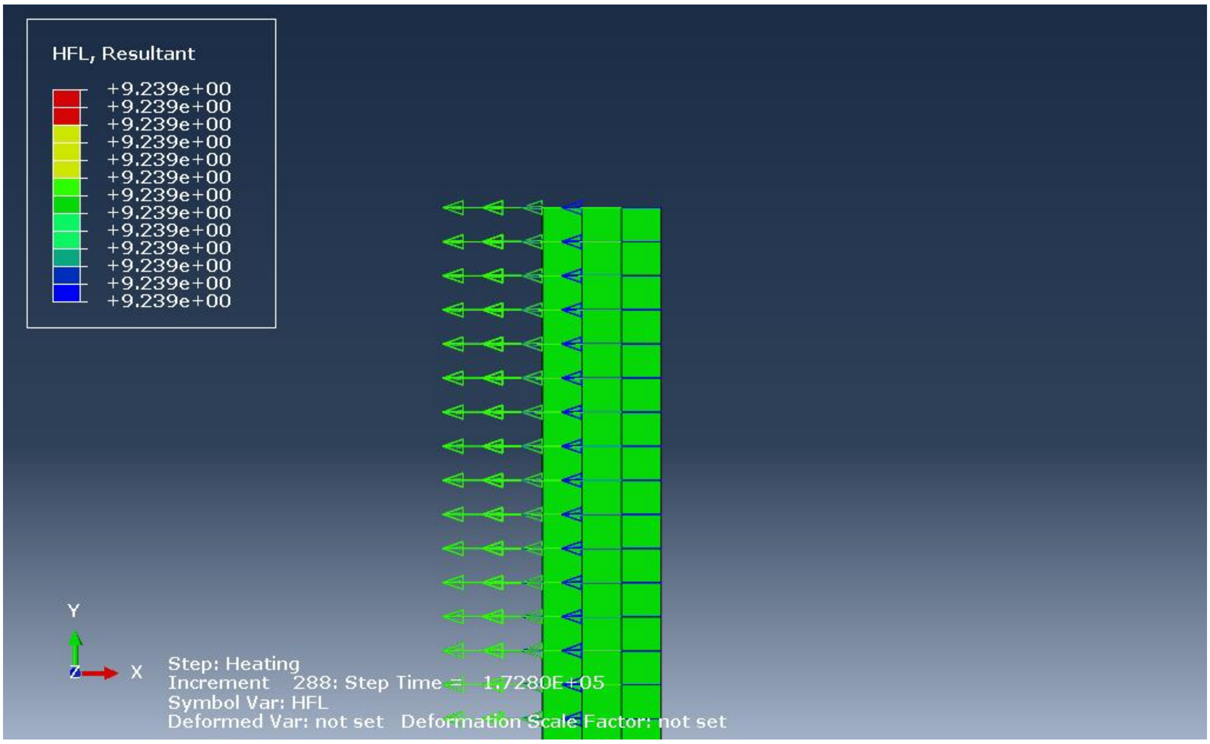
X
Step: Heating
Increment 288: Step Time = 1.7280E+05
Primary Var: NT11
Deformed Var: not set Deformation Scale Factor: not set

(b)



(c)



(d)

Figure A.14: (a) Nodal temperatures of the wall section at t = 172800 s for the adiabatic case in Abaqus (b) Magnified nodal temperatures of the wall section at t = 172800 s for the adiabatic case in Abaqus (c) Heat flux magnitude of the wall section at t = 172800 s for the adiabatic case in Abaqus (d) Magnified heat flux magnitude vectors of the wall section at t = 172800 s for the adiabatic case in Abaqus

A.4 Comparison of Results

A.4.1 Comparison of Results for Non-Adiabatic Case

For the purpose of comparing the DesignBuilder and Abaqus results, the relative difference, expressed as a percentage and rounded to five decimal places, was calculated between the final reported DesignBuilder and Abaqus value. A positive value would indicate the result produced by Abaqus is larger compared to the result produced by DesignBuilder. For the difference in heat flux, the conduction heat flux simulated by DesignBuilder was used for comparison. A summary of the relative difference between the reported results are presented in Table A.4. The comparison reveals that the difference between the DesignBuilder and Abaqus results is less than 0.01% for all reported values.

Table A.4: Comparison of the results for the non-adiabatic case

Reported Value	DesignBuilder	Abaqus	Difference (%)
Inside Surface Temperature (°C)	15.79912	15.79909	-0.00019
Outside Surface Temperature (°C)	10.77381	10.77383	0.00019
Inside Surface Heat Flux (W/m^2)	9.24194	9.24186	-0.00087
Outside Surface Heat Flux (W/m^2)	9.24195	9.24186	-0.00097

A.4.2 Comparison of Results for Adiabatic Case

Results for the Adiabatic Case was compared in the exact manner as the non-adiabatic case. A summary of the relative difference between the reported results are presented in Table A.5. Similar to the non-adiabatic case, the difference between the DesignBuilder and Abaqus results is less than 0.01% for all reported values.

Table A.5: Comparison of the results for the adiabatic case

Reported Value	DesignBuilder	Abaqus	Difference (%)
Inside Surface Temperature (°C)	15.80031	15.80029	-0.00013
Outside Surface Temperature (°C)	10.77642	10.77639	-0.00028
Inside Surface Heat Flux (W/m^2)	9.23935	9.23928	-0.00076
Outside Surface Heat Flux (W/m^2)	9.23936	9.23928	-0.00087

Appendix B: Model and Simulation Settings of DesignBuilder

The following sections serve as a template for creating the building models in DesignBuilder contained within this study. The section is divided into several subsections, each containing information related to choices made regarding the choice of model variable and calculation method input.

DesignBuilder allows simulation settings to be applied at five levels: site, building, zone, surface, and opening level. The site level is the highest in the hierarchy chain. It represents all the buildings being modelled. The building level is below the site level and represents a single building. The zone level represents a single zone in or outside a building. The surface level represents any surface in a zone that is not an opening.

B.1 Model Options

Before model data can be supplied, the method of input must be specified. The information provided under model options defines how information related to construction and glazing, internal heat gains, timing, and ventilation and infiltration is specified.

B.1.1 Construction and Glazing Data

Construction and glazing data can be defined through two methods: pre-design or general. The pre-design method allows constructions to be set from two sliders defining the level of insulation and level of thermal mass. The general method allows constructions to be set from a list of available constructions. The general method is chosen for construction and glazing data input in Chapters 3 to 5 because it provides a detailed level of input.

If zones are excluded from thermal analysis, their geometry can still be included in the overall thermal analysis to account for the shading that the excluded zones provide. However, because all the zones are considered during analysis in Chapters 3 to 5, this input is not required for these chapters.

If tintable windows are present in the model, they can be controlled through sensors. The sensor control method can be one of two: sensor groups or individual sensors. Sensor groups mimic a single sensor that controls multiple windows. Individual sensors mimic multiple sensors controlling multiple windows. However, because tintable windows are not present during analysis in Chapters 3 to 5, this input is not required for these chapters.

B.1.2 Gains Data

B.1.2.1 Gains Data Method

Internal gains can be defined using the lumped method, early method, or detailed method. The lumped method combines the internal gains into a single value but has the disadvantage of not generating output for comfort data (e.g. internal air temperature and ventilation) due to the occupancy not being detailed. The early gains method divides the internal gains into various categories and allows the occupancy to be specified. The detailed method allows the user to specify all the equipment in a zone individually. To provide a balance between providing detailed data and general assumptions, internal heat gains are provided using the early method for Chapters 3 to 5.

B.1.2.2 Occupancy Method

Occupancy can be specified through three means: occupancy density, area per person, and the number of people. The number of occupants in a room is calculated based on the chosen method and detailed in Table B.1. To standardise internal gains inputs, occupancy density is chosen as the occupancy method for Chapters 3 and 4. The occupancy density for each area is calculated by dividing the number of occupants by the internal floor area. Because of the different heat gains associated with occupants in Chapter 5, the number of people is chosen as the occupancy method in Chapter 5.

Table B.1: Occupancy Methods

Occupancy Method	Calculated Occupancy
1 - Occupancy Density	No. of People = Occupancy density x Floor Area
2 - Area per Person	No. of People = Floor Area / Area per person
3 - Number of People	No. of People = No. of People

B.1.2.3 Occupancy latent gains

The latent gains associated with occupancy can be calculated using one of two methods: dynamic calculation and fixed fraction. The dynamic calculation method calculates the latent fraction based on internal temperature and metabolic rate. The fixed fraction method calculates the latent fraction based on a specified constant independent of environmental conditions. Due to the unknown latent fractions of the occupants, methods chosen to calculate the latent fractions of the Alice Lane and Bridge Park models are left unchanged from their original models. For Alice Lane, the fixed fraction method is used, with a fixed fraction of 0.5. For Bridge Park, the dynamic calculation method is used. The dynamic calculation method is also chosen for Chapters 4 and 5.

B.1.2.4 Equipment Gain Units

The internal gains can be specified using one of two methods: power density and absolute zone power. Internal gains are expressed as W/m^2 when using the power density method. Internal gains are expressed as W when using the absolute zone power method. To provide heat gains in similar units, equipment heat gains are specified using the power density method for Chapters 3 and 4 but specified using the absolute zone power method for Chapter 5.

B.1.2.5 Lighting Gain Units

Internal gains due to lighting are expressed using three methods: power density, normalised power density, and absolute zone power. Lighting gains are expressed in W/m^2 when using the power density method. Lighting gains are expressed in W/m^2 per 100 lux when using the normalised power density method, allowing for internal gains to be associated with lighting requirements. Lighting gains are expressed in W when using the absolute zone power method. As there are no lux requirements, lighting heat gains are expressed using the power density method for Chapters 3 and 4 but specified using the absolute zone power method for Chapter 5.

B.1.3 Timing

Timing can be set to either follow a typical workday or a pre-defined schedule. When timing is based on a typical workday, a start time, end time, and the number of days per week is defined. When timing is based on a pre-defined schedule, a schedule for all minutes can be defined. If internal gains are to operate with occupancy, an option to couple occupancy and internal gains can be enabled. Due to the different aspects of the building operating at different times, a pre-defined schedule is used for Chapters 3 to 5. Furthermore, occupancy and internal gains schedules are not coupled but operate with their pre-defined schedule.

B.1.3.1 Type of Schedules

Schedules can be one of three types: 7/12 Schedule, Compact schedule, and Day schedule. The 7/12 schedule requires operation times to be set in tabular format, with the option to define the schedule to be used for a specific end-use or profiles when used for HVAC sizing. Compact schedules require operation times to be set in text format using ‘Through’ to define dates, ‘For’ to define days, and values to define the operation. Day schedules are used for the range multipliers in cooling design. As a result, day schedules give a schedule for a single day. To provide complete control over schedules, the compact schedule is used for Chapters 3 to 5.

B.1.4 Natural Ventilation and Infiltration

Natural ventilation can either be scheduled or calculated. Natural ventilation using scheduled natural ventilation is defined by supplying an infiltration rate using one of four units: ac/h, $m^3/(h.m^2)$ at 50 Pa, $m^3/(h.m^2)$ at 4 Pa, and n_{50} (ac/h at 50 Pa). Time schedules and temperature setpoints further adjust the infiltration. Calculated natural ventilation and infiltration are defined by one of two methods: template slider or crack template. The template slider defines air infiltration through five values: very poor, poor, medium, good, and excellent. A crack template defines the air leakage from a template containing the flow coefficients and flow exponents for a range of building components. Building ventilation and infiltration, natural ventilation is selected to be scheduled for Chapters 3 and 4 but calculated for Chapter 5. Infiltration is adjusted using the crack template for Chapter 5.

B.2 Site-Level Data Input

The site level is used to adjust specific properties of the building and provide the boundary conditions of the buildings being modelled. The inputs defined at the site level for analysis are:

- Building location, including latitude, longitude, and elevation above sea level;
- The expected exposure to wind for the building (classified as either sheltered, normal, or exposed);
- The orientation of the building (with 0 degrees defined as true north);
- The ground temperatures to which the foundation is exposed to;
- Ground surface reflection parameters (including solar and visible reflectance for normal and snow conditions); and
- The weather file.

Parameters related to the wind exposure, ground temperatures, and ground surface reflection parameters are left as default unless specified in the Appendix related to the building model.

B.3 Model Data Input

Model data is given under five main categories: activity data, construction data, openings data, lighting data, and HVAC data. These five categories determine the response of a structure to the loads it is subjected to.

B.3.1 Activity Data

The activity data section is used to specify internal heat gains, the HVAC system's behaviour, and when building openings are opened or closed. Activity data is divided into the activity template (containing the data of all activity data), floor areas and volumes (providing data relating to the floor area and volume of interior zones), occupancy, metabolic options, domestic hot water options (disabled due to lack of hot water), computers and office equipment data, catering, process, and miscellaneous data, as well as environmental controls. Activity can be defined at the building, block, and zone level.

B.3.1.1 Activity Template

An activity template can be applied at building level, block level, and zone level. Zones can be chosen to be excluded from zone thermal calculations and/or radiance daylighting calculations under this sub-heading. For a multiple storey building, a zone multiplier (which multiplies calculated building loads) can be applied to floors with similar characteristics to reduce computational time.

B.3.1.2 Floor Areas and Volumes

Net floor areas and volumes of zones can be verified under this sub-heading. The net floor area is considered the floor area of a zone measured using the inner perimeter. The net volume is the product of the floor area and height, measured from the floor surface to the ceiling.

B.3.1.3 Occupancy

The number of people, or people density, can be applied at building level, block level, and zone level. The occupancy value at the zone level is used during analysis. The occupancy is set according to a user-defined schedule using a compact schedule.

B.3.1.4 Metabolic

Five values are set under this sub-heading: metabolic rate per person (measured in W/person), metabolic factor, CO_2 generation rate (measured in $m^3/(s.W)$), winter clothing factor, and summer clothing factor. The metabolic rate is used for the sensible and latent internal heat gains. The metabolic rate is multiplied by the metabolic factor to account for different sexes and ages. The clothing factor is used to calculate the number of discomfort hours in summer and winter. The CO_2 generation is used when setting concentration setpoints to ensure enough fresh air is present. Clothing factors and the CO_2 generation rate is left at default values for Chapters 3 to 5.

B.3.1.5 Environmental Control

Five control measures are defined under the environmental control sub-heading: heating setpoint temperatures, cooling setpoint temperatures, ventilation setpoint temperatures, minimum fresh air, and lighting.

For heating setpoint controls, a heating setpoint and heating set back is set. The heating setpoint is the preferred temperature at which the zone is to be run at. When the zone temperature (dependent on temperature control) is below this value, the zone is heated until the heating setpoint is achieved. The heating setpoint during periods without occupancy is known as the heating set back. This value is used to prevent system damage due to lower temperatures (such as surface condensation) and reduce start-up heat load.

For cooling setpoint controls, a cooling setpoint and cooling set back are set. The cooling setpoint is the preferred temperature at which the zone is to be run at. When the zone temperature (dependent on temperature control) is above this value, the zone is cooled until the cooling setpoint is achieved. The cooling setpoint during periods without occupancy is known as the cooling set back. This value is used to reduce start-up cooling load.

For natural ventilation setpoint controls, it is possible to set indoor maximum and minimum control. Minimum and maximum temperature control can either be set using a value for all times or values corresponding to a schedule. If the indoor or outdoor air temperature is lower than the minimum temperature value, the opening is closed. Maximum temperature controls operate similarly. When ventilation is done mechanically, a cooling setpoint is specified as well as a delta temperature value. Mechanical ventilation takes place when the inside air temperature is higher than the cooling setpoint. When using a schedule, mechanical ventilation only occurs when the difference between the inside and outside air temperature is equal to or bigger than the delta temperature. Setpoint values are based on section 4.6.7 of SANS 204:2011 (South African Bureau of Standards, 2011c) for Chapters 4 and 5. The temperature setpoint can further be adjusted by the 2 °C deadband suggested by section 4.6.7 of SANS 204:2011 (South African Bureau of Standards, 2011c).

Fresh air requirements are defined by the fresh air required per person (measured in litre per person) and the fresh air supplied by mechanical ventilation (measure in litre per second per floor area).

Lighting requirements are defined by a minimum target illuminance (measured in lux) and a default display lighting density (measured in W/m^2).

B.3.1.6 Computers and Office Equipment

Internal gains are specified by specifying an absolute zone power (measure in W). Latent internal gains are specified as a fraction of the absolute zone power.

B.3.1.7 Catering, Process, and Miscellaneous

Internal gains are specified by specifying an absolute zone power (measure in W). Latent and radiant internal gains are specified as a fraction of the absolute zone power. Lost heat is specified as a fraction. Fuel used for the internal gains can be specified as electricity from the grid or natural gas. When natural gas is the chosen fuel source, a CO_2 generation rate must also be specified. Data for appliance and other electronic gains are obtained from Section 6.7 and 6.10 of CIBSE Guide A (Butcher and Craig, 2015) , providing internal gains for cooking appliances and internal gains for domestic appliances and equipment.

B.3.2 Construction Data

Construction data is provided under a main construction subheading and airtightness subheading.

B.3.2.1 Construction input data

Six main constructions can be specified at the building level: external walls, below-grade walls, flat roof, pitched roof (occupied), pitched roof (unoccupied), and internal partitions.

B.3.2.2 Semi-Exposed construction input data

Semi-exposed construction data are provided for construction located between an unconditioned zone and a conditioned zone. A typical example is the ceiling dividing the roof and main building. Three construction can be specified at the building level: semi-exposed walls, semi-exposed ceiling, and semi-exposed floor.

B.3.2.3 Floor construction input data

Three constructions are specified at the building level: ground floor, internal floor, and external floor.

B.3.2.4 Sub-Surfaces input data

Sub surfaces are surface within a surface which has different properties to the rest of the surface. Five sub-surfaces can be specified: sub-surface walls, internal sub-surface, sub-surfaces created for pitched roofs, and internal and external doors.

B.3.2.5 Internal Thermal Mass

To account for various loose objects in a room, a thermal mass can be specified. The thermal mass can also be used to combine zones with similar characteristics. A zone capacitance multiplier can also be used to increase the heat storage capacity of air.

B.3.2.6 Component Block

Component blocks are used as shading and transmittance objects. They do not absorb or conduct thermal energy. Three types of component blocks can be created: standard component block, ground component block, and adiabatic component block. A standard component block creates objects which cast shadows and reflect solar radiation/incoming light. Ground and adiabatic component blocks are used to change the adjacency of surfaces.

Building blocks can be associated with building rotation when set as building level. If the component block is set as site level, the component block does not rotate when the building is rotated. The solar and visible reflectance properties for each component block can be adjusted. If an object is to be modelled with changing shading, a maximum transmittance with a schedule can be specified.

B.3.2.7 Geometry, Areas and Volumes

How geometry is defined under this subheading. Two options are available for geometry calculation: outer and inner. Geometry calculations are performed for four parts: zone geometry and surface area definition, zone volume calculation, zone floor area calculation, and window to wall ratio calculation. These settings are used for thermal calculations. The default option for geometry calculation is inner for all the part except for zone geometry and surface area, chosen as outer. Suppose the geometry thickness of an object is to be modelled with a thickness other than that specified for the construction. In that case, a fixed surface thickness can be specified, which adjusts geometry but not thickness used for thermal properties. Void depths for the ceiling and floor can also be specified if an air gap is not provided for the constructions.

B.3.2.8 Surface Convection

The heat convection coefficient is set under this subheading. This is done for the inside and outside convection coefficient for heating and cooling design and simulations. The algorithm used is determined from a list of options. The heat convection coefficient is left at default for Chapters 3 to 5.

B.3.2.9 Linear Thermal Bridging at Junctions

A psi value for junctions can be specified to account for thermal bridging at locations where different construction meets. Linear thermal bridging is not taken into account for Chapters 3 to 5.

B.3.2.10 Airtightness

Air infiltration through the building envelope is defined under this subheading. This is done through scheduled natural ventilation or calculated natural ventilation. When using scheduled natural ventilation, an infiltration rate and schedule are specified. When using calculated natural ventilation, a ‘crack’ template is specified at the building level. The crack template specifies flow exponents and flow coefficients for different constructions.

B.3.3 Construction input data

A construction is a composite made from several layers, with each layer being a different layer. Construction data is specified under the layers and surface properties tab.

Regarding layer properties, if surface heat balance is calculated differently from the default solution algorithm, the simulation solution algorithm for the construction must be specified to be either CTF, Finite Difference, HAMT, or EMPD. If one or more layers contain metal cladding, it must be indicated that the construction contains metal cladding. For each layer specified, the material, layer thickness, and bridging must be defined. Bridging is defined by specifying the material data for the bridging material and the % cross-section area it bridges. The CTF solution algorithm is employed for Chapter 3 whereas two solution algorithms are employed in Chapters 4 and 5: CTF and HAMT. Furthermore, no thermal bridging is assumed to occur.

Only two properties can be changed regarding surface properties: the convective heat transfer coefficient for the inside and outside surface. A single value is defined to override the value calculated by the software. The convective heat transfer properties are not changed and chosen to be calculated by the software for Chapters 3 to 5.

B.3.3.1 Material Properties

Material properties are defined under five headings: general, surface properties, green roof, embodied carbon, and phase change. Due to the material used in the model, only the general and surface properties headings will be discussed.

General properties include thermal properties, vapour resistance data, and moisture transfer data. The thermal properties can either be detailed or a resistance value (requiring only the thermal resistance value). Detailed properties require conductivity, specific heat, and density to be specified. Vapour resistance can be defined using either a vapour factor, vapour resistivity or made non-permeable.

Moisture transfer data is defined under seven headings: general, EMPD, HAMT Settings, sorption isotherm, suction, redistribution, diffusion, and thermal conductivity. Moisture transfer data can be provided for both the EMPD and HAMT simulation data. EMPD data requires an effective moisture depth to be specified with four coefficients. HAMT settings require information regarding the porosity and initial water content of a material. The sorption isotherm of a material is defined by a maximum of 25 relative humidity data points corresponding to 25 moisture content data points. The suction and redistribution data of a material are defined by a maximum of 25 moisture content data points corresponding to 25 liquid transport coefficient data points. The diffusion data of a material is defined by a maximum of 25 relative humidity data points corresponding to 25 diffusion resistance factor data points. The thermal conductivity of a material is defined by a maximum of 25 moisture content data points corresponding to 25 thermal conductivity data points.

Surface properties for a material are defined through 6 inputs: thermal emissivity, solar absorptance, visible absorptance, surface roughness, specularity, and material class. Surface roughness can be very rough, medium rough, rough, medium, smooth, and very smooth. The material class can be defined as plastic or metal. Surface roughness is assumed rough for all materials in Chapters 4 and 5.

B.3.4 Openings

Five types of openings can be defined: External windows, internal windows, sloped roof windows/skylights, doors, and vents. Due to only external windows and doors present in RDP housing, only these two will be expanded upon.

B.3.4.1 External Windows

External windows are defined using dimensions data, reveal data, frame and dividers, local and window shading, airflow control, operation, and free aperture.

For dimension data, window geometry is defined by the window to wall %, window height, window spacing and sill height. How the geometry is applied is determined by the six dimension types: None, continuous horizontal, fixed height, preferred height, fixed width and height, and fill surface. Window reveals that data is specified using three values: outside reveal depth, inside reveal depth, and sill depth.

A frame with dividers can be specified for external windows. Dividers can either be divided lite or suspended. The following is specified for dividers: divider width, number of vertical and/or horizontal dividers, outside and insider projection, and glass edge-centre conduction ratio.

The window frame is defined from four inputs: frame width, frame inside and outside projection, and glass edge-centre conduction ratio. The frame material is also defined using standard construction data input.

Shading can be chosen to be window shading or local shading. Window shading are shading provided adjacent to the windows surface. Local shading is either shading provided using louvres, sidefins or an overhang.

Airflow control is used for curtain walls with more than one layer of glazing. As a result, this is not discussed due to only a single layer of glazing is considered.

Free Aperture is defined as the airflow through windows when opening. To model free aperture, four inputs are required: opening position, % glazing area opens, discharge coefficient, and operation schedule.

B.3.4.2 Glazing input data

Glazing can be defined using one of two methods: layers and simple. When the simple method is selected, three properties must be defined to represent the glazing performance of the entire unit: total solar transmission, light transmission, and U-value. When layers are selected, each pane of glazing must be defined.

Glazing properties are defined under six subheadings: general, thermal, solar, visible, infra-red, and spectral. Under the general section, the data input type is chosen as either broadband or spectral data. Under the thermal section, the thickness of the glazing and its thermal conductivity is specified. Under the solar section, solar transmittance and outside and inside solar reflectance are defined. Under the visible section, visible transmittance and outside and inside visible reflectance are defined. Under the infra-red section, infra-red transmittance, as well as outside and inside emissivity, is defined. When spectral data is the data input method, solar transmission and reflectance for all available wavelengths.

In addition to the solar properties, radiance daylighting properties are also defined for glazing units. These properties are defined with three inputs: specularity, roughness, and transmitted specularity.

B.3.4.3 Doors

Doors are generated and operated from six input values: preferred width and height, % area door opens, % time door is open, the opening position, and the operation schedule.

B.3.5 Lighting

Zone lighting is defined through five inputs: power density, luminaire type, return air fraction, radiant fraction, and visible fraction. The luminaire type determines the convection fraction and can be one of five luminaire types: suspended, surface mount, recessed, luminous and louvred ceiling mount, and return-air ducted mount.

B.3.6 HVAC

B.3.6.1 Natural Ventilation

Natural ventilation can be set as scheduled or calculated. Regardless of calculation type, inputs for both types are requested. Natural ventilation is defined under six subheadings: operation, outdoor temperature limits, Delta T limits, Delta T and Wind Speed Coefficients, Options, and Mixed Mode Zone Equipment. Before natural ventilation options are set, the outside air definition method must be chosen. The outside air requirement can be based on the minimum fresh air require per person or the ventilation requirement set for the zone.

The operation schedule defines when natural ventilation can take place. Fractions specified in the schedule represents the fraction of the maximum design natural volume flow rate.

Outdoor temperature can be set for minimum and maximum outdoor temperature control. Minimum and maximum temperature control can either be set using a value for all times or values corresponding to a schedule. If the indoor or outdoor air temperature is lower than the minimum temperature value, ventilation is turned off. Maximum temperature controls operate similarly.

Delta T limit control limits ventilation based on the difference between the inside and outside air temperature. When the difference between the inside and outside air temperature is equal to or bigger than the delta temperature, ventilation is enabled. The Delta T limit can be set as a constant value or defined using a schedule.

Delta T and Wind Speed Coefficients are used to define ventilation. The four coefficients are constant coefficient, temperature coefficient, velocity coefficient and velocity squared coefficient.

Three standard options must be defined for calculated ventilation: the wind factor, control mode, and internal control mode. If opening areas are to be modulated, three option must be defined: a lower and upper value of the difference between inside and outside temperature, and the limit value of the opening modulation factor.

If mechanical ventilation is combined with natural ventilation, operation for both must be defined under the mixed-mode option.

B.3.6.2 Air Temperature Distribution

EnergyPlus, by default, assumes that air in a zone is fully mixed and that air temperature is uniform. However, four other options are available: dynamic gradient, three node displacement ventilation, underfloor air distribution interior, and underfloor air distribution exterior.

B.4 Advanced Model Options

Advanced model options include settings for simplification, adjacency, natural ventilation, lighting, filters, and component blocks.

B.4.1 Simplification

Two types of simplification can be performed: zone merging and lumping of surface openings. Zones can be merged when: they share the same activity, when holes connect an entire surface between the zones, and when zones are selected to merged. Windows and cracks on a surface can be lumped together when they are similar. All the zones in the building models of Chapter 4 and 5 are not merged. Furthermore, to ensure surface openings are specified with the desired dimensions and properties, lumping of surface openings are disabled.

B.4.2 Adjacency Settings

The maximum gap between two surfaces to be considered adjacent is defined by supplying an adjacency separation tolerance. Internal adjacency is defined by supplying an adjacency angular tolerance, limiting the angle between surfaces for them to be considered adjacent. It is possible to remove surface objects adjacent to the standard component block by enabling this option under adjacency settings. For Chapters 3 to 5, adjacency settings were disabled and left as default.

B.4.3 Natural Ventilation

If airflow through internal openings and virtual partitions should be modelled, the option for this should be enabled under natural ventilation. Options for calculated and scheduled natural ventilation for the modelling of airflow through internal openings and virtual partitions.

For calculated natural ventilation, airflow through internal openings and virtual partitions is defined through two inputs: wind factor and discharge coefficient for open doors and holes. An additional three inputs are required when openings are to be modulated (i.e. when the opening factor must be changed): the lower and upper value of Tin -Tout and the limit value of the opening modulation factor. As discussed earlier, calculated natural ventilation and infiltration are used for Chapter 5. Thus, only calculated natural ventilation and infiltration options are considered. The wind factor and discharge coefficient are left at the default values of 1 and 0.6.

For scheduled natural ventilation, airflow through internal openings is defined by a single input: airflow rate per opening area. Airflow through internal openings is ignored for Chapter 4.

Appendix C: Data Inputs for Chapter 3

The following data was used as input for the analysis of models simulated in Chapter 3.

C.1 Weather Data Used for Alice Lane

Weather data used to analyse the Alice Lane building's thermal performance is presented in Figures C.1 to C.9.

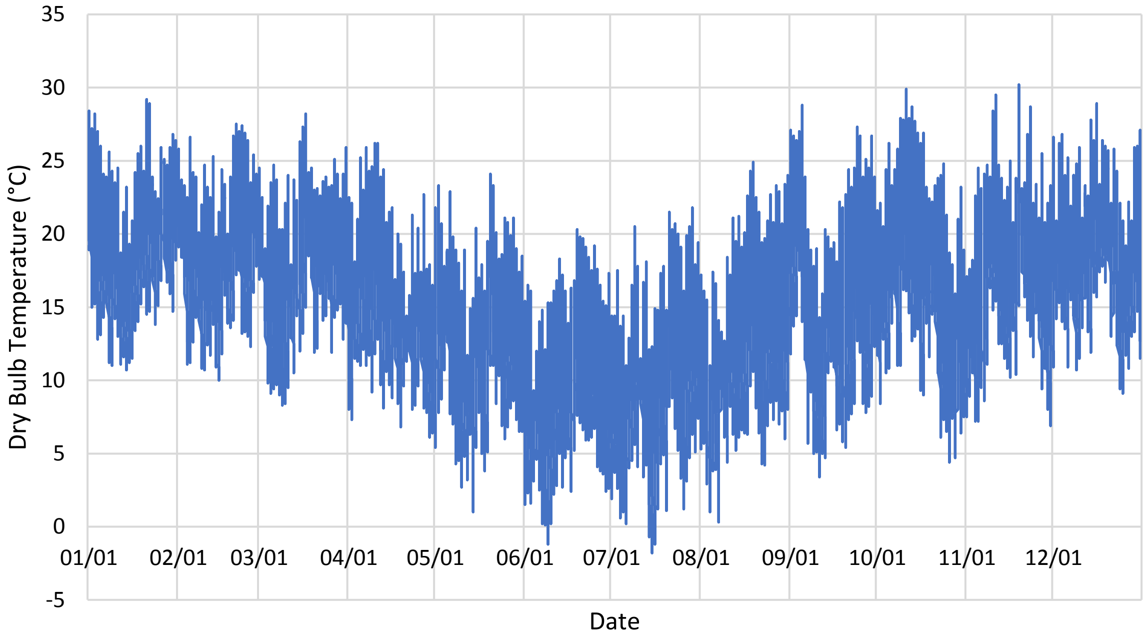


Figure C.1: Dry Bulb Temperature Data from Meteonorm Data

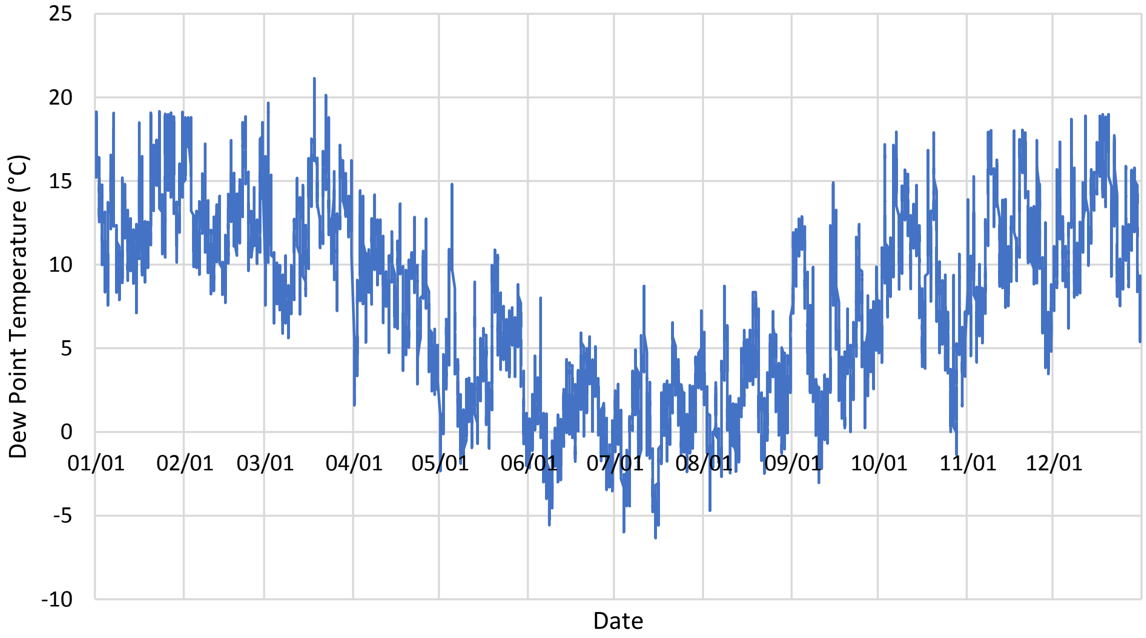


Figure C.2: Dew Point Temperature Data from Meteonorm Data

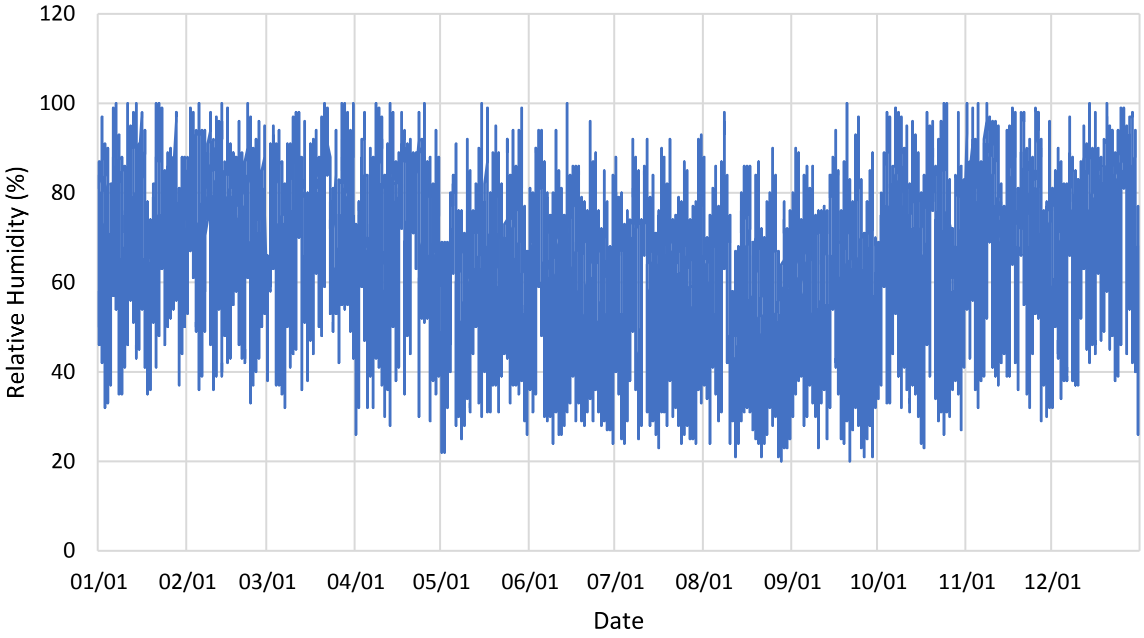


Figure C.3: Relative Humidity Data from Meteonorm Data

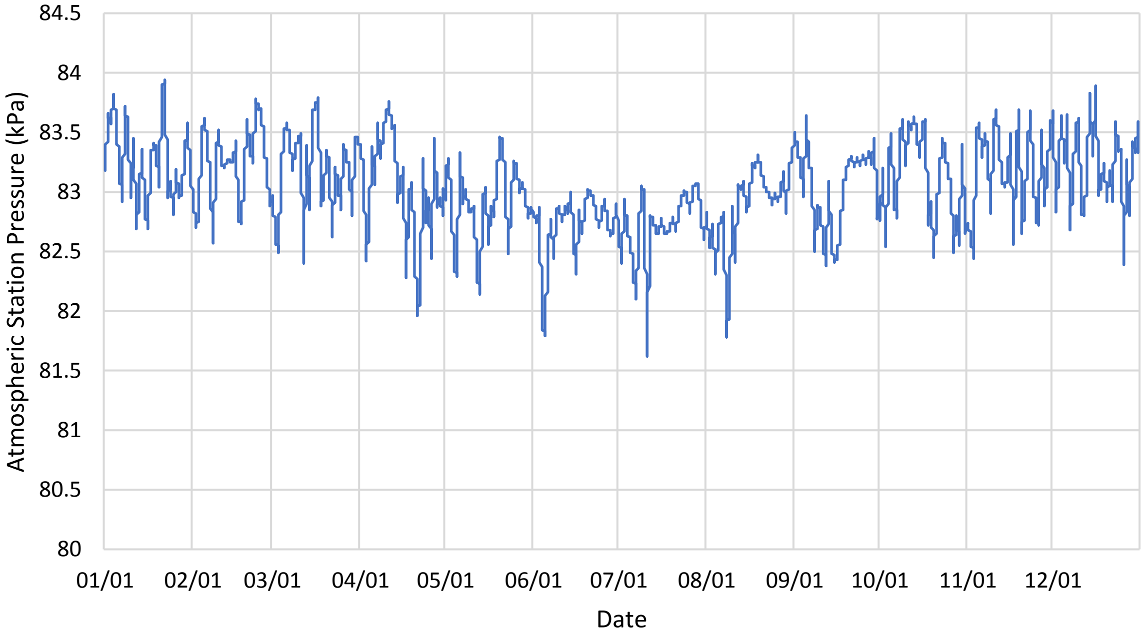


Figure C.4: Atmospheric Station Pressure Data from Meteonorm Data

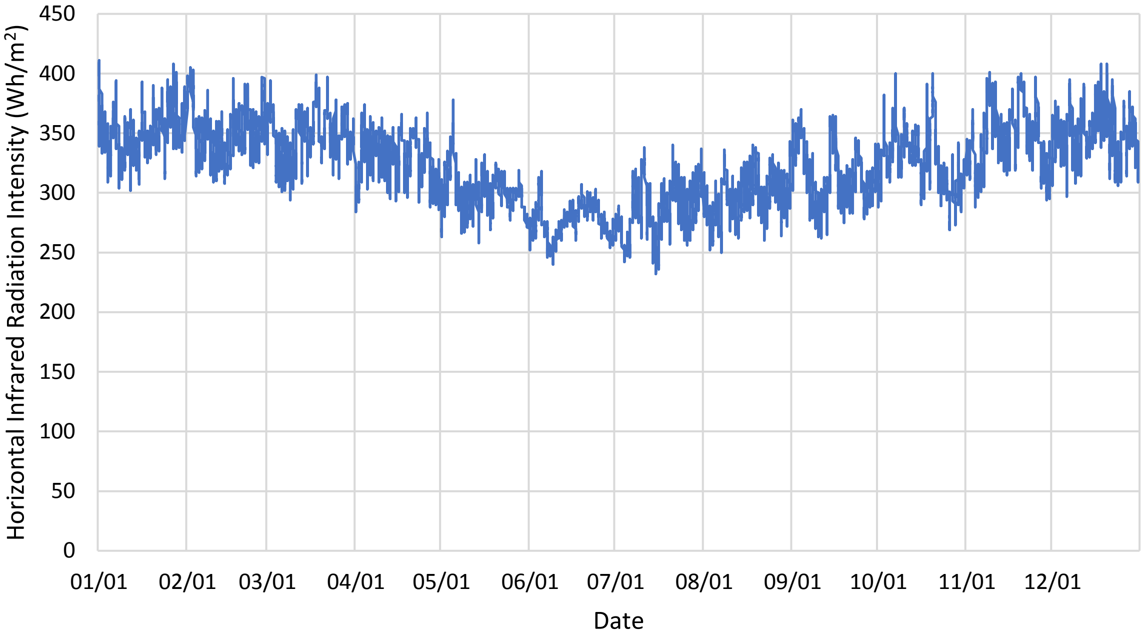


Figure C.5: Horizontal Infrared Radiation Intensity Data from Meteonorm Data

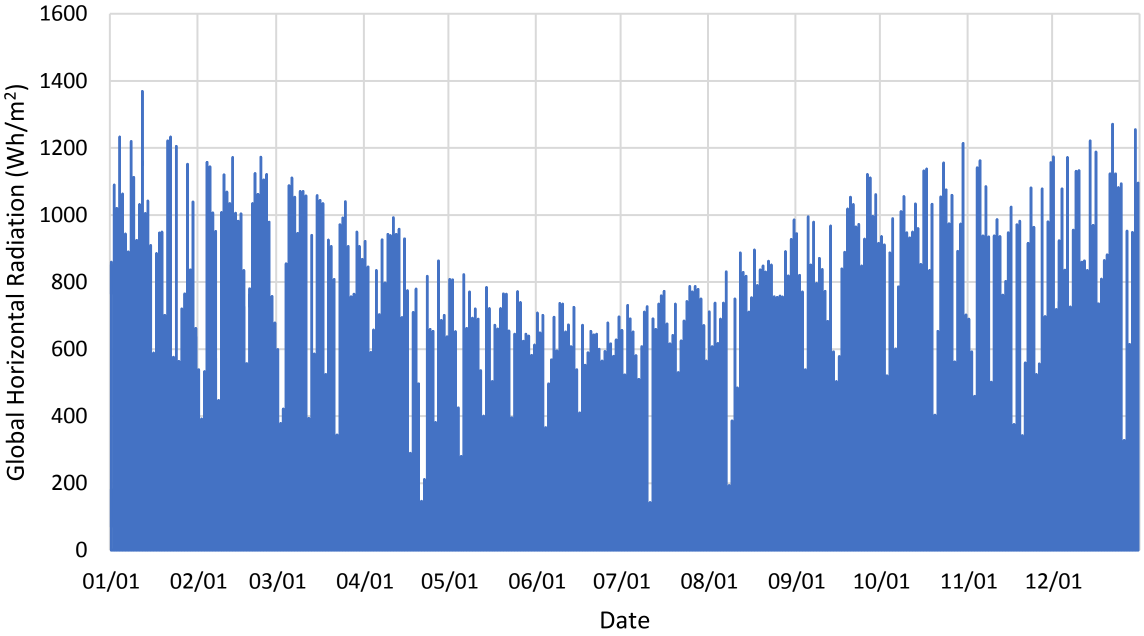


Figure C.6: Global Horizontal Irradiation Data from Meteonorm Data

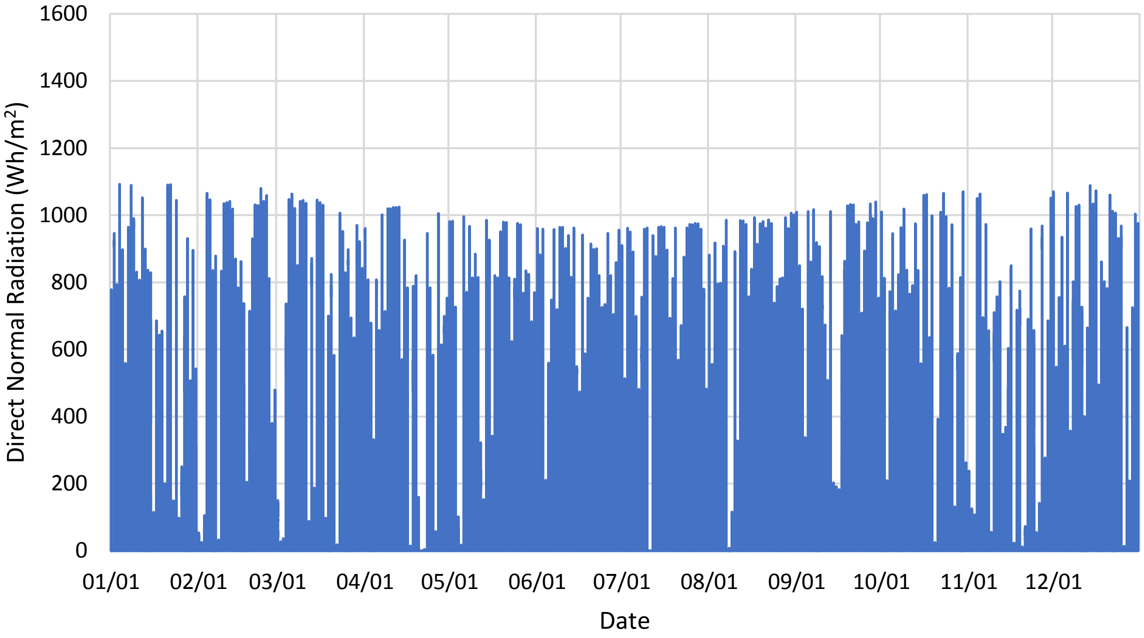


Figure C.7: Direct Normal Irradiation Data from Meteonorm Data

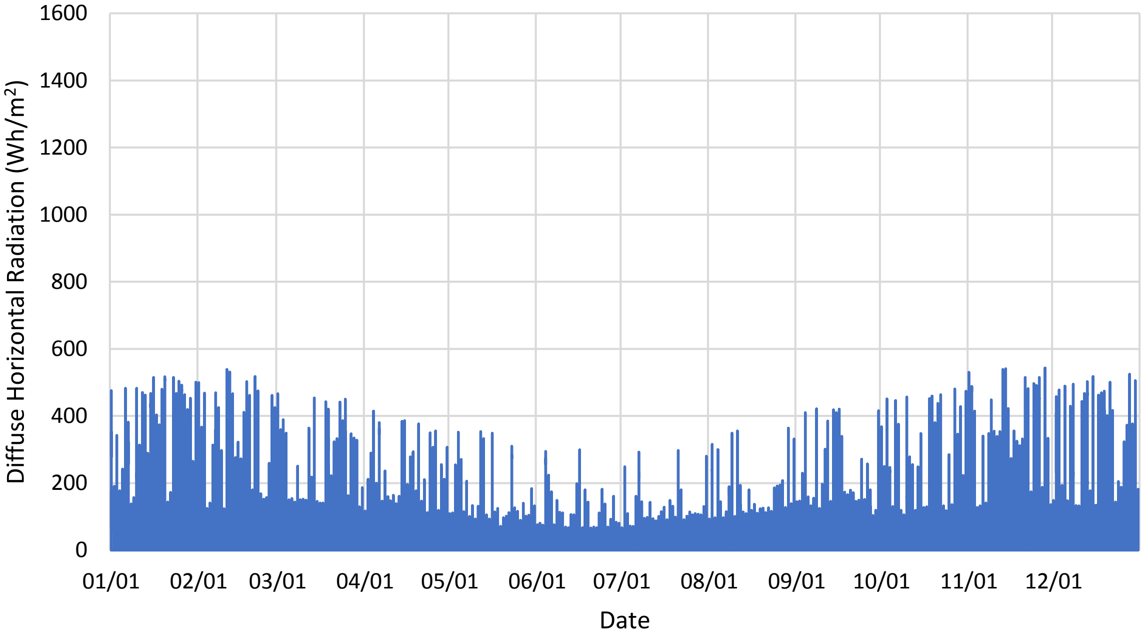


Figure C.8: Diffuse Horizontal Irradiation Data from Meteonorm Data

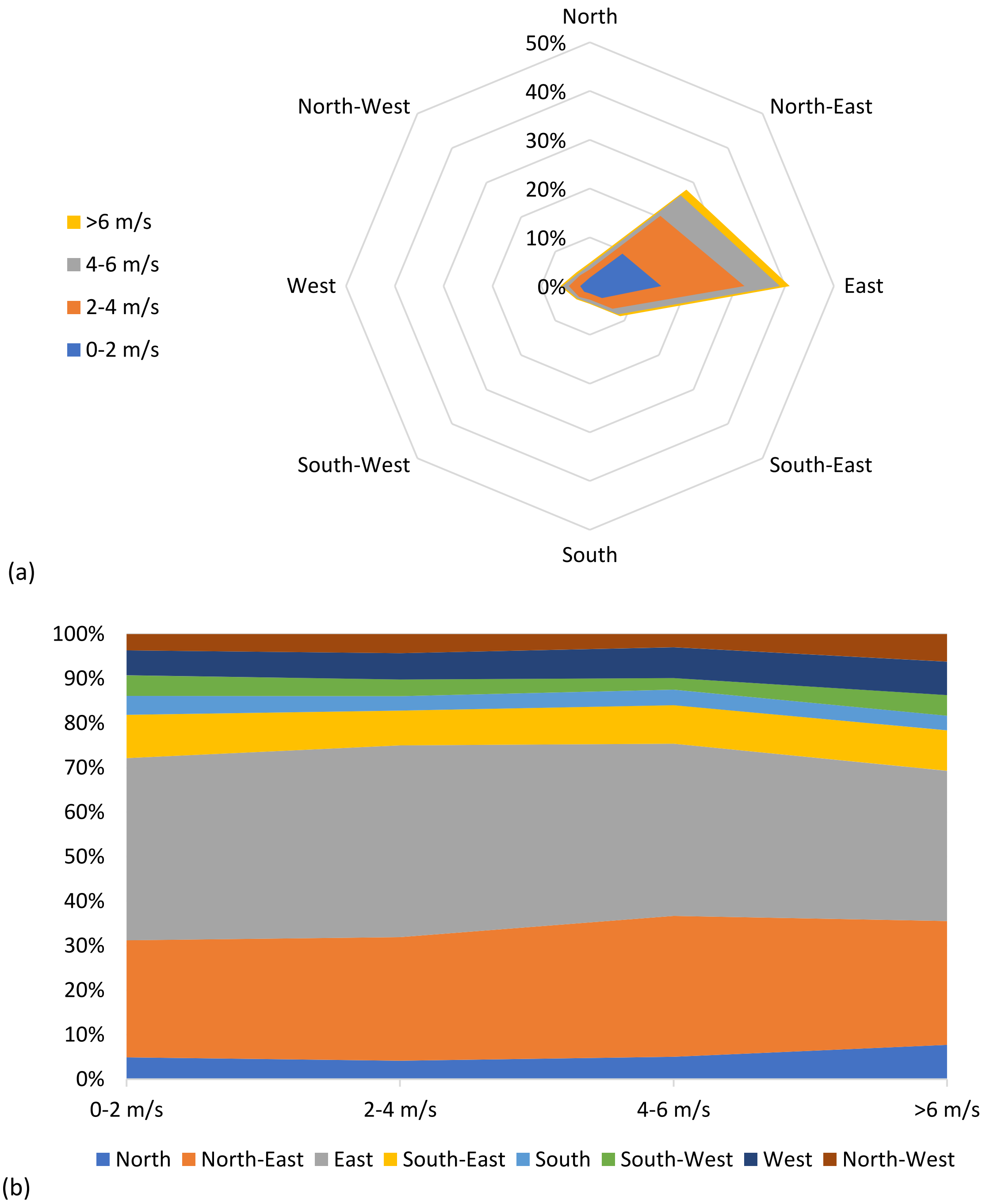


Figure C.9: (a) Wind Rose of Meteonorm Data (b) Wind Speed Within Wind Direction Distribution

C.2 Weather Data Used for Bridge Park

Weather data used to analyse the Bridge Park building's thermal performance is presented in Figures C.10 to C.18.

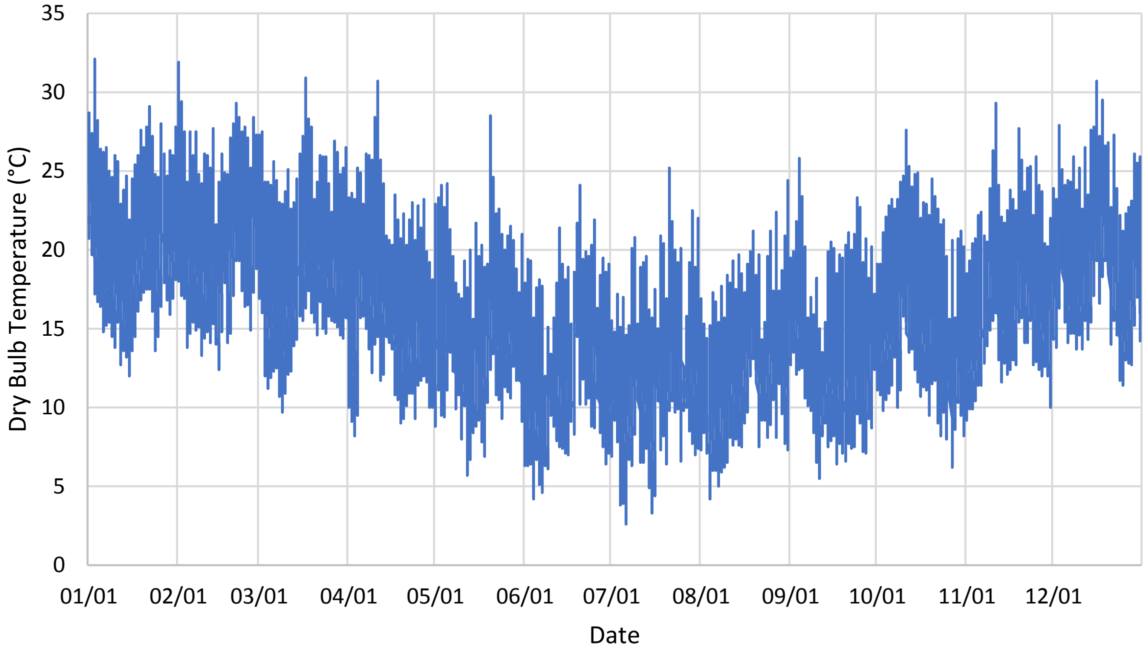


Figure C.10: Dry Bulb Temperature Data from Meteonorm Data

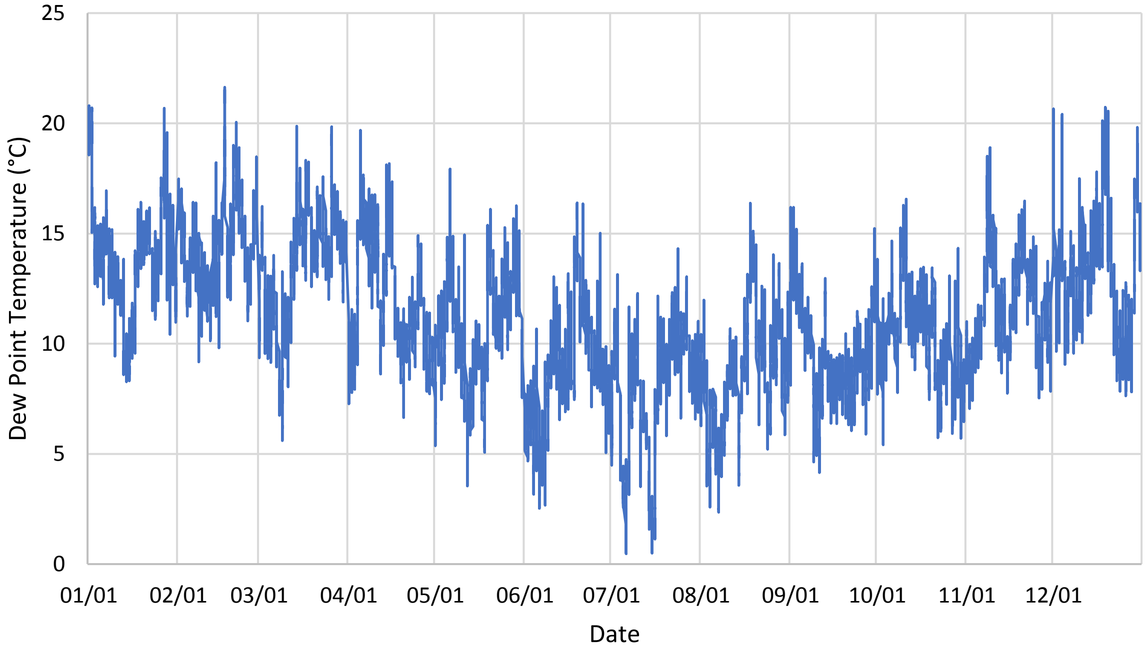


Figure C.11: Dew Point Temperature Data from Cape Town IWEC Data

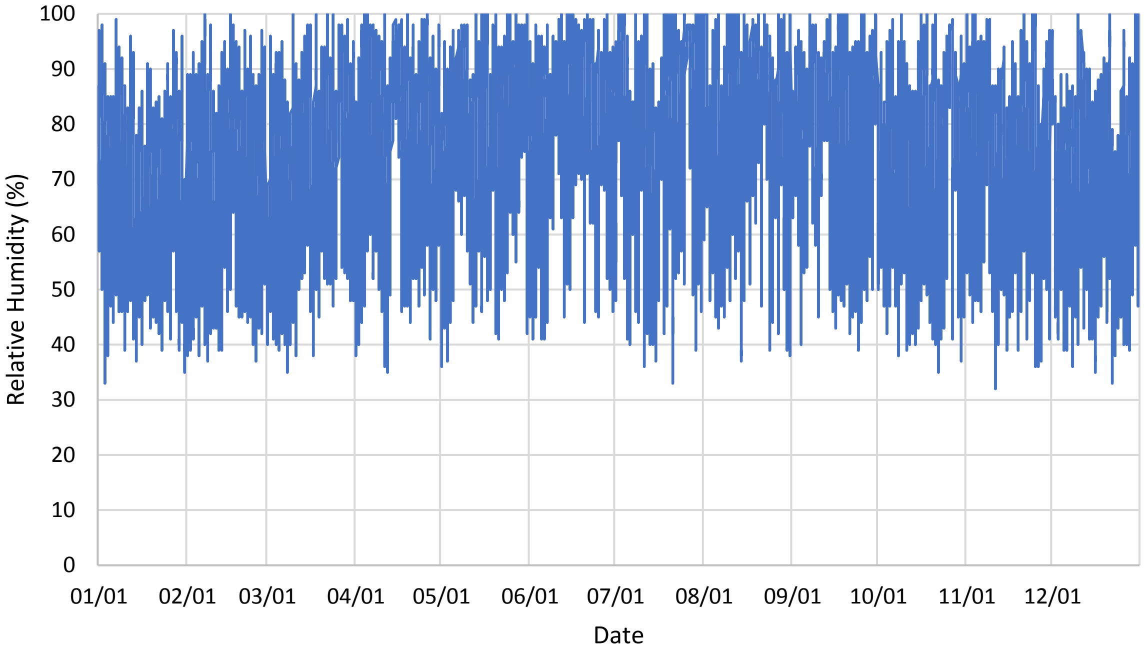


Figure C.12: Relative Humidity Data from Cape Town IWEC Data

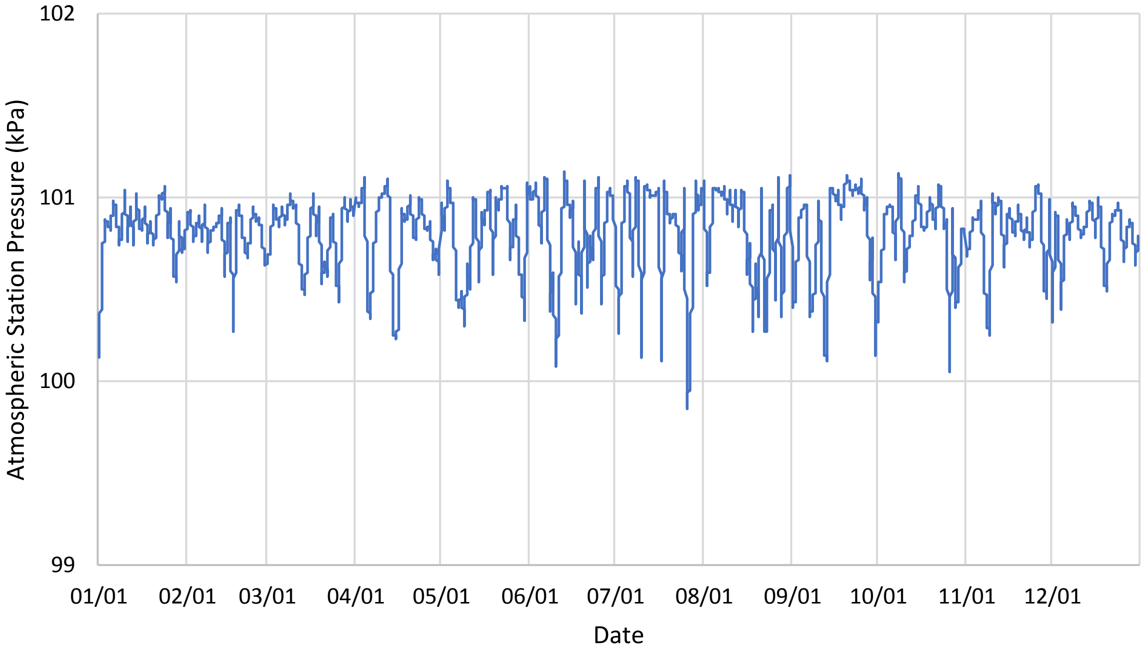


Figure C.13: Atmospheric Station Pressure Data from Cape Town IWEC Data

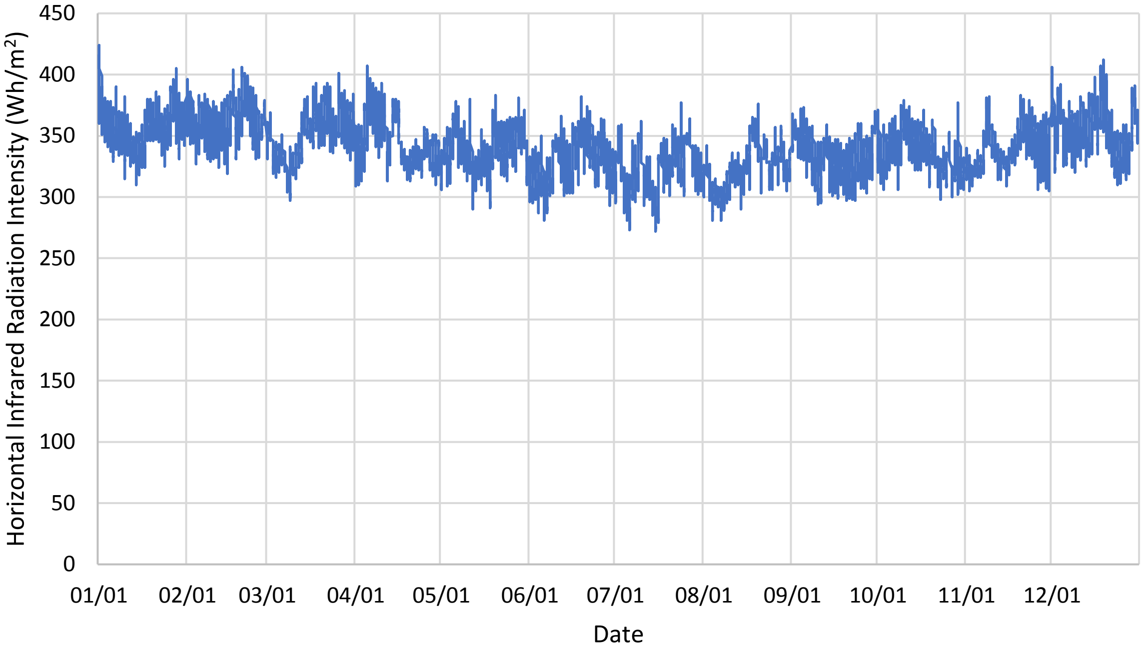


Figure C.14: Horizontal Infrared Radiation Intensity Data from Cape Town IWEC Data

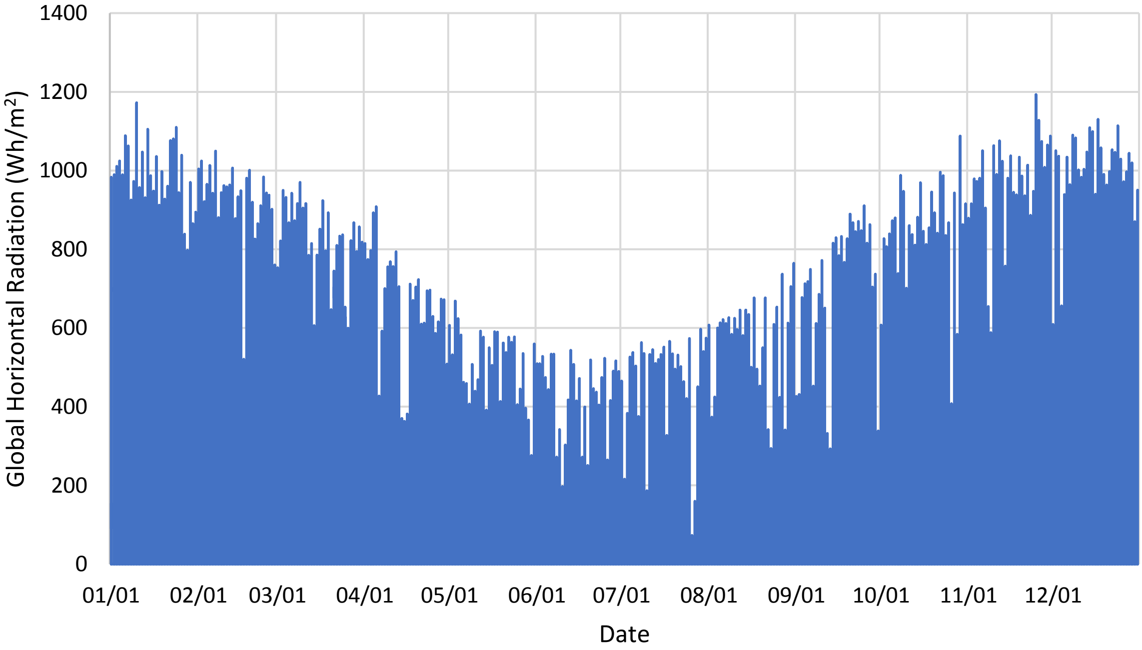


Figure C.15: Global Horizontal Irradiation Data from Cape Town IWEC Data

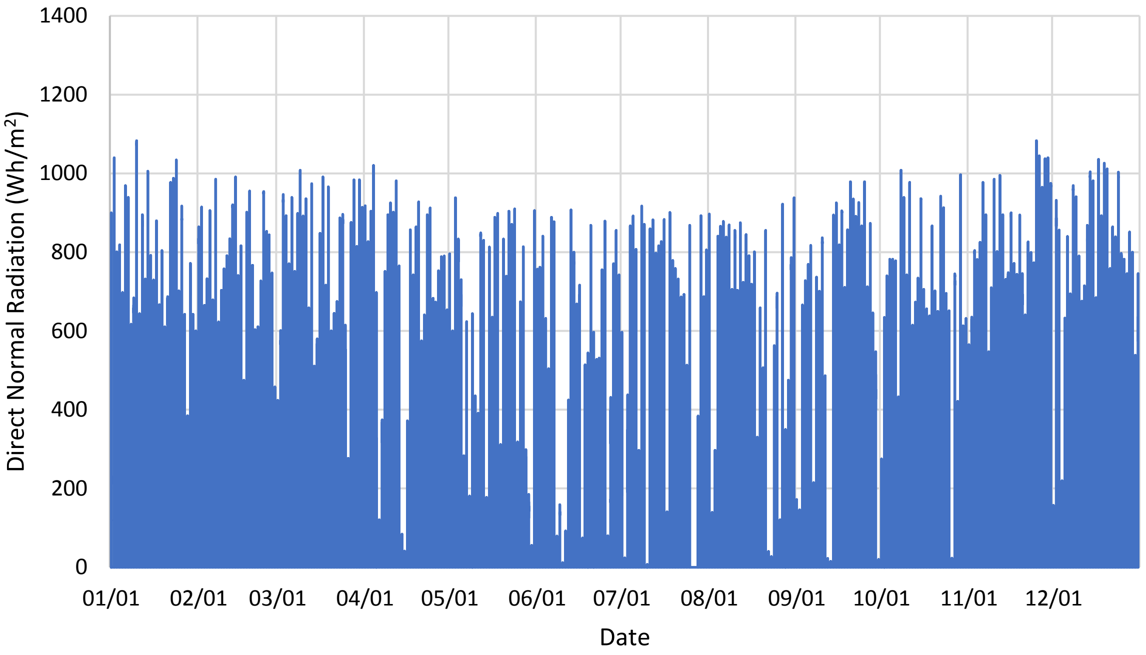


Figure C.16: Direct Normal Irradiation Data from Cape Town IWEC Data

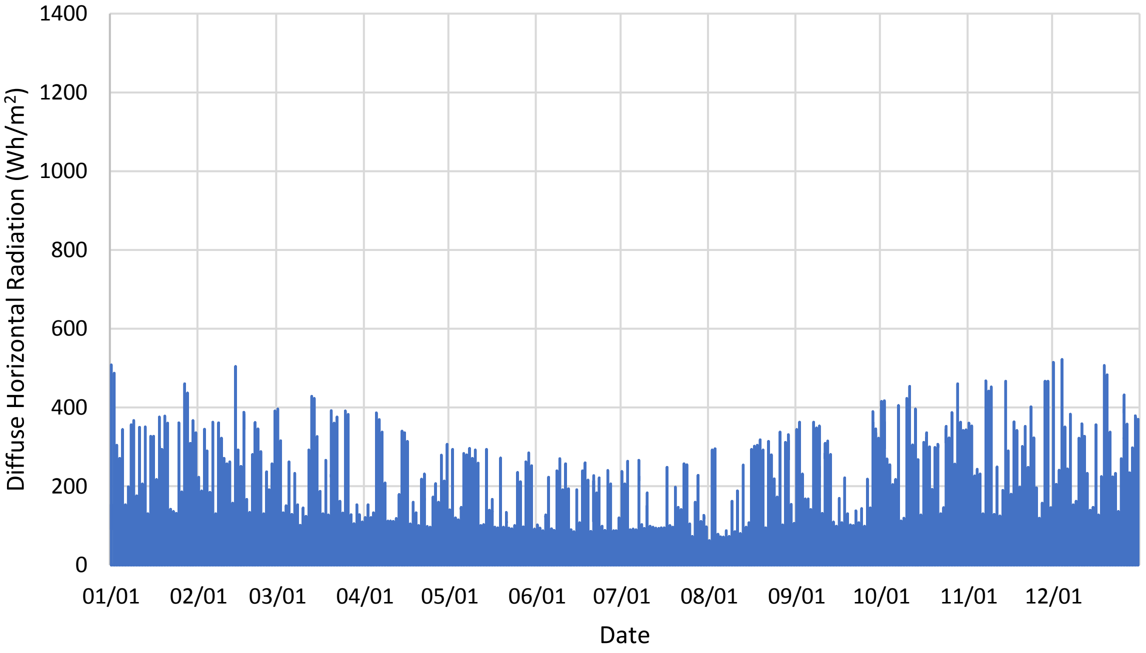
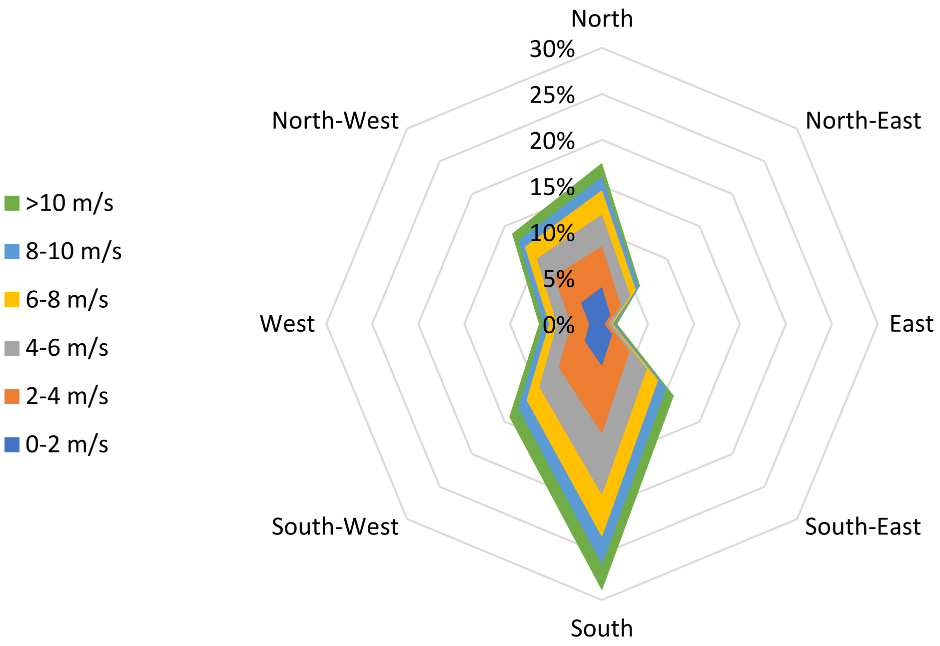
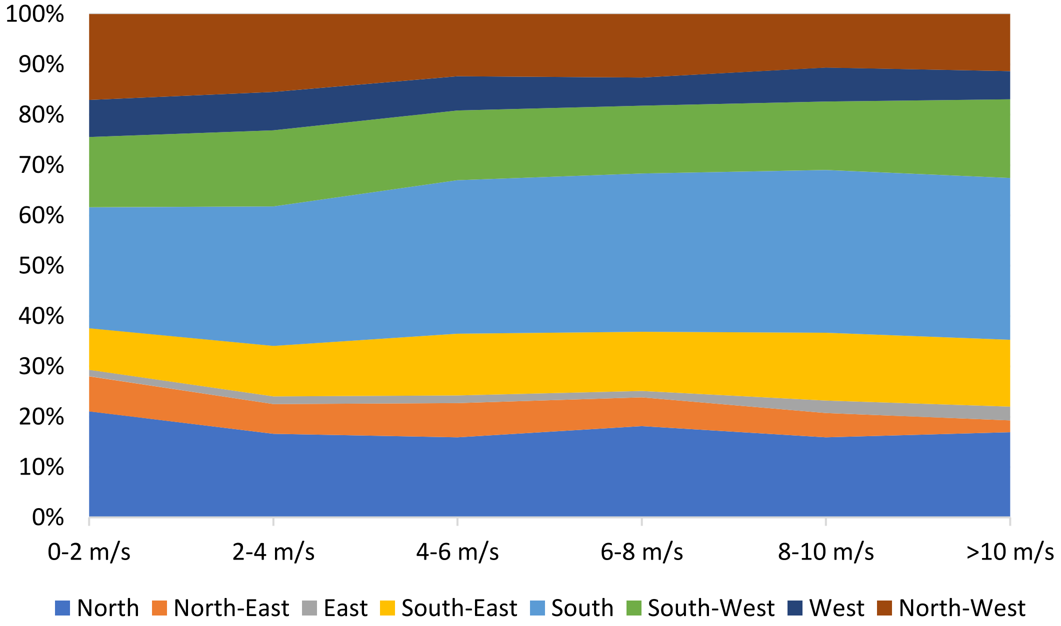


Figure C.17: Diffuse Horizontal Irradiation Data from Cape Town IWEC Data



(a)

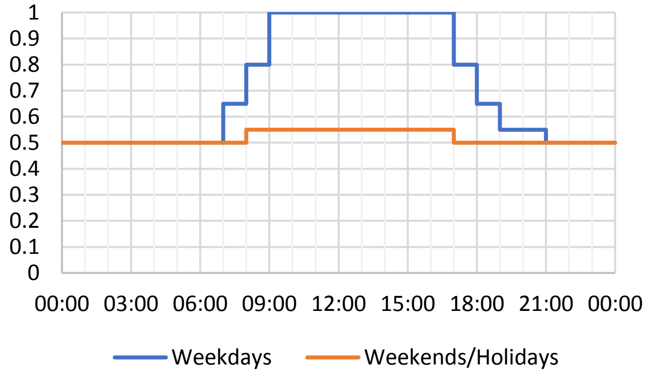


(b)

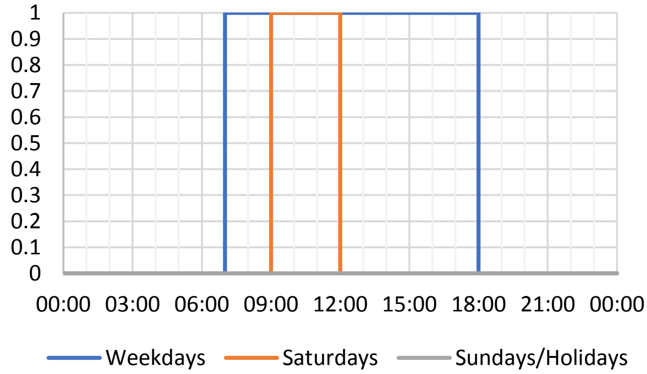
Figure C.18: (a) Wind Rose of Cape Town IWEC Data (b) Wind Speed Within Wind Direction Distribution

C.3 Internal Heat Gains

The schedule of internal heat gains associated with equipment and miscellaneous heat gains for Alice Lane is provided in Figure C.19. The graphs present a visualisation of times when equipment and miscellaneous heat gains are active during weekends/holidays and weekdays. The power density of equipment and miscellaneous heat gains in each zone is presented in Table C.1.



(a)



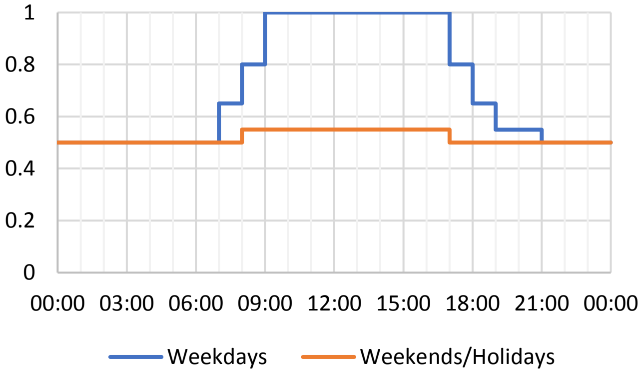
(b)

Figure C.19: (a) Equipment Heat Gains for offices based on Green Building Council of South Africa (GBCSA) recommendations (b) Miscellaneous Heat Gains associated with HVAC systems for offices based on GBCSA recommendations

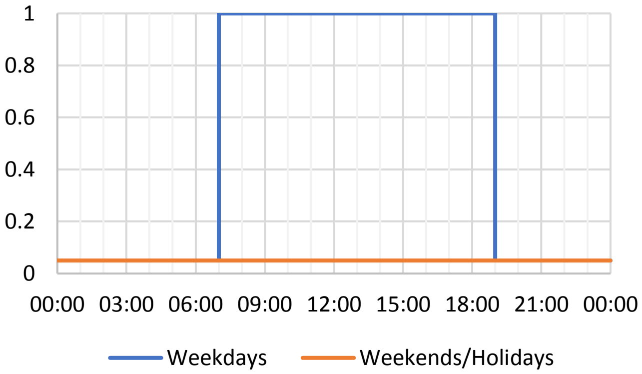
Table C.1: Internal Heat Gain Details of Equipment and Miscellaneous Items in Each Building Zone for Alice Lane

Building Level	Zone	Equipment Power Density (W/m^2)	Miscellaneous Power Density (W/m^2)
Lower Ground	Carpark	0	5.18
Ground Floor	Atrium	0	0
	Common Areas	0	0
	Internal Areas	11	0
	Perimeter	11	0
First to Fourth Floor	Atrium	0	0
	Common Areas	0	5.18
	Internal Areas	11	5.18
	Perimeter	11	5.18
Roof		0	0
Skylights		0	0

The schedule of internal heat gains associated with equipment and miscellaneous heat gains for Bridge Park is provided in Figure C.20. The graphs present a visualisation of times when equipment and miscellaneous heat gains are active during weekdays/holidays and weekdays. The power density of equipment and miscellaneous heat gains in each zone is presented in Table C.2.



(a)



(b)

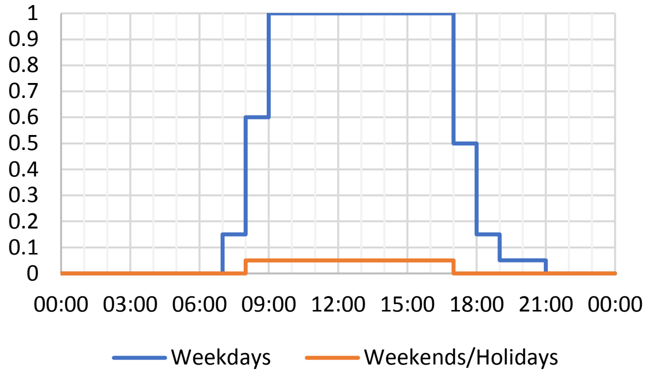
Figure C.20: (a) Equipment Heat Gains for offices based on Green Building Council of South Africa (GBCSA) recommendations (b) Miscellaneous Heat Gains for offices based on GBCSA recommendations

Table C.2: Internal Heat Gain Details of Equipment and Miscellaneous Items in Each Building Zone for Bridge Park

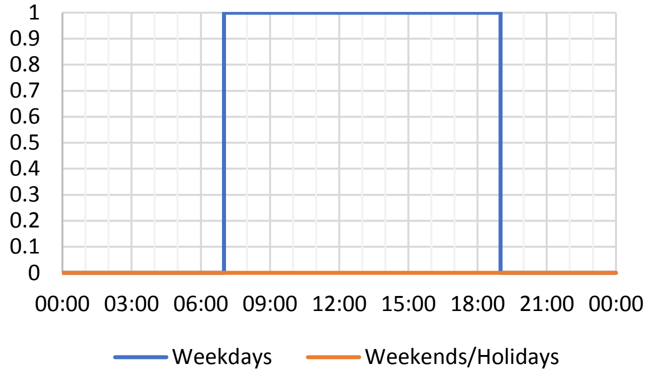
Building Level	Zone	Equipment Power Density (W/m^2)	Miscellaneous Power Density (W/m^2)
Lower Ground		0	0
Ground Level	Common Areas	0	6 and 0
	Ablutions	0	0
	Stairs	0	0
	Internal Areas	11	4 and 3.1
	Perimeter Areas	11	4 and 3.1
First to the Third Floor	Atrium	0	0
	Common Areas	0	0 and 3.1
	Ablutions	0	0
	Stairs	0	0
	Internal Areas	11	3.1
	Perimeter Areas	11	3.1
Clerestory		0	0

C.4 Occupancy

The schedule of zone occupancy for Alice Lane is provided in Figure C.21. The graphs present a visualisation of times when zones are occupied during weekends/holidays and weekdays. The metabolic rate of occupants in each zone is presented in Table C.3.



(a)



(b)

Figure C.21: (a) Occupancy Schedule for offices based on Green Building Council of South Africa (GBCSA) recommendations (b) Occupancy Schedule for offices based on SANS 10400-XA recommendations

Table C.3: Metabolic Rate of Occupants in Each Building Zone for Alice Lane

Building Level	Zone	Metabolic Rate (W)	Persons/m^2	Factor	Heat Gain (W/m^2)
Lower Ground	Carpark	126	0.01	1	1.26
Ground Floor	Atrium	126	0.066	0.9	7.4844
	Common Areas	126	0.066	0.9	7.4844
	Internal Areas	126 and 120	0.066	0.9	7.4844 and 7.128
	Perimeter	126 and 120	0.066	0.9	7.4844 and 7.128
First to Fourth Floor	Atrium	126	0.066	0.9	7.4844
	Common Areas	126	0.066	1	8.316
	Internal Areas	126	0.066	1	8.316
	Perimeter	126	0.066	1	8.316
Roof		126	0.066	0.9	7.4844
Skylights		126	0.066	0.9	7.4844

The schedule of zone occupancy for Bridge Park is provided in Figure C.22. The graphs present a visualisation of times when zones are occupied during weekends/holidays and weekdays. The metabolic rate of occupants in each zone is presented in Table C.4.

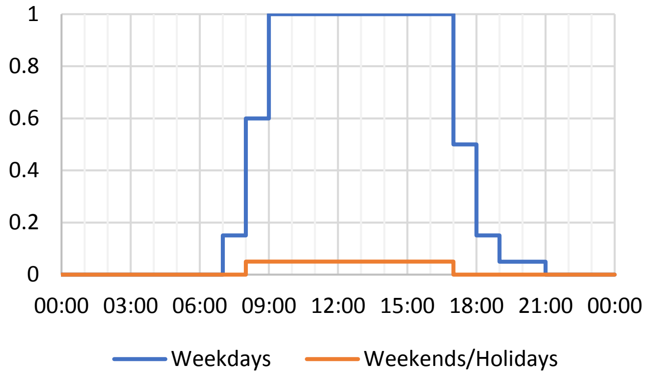


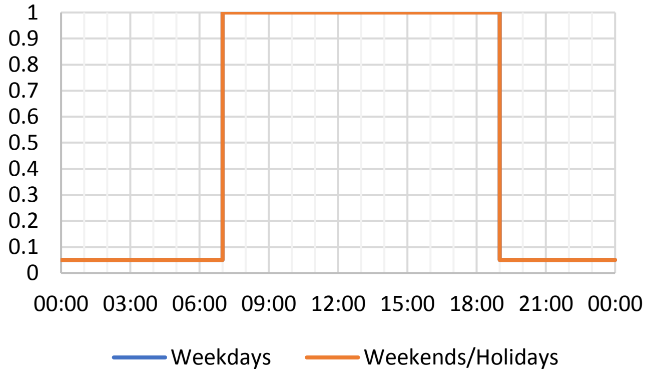
Figure C.22: Occupancy Schedule for offices based on GBCSA recommendations

Table C.4: Metabolic Rate of Occupants in Each Building Zone for Bridge Park

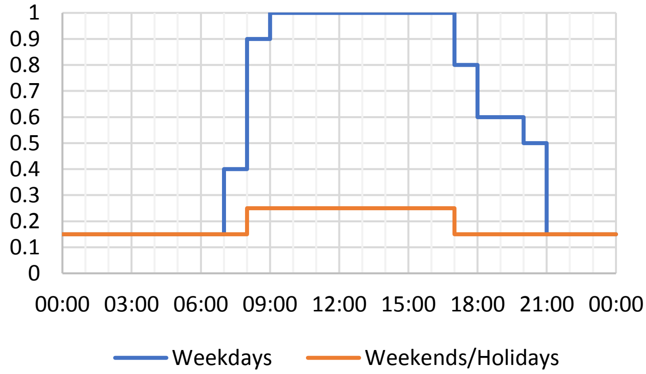
Building Level	Zone	Metabolic Rate (W)	Persons/m^2	Factor	Heat Gain (W/m^2)
Lower Ground		120	0.07	0.9	7.56
Ground Level	Common Areas Ablutions Stairs Internal Areas Perimeter Areas	120	0.07	0.9	7.56
First to the Third Floor	Atrium Common Areas Ablutions Stairs Internal Areas Perimeter Areas	120	0.07	0.9	7.56
Clerestory		120	0.07	0.9	7.56

C.5 Lighting

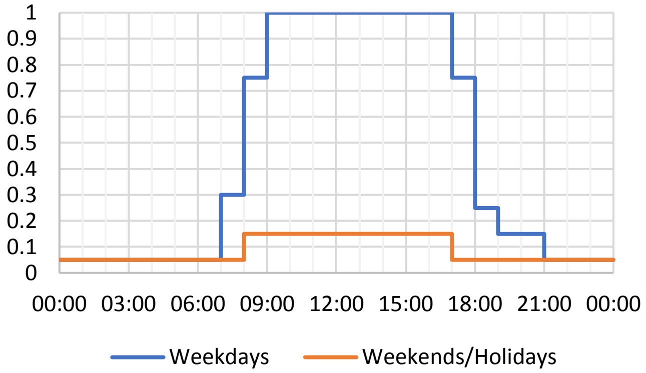
The schedule of zone lighting data for Alice Lane is provided in Figure C.23. Graphs should be read similarly to that of occupancy. The value inside the cells represents the fraction of lighting energy being modelled. Details regarding the heat fractions associated with the lighting are presented in Table C.5.



(a)



(b)



(c)

Figure C.23: (a) Zone Lighting Schedule for the Parking Lot based on Green Building Council of South Africa (GBCSA) recommendations (b) Zone Lighting Schedule for offices based on GBCSA recommendations (c) Zone Lighting Schedule for offices based on GBCSA recommendations with lighting control

Table C.5: Lighting Details of Lighting in Each Building Zone for Alice Lane

Building Level	Zone	Lighting Density (W/m^2)	Luminaire Type	Return Air Fraction	Radiant Fraction	Visible Fraction	Convective Fraction
Lower Ground	Carpark	1.5	Suspended	0.54	0.42	0.18	0.4
Ground Floor	Atrium	0	NA	0	0	0	0
	Common Areas	9	Suspended	0.54	0.42	0.18	0.4
	Internal Areas	7.58	Suspended	0.54	0.42	0.18	0.4
	Perimeter	7.58	Suspended	0.54	0.42	0.18	0.4
First to Fourth Floor	Atrium	0	NA	0	0	0	0
	Common Areas	9	Suspended	0.54	0.42	0.18	0.4
	Internal Areas	7.58	Suspended	0.54	0.42	0.18	0.4
	Perimeter	7.58	Suspended	0.54	0.42	0.18	0.4
Roof		0	NA	0	0	0	0
Skylights		0	NA	0	0	0	0

The schedule of zone lighting data for Bridge Park is provided in Figure C.24. Graphs should be read similarly to that of occupancy. The value inside the cells represents the fraction of lighting energy being modelled. Details regarding the heat fractions associated with the lighting are presented in Table C.6.

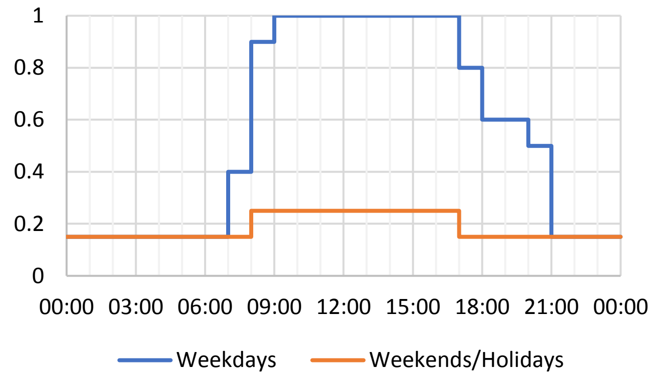


Figure C.24: Zone Lighting Schedule for offices based on GBCSA recommendations

Table C.6: Lighting Details of Lighting in Each Building Zone for Bridge Park

Building Level	Zone	Lighting Density (W/m^2)	Luminaire Type	Return Air Fraction	Radiant Fraction	Visible Fraction	Convective Fraction
Lower Ground		4.5999	Suspended	0.54	0.42	0.18	0.4
Ground Level	Common Areas	2.7	Suspended	0.54	0.42	0.18	0.4
	Ablutions	3.4998	Suspended	0.54	0.42	0.18	0.4
	Stairs	4.8	Suspended	0.54	0.42	0.18	0.4
	Internal Areas	7.8	Suspended	0.54	0.42	0.18	0.4
	Perimeter Areas	7.8	Suspended	0.54	0.42	0.18	0.4
First to the Third Floor	Atrium	0	NA	0	0	0	0
	Common Areas	2.7	Suspended	0.54	0.42	0.18	0.4
	Ablutions	3.4998	Suspended	0.54	0.42	0.18	0.4
	Stairs	4.8 and 2.7	Suspended	0.54	0.42	0.18	0.4
	Internal Areas	7.8	Suspended	0.54	0.42	0.18	0.4
	Perimeter Areas	7.8	Suspended	0.54	0.42	0.18	0.4
Clerestory		0	NA	0	0	0	0

C.6 Heating and Cooling

The schedules of HVAC components data for Alice Lane are provided in Figure C.25. Graphs should be read similar to that of occupancy. The cells' value indicates an on or off indicator, with 1 indicating heating and cooling are scheduled to be active for that time and 0 indicating heating and cooling are scheduled to be inactive. Details regarding zones which was subject to heating/cooling are presented in Table C.7.

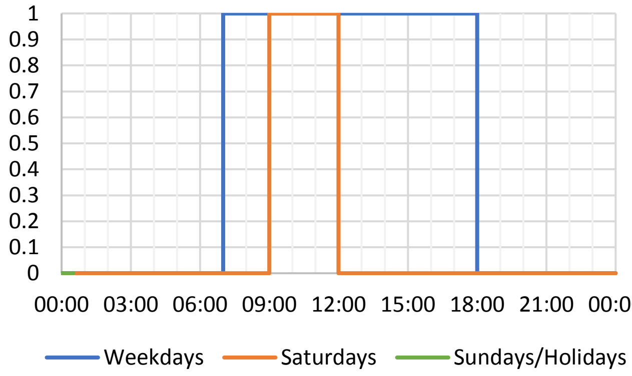


Figure C.25: HVAC schedule for offices based on GBCSA recommendations

Table C.7: HVAC Details of Heating and Cooling in Each Building Zone for Alice Lane

Building Level	Zone	Heated/Cooled?
Lower Ground	Carpark	No
Ground Floor	Atrium	No
	Common Areas	No
	Internal Areas	Yes
	Perimeter	Yes
First to Fourth Floor	Atrium	No
	Common Areas	No
	Internal Areas	Yes
	Perimeter	Yes
Roof		No
Skylights		No

The schedules of HVAC components data for Bridge Park are provided in Figure C.26. Graphs should be read similar to that of occupancy. The cells' value indicates an on or off indicator, with 1 indicating heating and cooling are scheduled to be active for that time and 0 indicating heating and cooling are scheduled to be inactive. Details regarding zones which was subject to heating/cooling are presented in Table C.8.

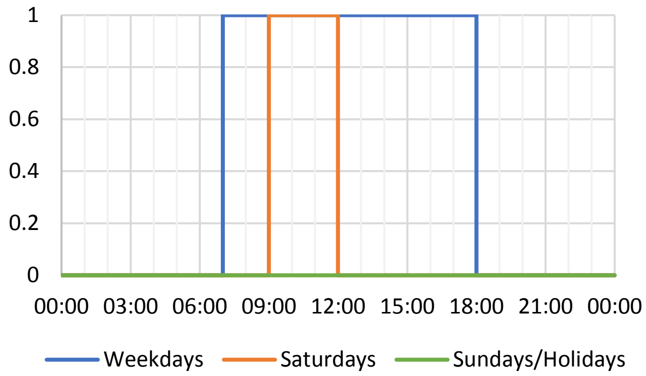


Figure C.26: HVAC schedule for offices based on GBCSA recommendations

Table C.8: HVAC Details of Heating and Cooling in Each Building Zone for Bridge Park

Building Level	Zone	Heated/Cooled?
Lower Ground		No
Ground Level	Common Areas	Yes
	Ablutions	No
	Stairs	No
	Internal Areas	Yes
	Perimeter Areas	Yes
First to the Third Floor	Atrium	No
	Common Areas	Yes
	Ablutions	No
	Stairs	No
	Internal Areas	Yes
	Perimeter Areas	Yes
Clerestory		No

C.7 Air Infiltration/Leakage

Details regarding which Alice Lane Office building zones are subject to air infiltration/leakage are summarised in Table C.9.

Table C.9: Air Leakage/Infiltration Details of Alice Lane

Building Level	Zone	Air Infiltration/Leakage Present?
Lower Ground	Carpark	Yes
Ground Floor	Atrium	Yes
	Common Areas	No
	Internal Areas	No
	Perimeter	Yes
First to Fourth Floor	Atrium	Yes
	Common Areas	Zone Dependent
	Internal Areas	Zone Dependent
	Perimeter	Yes
Roof		Yes
Skylights		Yes

Details regarding which zones of the Bridge Park Office building is subject to air infiltration/leakage are summarised in Table C.10.

Table C.10: Air Leakage/Infiltration Details of Bridge Park

Building Level	Zone	Air Infiltration/Leakage Present?
Lower Ground		Yes
Ground Level	Common Areas	No
	Ablutions	No
	Stairs	Yes
	Internal Areas	No
	Perimeter Areas	Yes
First to the Third Floor	Atrium	No
	Common Areas	No
	Ablutions	No
	Stairs	Yes
	Internal Areas	No
	Perimeter Areas	Yes
Clerestory		No

C.8 Parametric Analysis

The parametric analysis consists of changing one of five variables. Three thermal bulk properties are investigated: conductivity, specific heat capacity, and density. Only the WWR of the building envelope is adjusted to investigate the influence of WWR. The SHGC is changed while keeping other thermal properties and WWR untouched to investigate the SHGC of external glazing. An overview of the models analysed is presented in Tables C.11 to C.15.

Table C.11: Configurations for Parametric Analysis of Thermal Conductivity

Configuration No.	Conductivity (W/(m.K))	Specific Heat (J/(kg.K))	Density (kg/m^3)
1	0.05	840	1920
2	0.235		
3	0.42		
4	0.605		
5	0.79		
6	0.975		
7	1.16		
8	1.345		
9	1.53		
10	1.715		

Table C.12: Configurations for Parametric Analysis of Specific Heat Capacity

Configuration No.	Conductivity (W/(m.K))	Specific Heat (J/(kg.K))	Density (kg/m^3)
1	0.72	100	1920
2		350	
3		600	
4		850	
5		1100	
6		1350	
7		1600	
8		1850	
9		2100	
10		2350	

Table C.13: Configurations for Parametric Analysis of Density

Configuration No.	Conductivity (W/(m.K))	Specific Heat (J/(kg.K))	Density (kg/m^3)
1	0.72	840	10
2			260
3			510
4			760
5			1010
6			1260
7			1510
8			1760
9			2010
10			2260

Table C.14: Configurations for Parametric Analysis of SHGC

Configuration No.	SHGC
1	0.1
2	0.2
3	0.3
4	0.4
5	0.5
6	0.6
7	0.7
8	0.8

Table C.15: Configurations for Parametric Analysis of Window-to-Wall Ratio

Configuration No.	Window-to-Wall Ratio (%)
1	0
2	10
3	20
4	30
5	40
6	50
7	60
8	70
9	80
10	90
11	100

Appendix D: Data Inputs for Chapter 4

The following data was used as input for the analysis of models simulated in Chapter 4.

D.1 Weather Data

Weather data used to analyse the RDP building's thermal performance is presented in Figures D.1 to D.9.

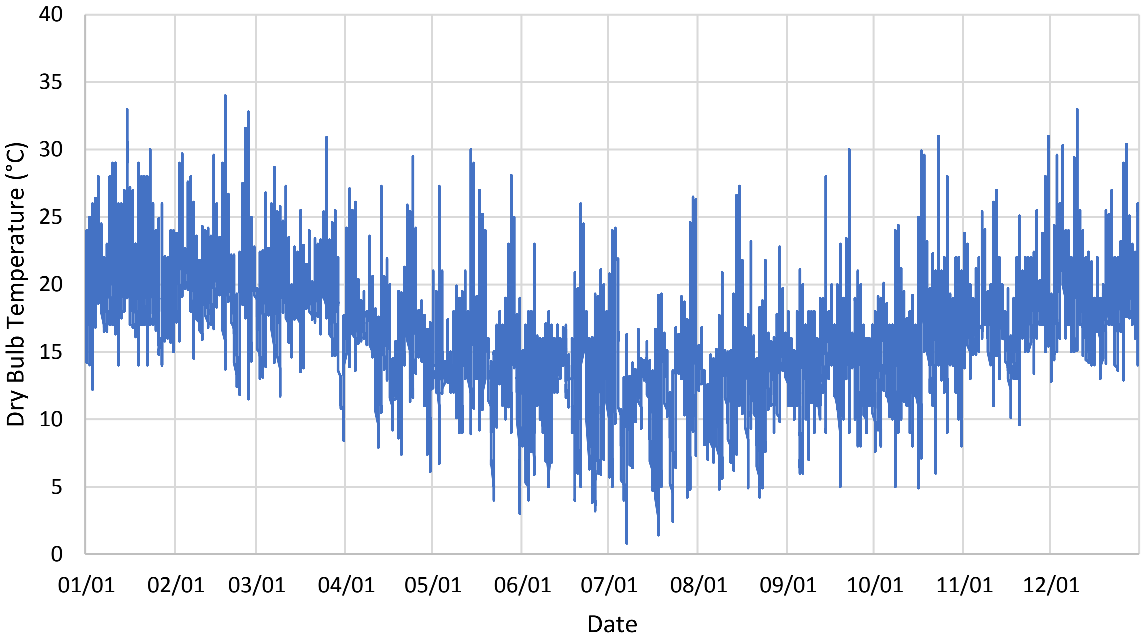


Figure D.1: Dry Bulb Temperature Data from Cape Town IWEC Data

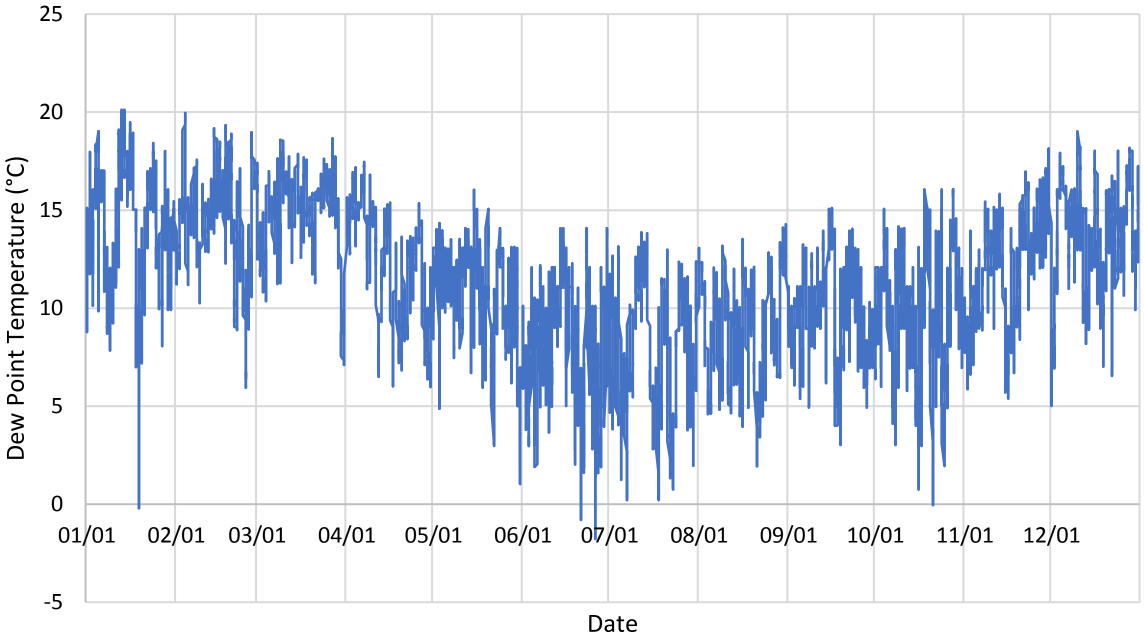


Figure D.2: Dew Point Temperature Data from Cape Town IWEC Data

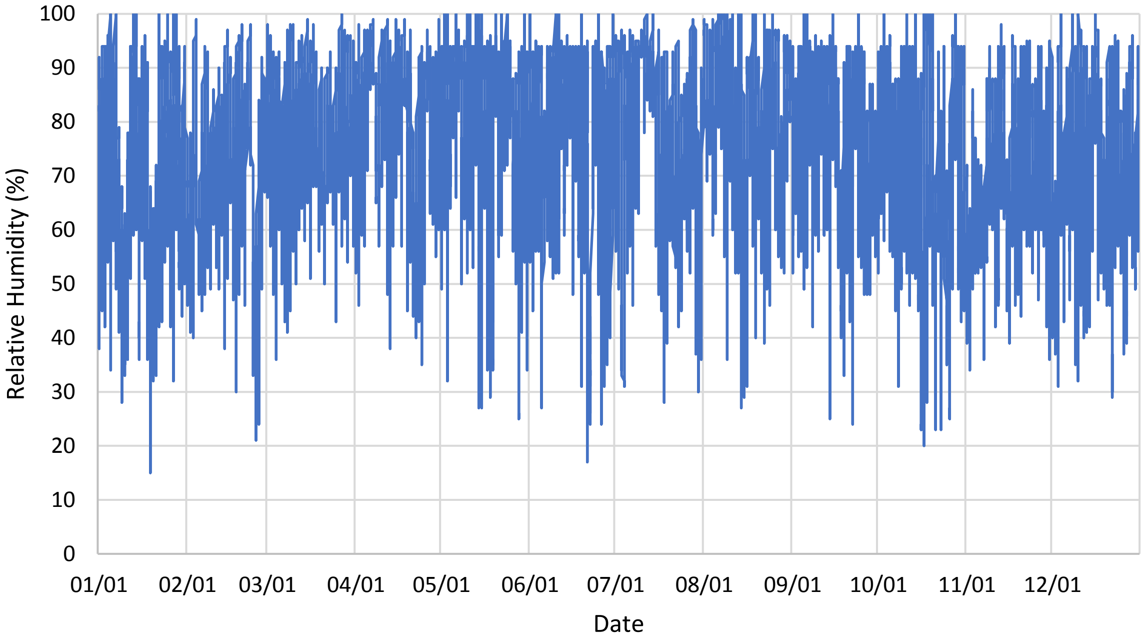


Figure D.3: Relative Humidity Data from Cape Town IWEC Data

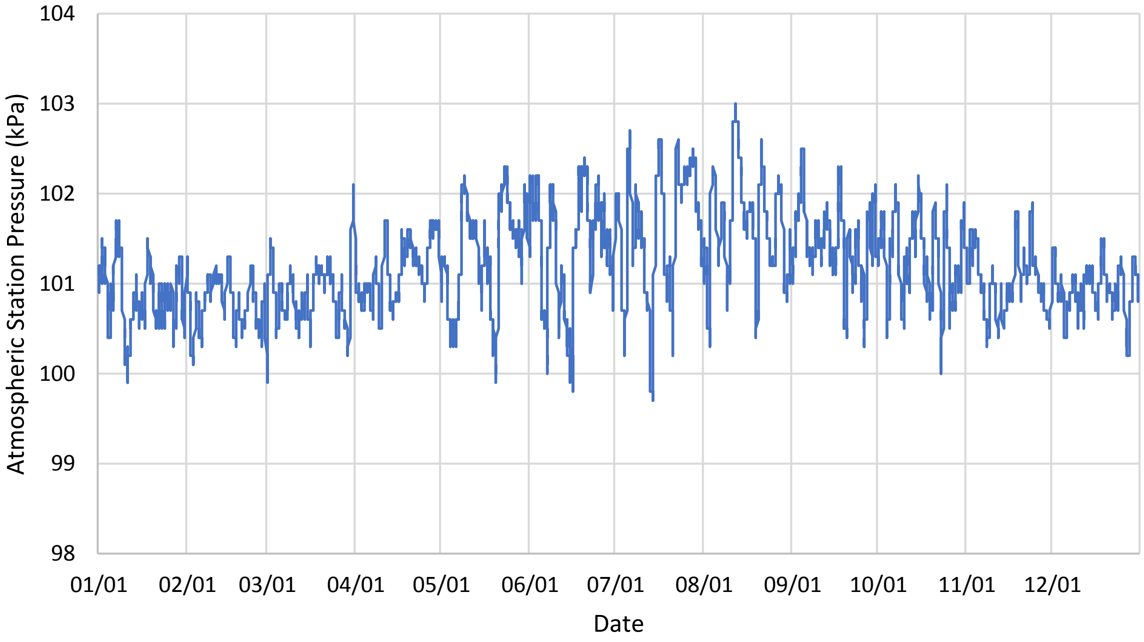


Figure D.4: Atmospheric Station Pressure Data from Cape Town IWEC Data

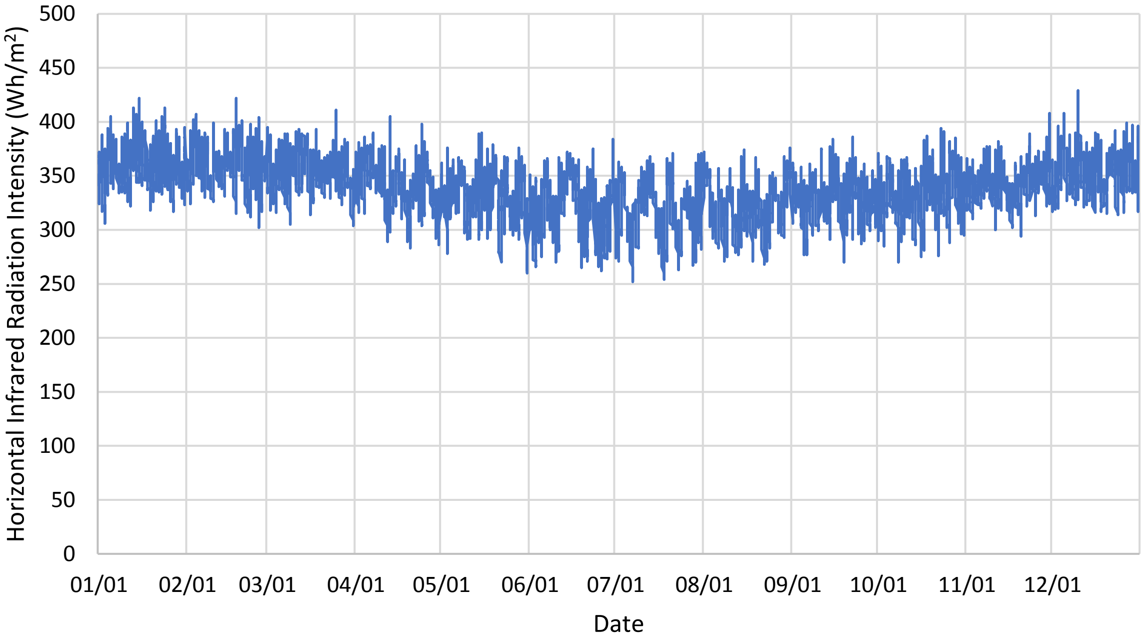


Figure D.5: Horizontal Infrared Radiation Intensity Data from Cape Town IWEC Data

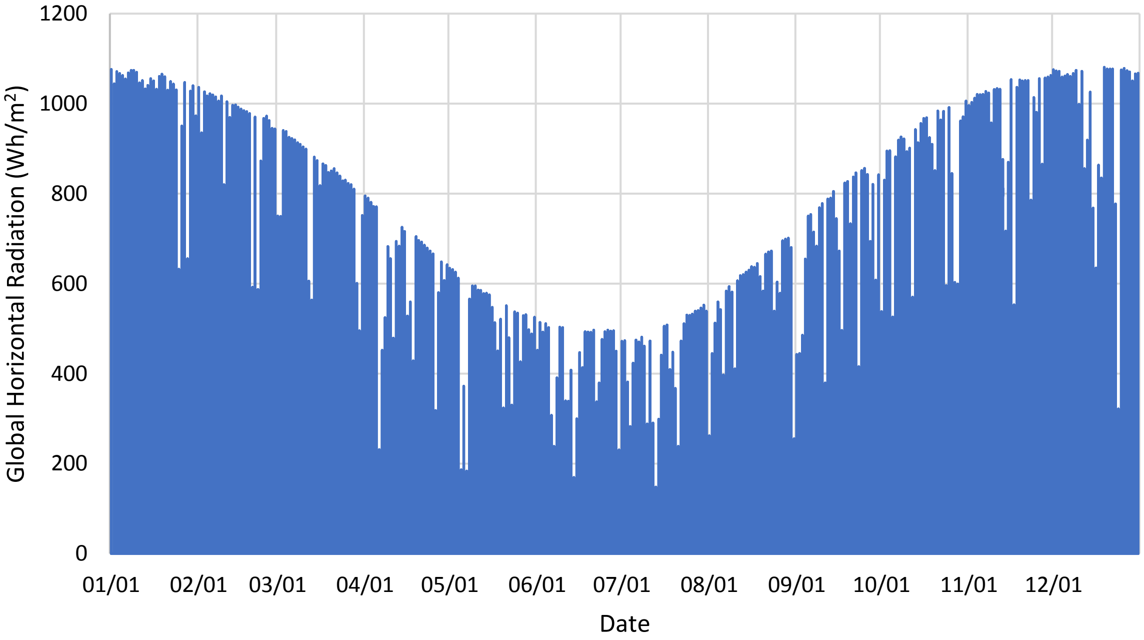


Figure D.6: Global Horizontal Irradiation Data from Cape Town IWEC Data

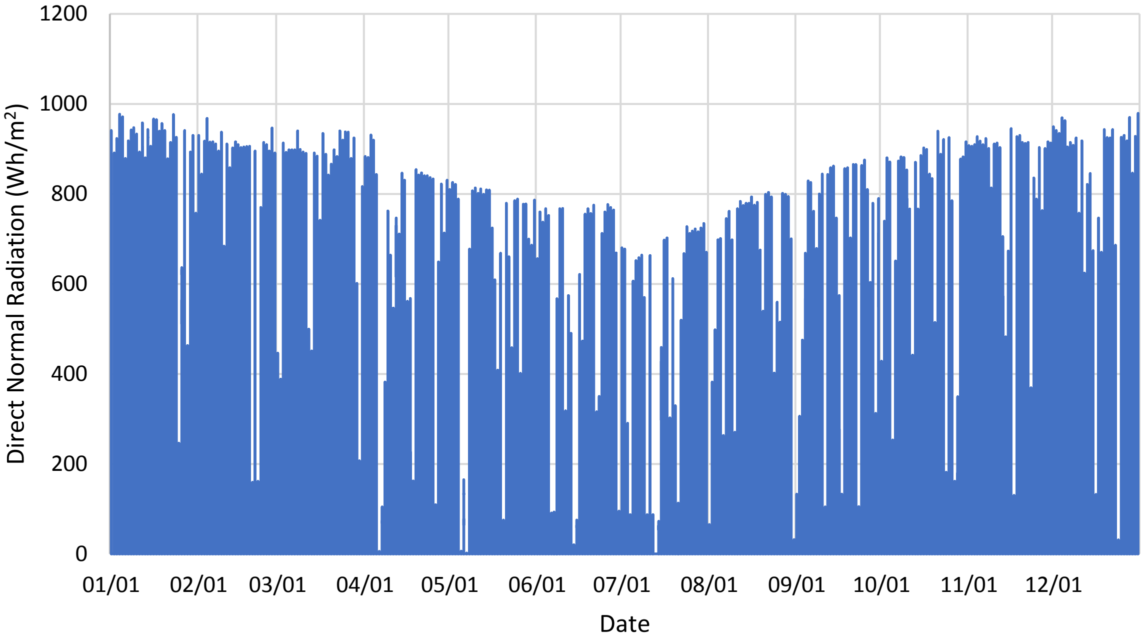


Figure D.7: Direct Normal Irradiation Data from Cape Town IWEC Data

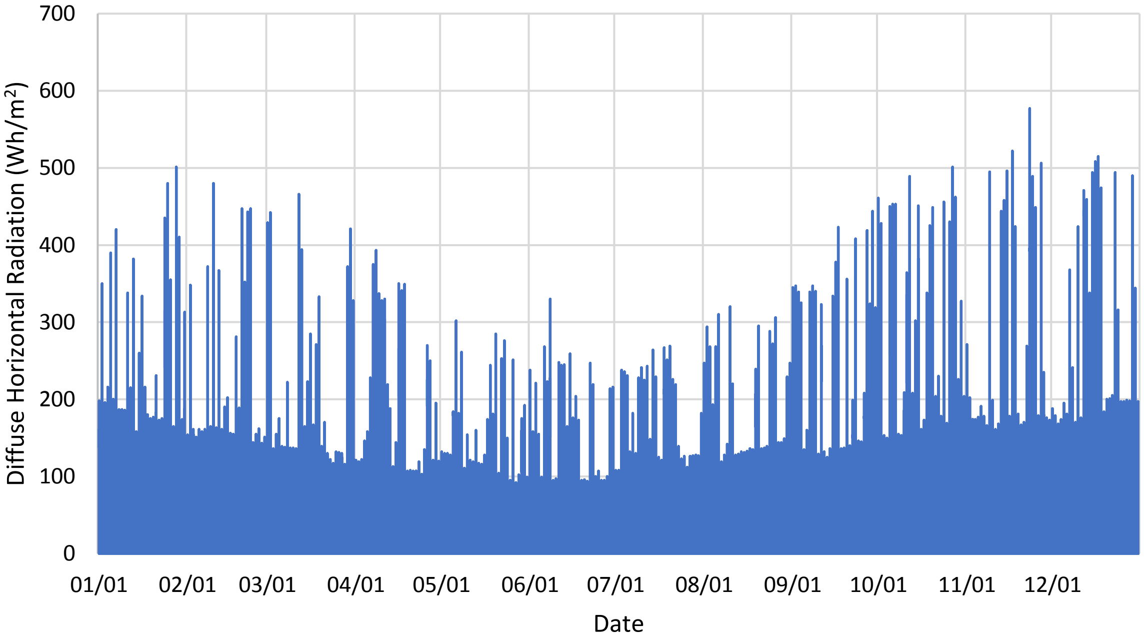
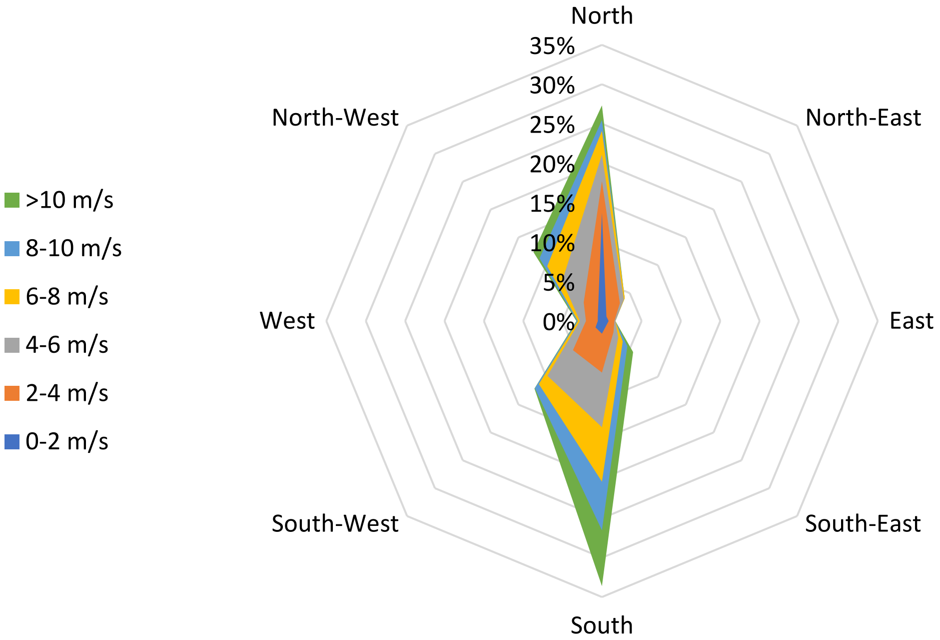
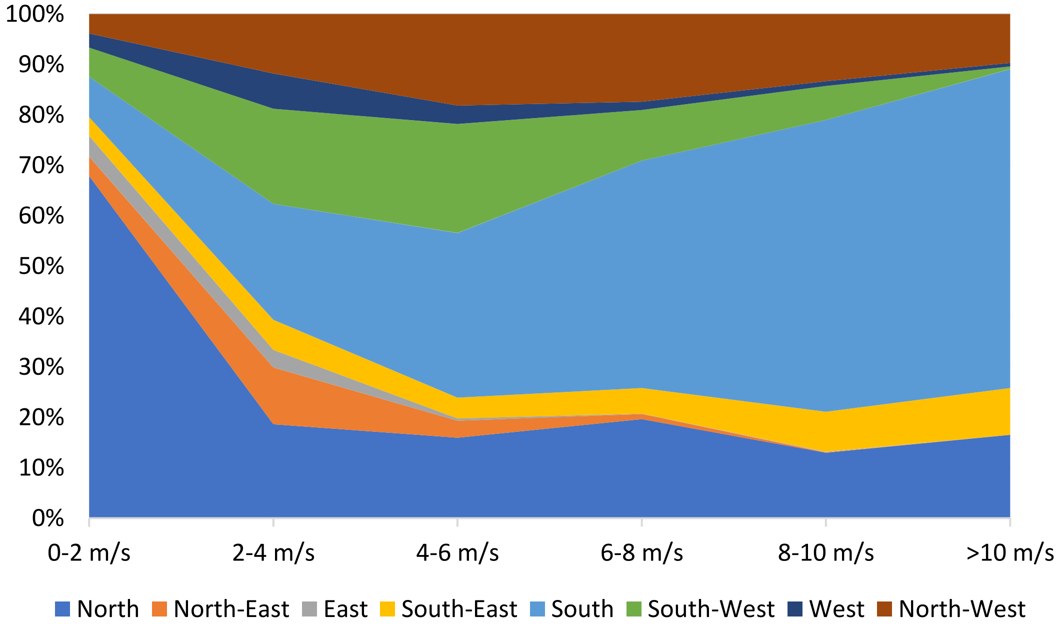


Figure D.8: Diffuse Horizontal Irradiation Data from Cape Town IWEC Data



(a)

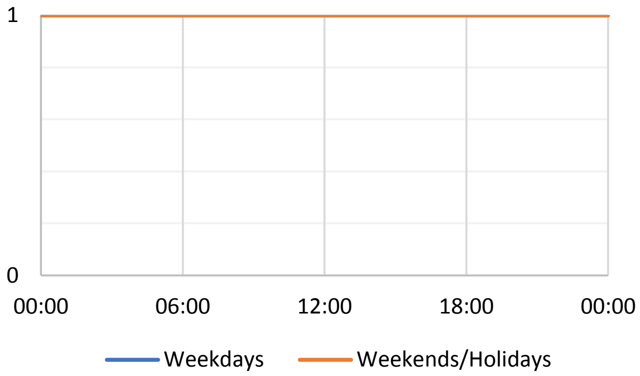


(b)

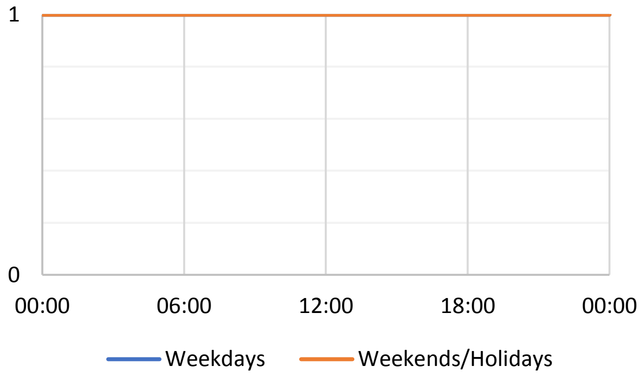
Figure D.9: (a) Wind Rose of Cape Town IWEC Data (b) Wind Speed Within Wind Direction Distribution

D.2 Occupancy

The schedule of zone occupancy is provided in Figure D.10. The graphs present a visualisation of times when zones are occupied during weekdays/holidays and weekdays. The metabolic rate of occupants in each zone is presented in Table D.1.



(a)



(b)

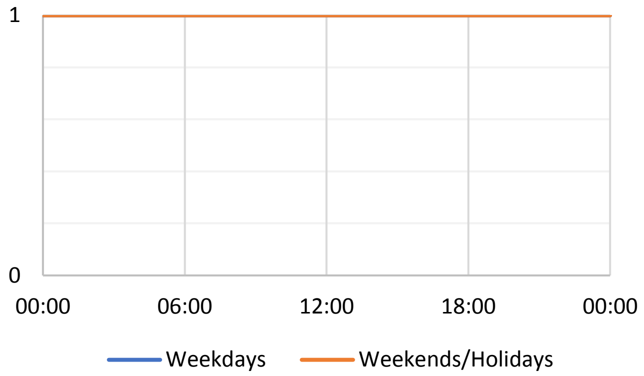
Figure D.10: (a) Zone Occupancy Schedule During Summer (b) Zone Occupancy Schedule During Winter

Table D.1: Metabolic Rate of Occupants in Each Building Zone

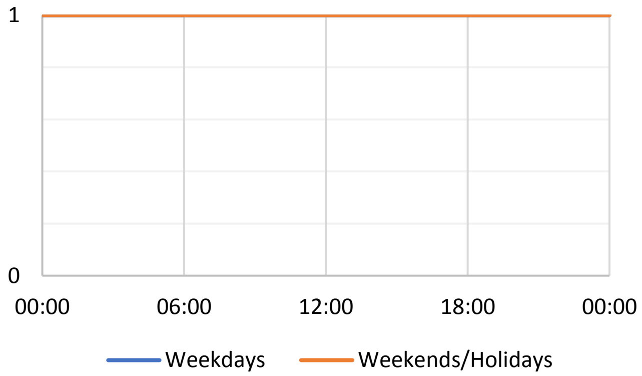
Zone	Metabolic Rate (W)
Kitchen North Bedroom South Bedroom Lounge Bathroom	75

D.3 Lighting

The schedule of zone lighting data is provided in Figure D.11. Graphs should be read similarly to that of occupancy. The value inside the cells represents the fraction of lighting energy being modelled. Details regarding the heat fractions associated with the lighting are presented in Table D.2.



(a)



(b)

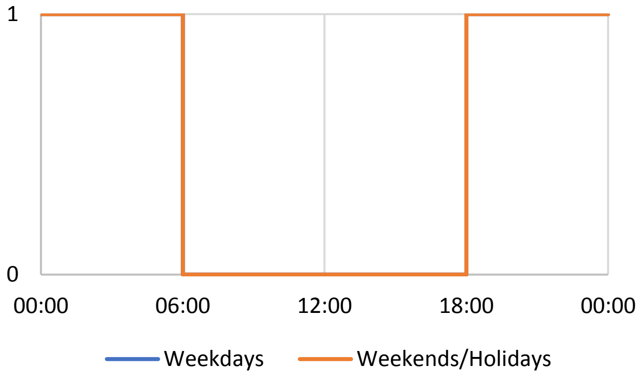
Figure D.11: (a) Zone Lighting Schedule During Summer (b) Zone Lighting Schedule During Winter

Table D.2: Lighting Details of Lighting in Each Building Zone

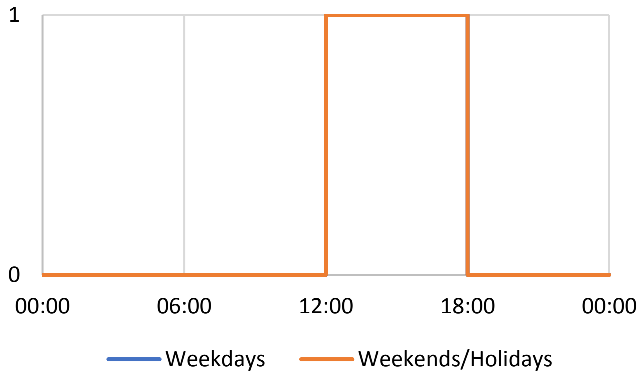
Zone	Absolute Zone Power (W)	Luminaire Type	Return Air Fraction	Radiant Fraction	Visible Fraction	Convective Fraction
Kitchen North Bedroom South Bedroom Lounge Bathroom	5	Surface Mount	0	0.72	0.18	0.1

D.4 Ventilation

The schedules of ventilation components data are provided by Figures D.12 and D.13. Graphs should be read similarly to that of occupancy. The value inside the cells indicates an on or off indicator, with 1 indicating ventilation components are scheduled to be opened for that time and 0 indicating ventilation components are scheduled to be closed for that time. Free aperture details of door openings are presented in Table D.3.

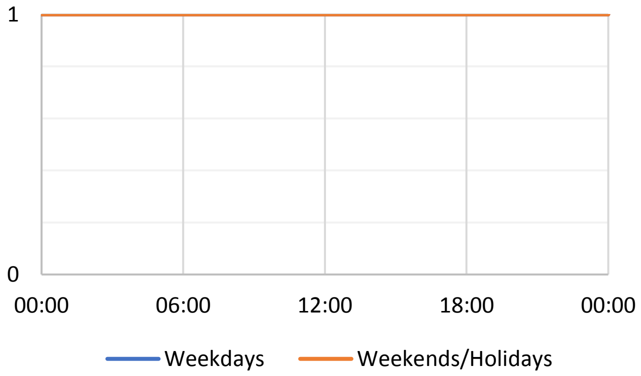


(a)

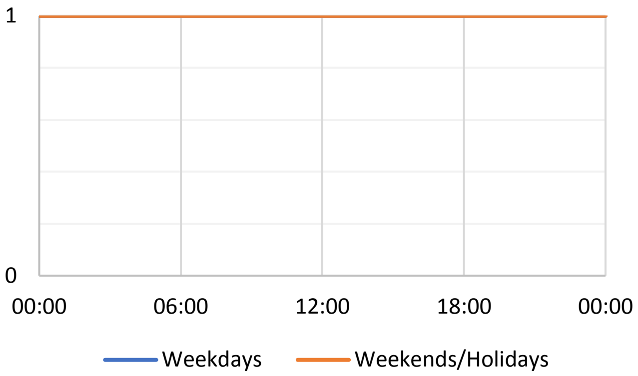


(b)

Figure D.12: (a) Zone Window Opening Schedule During Summer (b) Zone Window Opening Schedule During Winter



(a)



(b)

Figure D.13: (a) Zone Door Opening Schedule During Summer (b) Zone Door Opening Schedule During Winter

Table D.3: Free Aperture Details of Door Openings in Each Building Zone

Zone	% Area Door Opens	% Time Door is Open	Construction
North Bedroom	100	100	Internal Door
South Bedroom	100	100	Internal Door
Lounge	0	0	External Door
Bathroom	100	100	Internal Door

D.5 Material Properties

The material properties of opaque building components are summarised in Tables D.4 to D.7. A visual representation of the moisture transfer properties of building materials is presented in Figure D.14.

Table D.4: Thermal Bulk Properties of the Building Materials of the RDP House

Material	Conductivity (W/(m.K))	Specific Heat (J/(kg.K))	Density (kg/m^3)
Hardwood	0.17	1880	700
Hardboard	0.13	2000	900
Cement Mortar	0.854	840	1822
Lightweight Concrete	0.511	840	1187
Mediumweight Cast Concrete	0.8	840	1300
Cement Screed	1.4	650	2100
Glass Wool	0.037	840	16
Gypsum Plasterboard	0.25	1000	900
Metals - Steel	45	480	7800

Table D.5: Surface Properties of the Building Materials of the RDP House

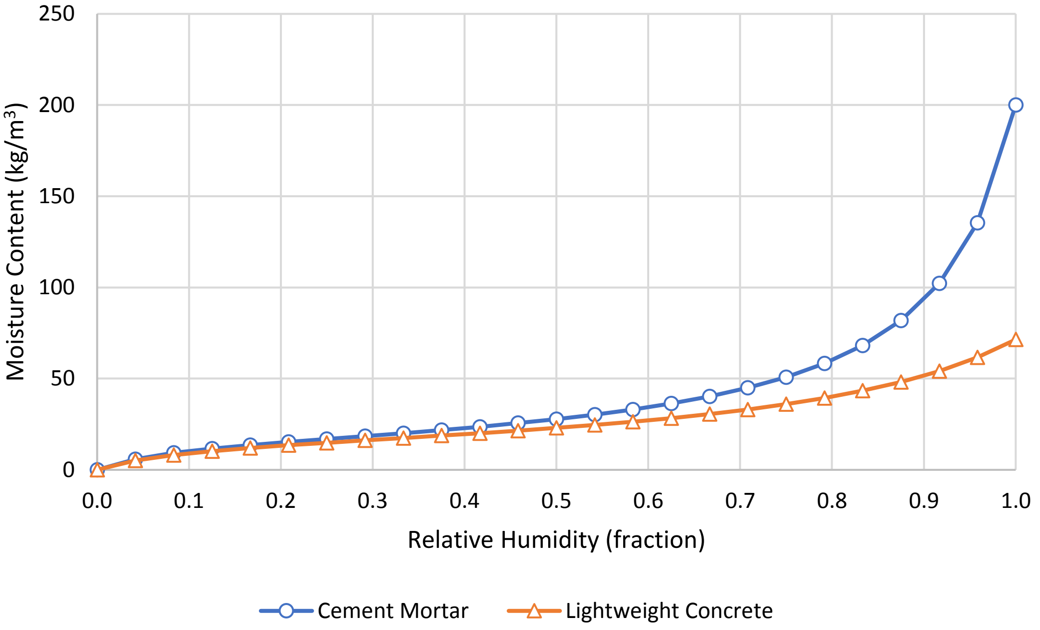
Material	Thermal Absorptance (Emissivity)	Solar Absorptance	Visible Absorptance	Roughness
Hardwood	0.9	0.6	0.6	Rough
Hardboard	0.9	0.78	0.78	Rough
Cement Mortar	0.9	0.6	0.6	Rough
Lightweight Concrete	0.9	0.6	0.6	Rough
Mediumweight Cast Concrete	0.9	0.6	0.6	Rough
Cement Screed	0.9	0.6	0.6	Rough
Glass Wool	0.9	0.6	0.6	Rough
Gypsum Plasterboard	0.9	0.5	0.5	Rough
Metals - Steel	0.9	0.6	0.6	Rough

Table D.6: Moisture Transfer Properties of Cement Mortar of the RDP House

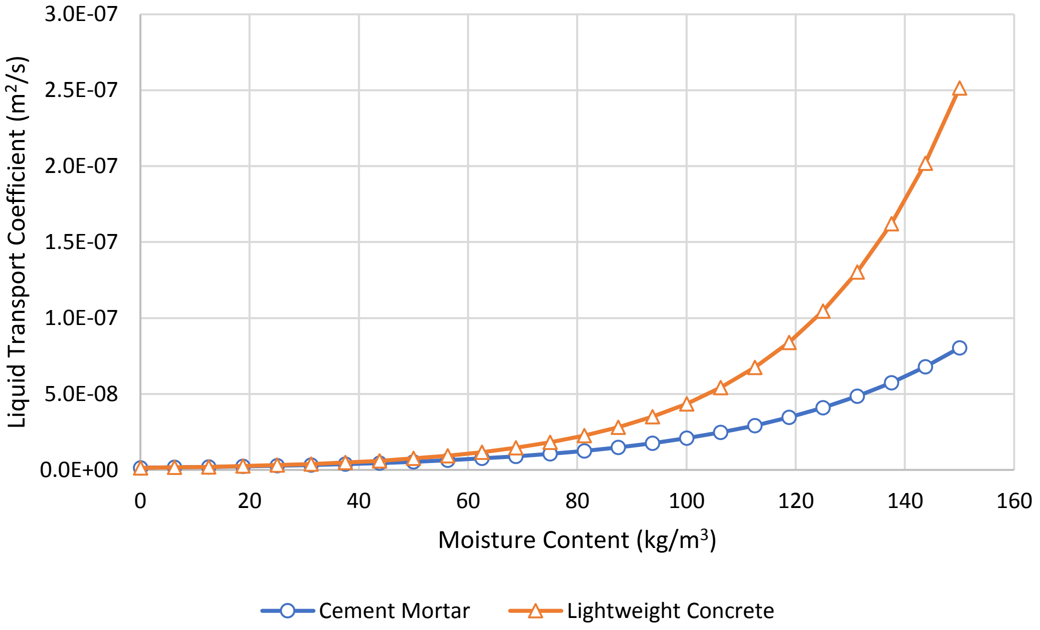
Sorption Isotherm		Suction/Redistribution		Diffusion		Thermal Conductivity	
Relative Humidity (fraction)	Moisture Content (kg/m^3)	Moisture Content (kg/m^3)	Liquid Transport Coefficient (m^2/s)	Relative Humidity (fraction)	Diffusion Resistance Factor	Moisture Content (kg/m^3)	Conductivity (W/(m.K))
0	0	0	1.400E-09	0	12.606	0	0.854
0.042	5.892	6.25	1.657E-09	0.042	12.543	6.25	0.882
0.083	9.286	12.5	1.962E-09	0.083	12.472	12.5	0.910
0.125	11.696	18.75	2.323E-09	0.125	12.389	18.75	0.938
0.167	13.638	25	2.750E-09	0.167	12.295	25	0.967
0.208	15.344	31.25	3.255E-09	0.208	12.187	31.25	0.995
0.250	16.949	37.5	3.853E-09	0.250	12.064	37.5	1.023
0.292	18.528	43.75	4.562E-09	0.292	11.924	43.75	1.051
0.333	20.133	50	5.400E-09	0.333	11.766	50	1.079
0.375	21.818	56.25	6.393E-09	0.375	11.586	56.25	1.107
0.417	23.624	62.5	7.568E-09	0.417	11.385	62.5	1.135
0.458	25.590	68.75	8.960E-09	0.458	11.160	68.75	1.163
0.500	27.778	75	1.061E-08	0.500	10.908	75	1.192
0.542	30.246	81.25	1.256E-08	0.542	10.630	81.25	1.220
0.583	33.068	87.5	1.486E-08	0.583	10.324	87.5	1.248
0.625	36.364	93.75	1.760E-08	0.625	9.990	93.75	1.276
0.667	40.272	100	2.083E-08	0.667	9.628	100	1.304
0.708	44.989	106.25	2.466E-08	0.708	9.239	106.25	1.332
0.750	50.847	112.5	2.919E-08	0.750	8.824	112.5	1.360
0.792	58.319	118.75	3.456E-08	0.792	8.386	118.75	1.388
0.833	68.173	125	4.091E-08	0.833	7.930	125	1.417
0.875	81.871	131.25	4.844E-08	0.875	7.457	131.25	1.445
0.917	102.187	137.5	5.734E-08	0.917	6.974	137.5	1.473
0.958	135.392	143.75	6.788E-08	0.958	6.486	143.75	1.501
1	200	150	8.036E-08	1	5.998	150	1.529

Table D.7: Moisture Transfer Properties of lightweight concrete of the Generic RDP House

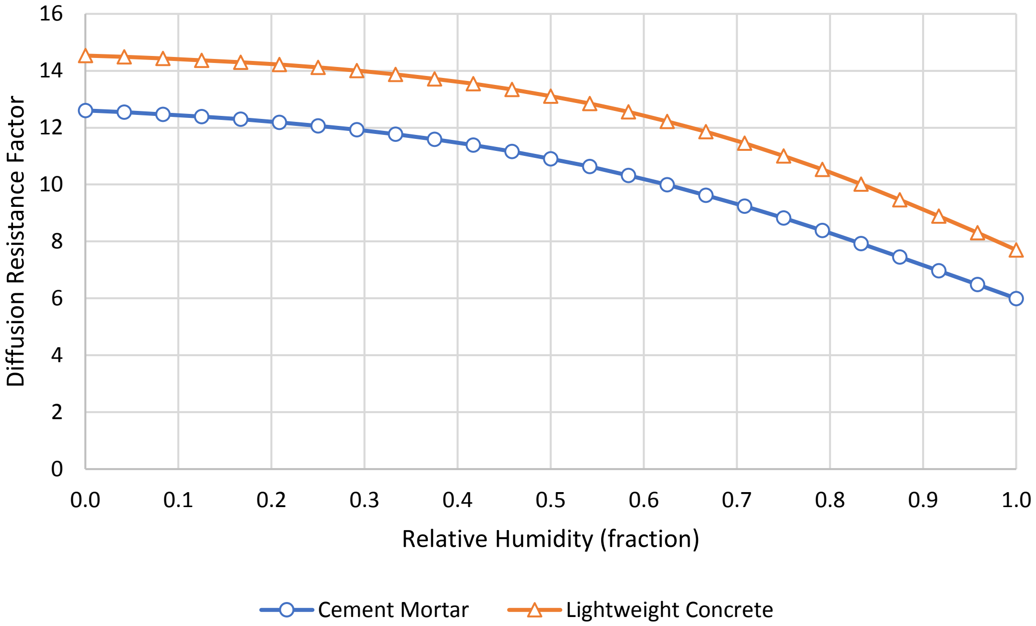
Sorption Isotherm		Suction/Redistribution		Diffusion		Thermal Conductivity	
Relative Humidity (fraction)	Moisture Content (kg/m^3)	Moisture Content (kg/m^3)	Liquid Transport Coefficient (m^2/s)	Relative Humidity (fraction)	Diffusion Resistance Factor	Moisture Content (kg/m^3)	Conductivity (W/(m.K))
0	0	0	1.300E-09	0	14.533	0	0.511
0.042	5.078	6.25	1.619E-09	0.042	14.487	6.25	0.527
0.083	8.123	12.5	2.016E-09	0.083	14.434	12.5	0.543
0.125	10.296	18.75	2.511E-09	0.125	14.372	18.75	0.559
0.167	12.025	25	3.126E-09	0.167	14.299	25	0.575
0.208	13.511	31.25	3.893E-09	0.208	14.215	31.25	0.591
0.250	14.870	37.5	4.848E-09	0.250	14.116	37.5	0.607
0.292	16.166	43.75	6.037E-09	0.292	14.002	43.75	0.623
0.333	17.441	50	7.518E-09	0.333	13.870	50	0.639
0.375	18.735	56.25	9.363E-09	0.375	13.717	56.25	0.654
0.417	20.075	62.5	1.166E-08	0.417	13.541	62.5	0.670
0.458	21.481	68.75	1.452E-08	0.458	13.340	68.75	0.686
0.500	22.989	75	1.808E-08	0.500	13.110	75	0.702
0.542	24.621	81.25	2.252E-08	0.542	12.849	81.25	0.718
0.583	26.405	87.5	2.804E-08	0.583	12.555	87.5	0.734
0.625	28.389	93.75	3.492E-08	0.625	12.225	93.75	0.750
0.667	30.614	100	4.348E-08	0.667	11.858	100	0.766
0.708	33.134	106.25	5.415E-08	0.708	11.453	106.25	0.782
0.750	36.036	112.5	6.743E-08	0.750	11.009	112.5	0.798
0.792	39.419	118.75	8.397E-08	0.792	10.528	118.75	0.814
0.833	43.412	125	1.046E-07	0.833	10.014	125	0.830
0.875	48.234	131.25	1.302E-07	0.875	9.468	131.25	0.846
0.917	54.170	137.5	1.622E-07	0.917	8.896	137.5	0.862
0.958	61.649	143.75	2.019E-07	0.958	8.306	143.75	0.878
1	71.429	150	2.515E-07	1	7.703	150	0.894


Moisture Content (kg/m³)
250
200
150
100
50
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Relative Humidity (fraction)
Cement Mortar
Lightweight Concrete

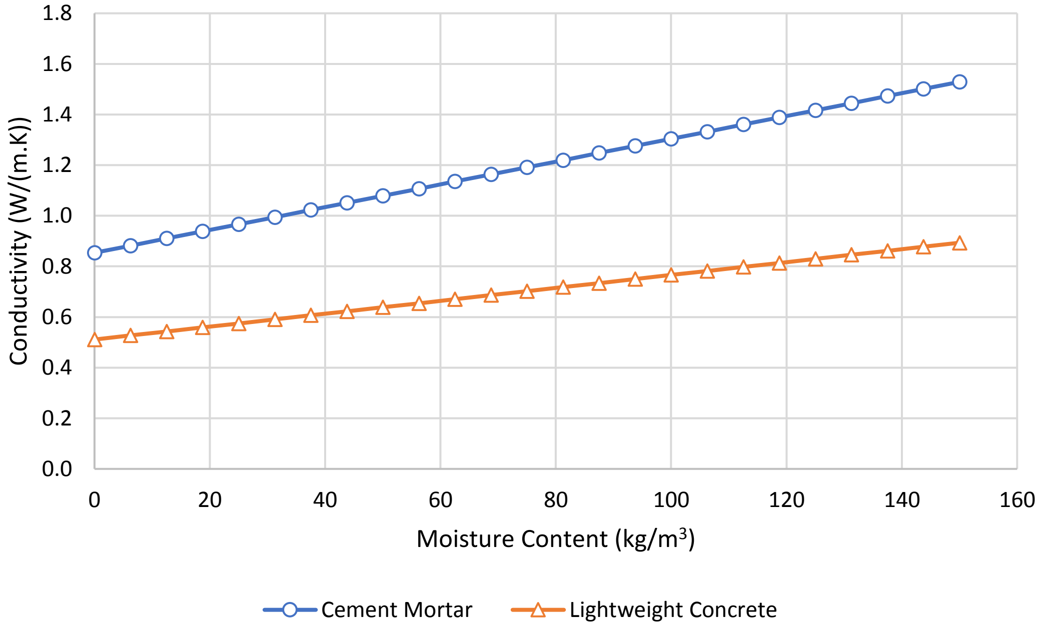
(a)


Liquid Transport Coefficient (m²/s)
3.0E-07
2.5E-07
2.0E-07
1.5E-07
1.0E-07
5.0E-08
0.0E+00
0
20
40
60
80
100
120
140
160
Moisture Content (kg/m³)
Cement Mortar
Lightweight Concrete

(b)



(c)



(d)

Figure D.14: (a) Sorption isotherm of RDP House Materials (b) Liquid Transport Coefficient Values of RDP House Materials (c) Diffusion Resistance Factor Values of RDP House Materials (d) Moisture Dependent Thermal Conductivity Values of RDP House Materials

Details regarding building construction layers and thickness are presented in Table D.8.

Table D.8: Building Construction Details of the RDP House

Construction	Material Layer	Thickness (m)
Wooden Window Frame	Hardwood	0.02
Internal Door	Hardboard	0.04
External Door	Hardwood	0.04
External Wall	Cement Mortar	0.012
	Lightweight Concrete	0.14
	Cement Mortar	0.012
Internal Wall	Cement Mortar	0.012
	Lightweight Concrete	0.09
	Cement Mortar	0.012
Ground Floor	Mediumweight Cast Concrete	0.075
	Cement Screed	0.02
Ceiling	Glass Wool	0.13
	Gypsum Plasterboard	0.0064
Roof	Metals - Steel	0.0005

The material properties of transparent building components are summarised in Table D.9. Details regarding the window frame, reveal, and free aperture of window openings are summarised in Table D.10.

Table D.9: Glazing Properties of the Clear 4mm glass of the Generic RDP House

Glazing Property	Variable	Value
Thermal Properties	Thickness (mm)	4
	Conductivity (W/(m.K))	1
Solar Properties	Solar Transmittance	0.816
	Outside Solar Reflectance	0.075
	Inside Solar Reflectance	0.075
Visible Properties	Visible Transmittance	0.892
	Outside Visible Reflectance	0.081
	Inside Visible Reflectance	0.081
Infra-Red Properties	Infra-Red Transmittance	0
	Outside Emissivity	0.84
	Inside Emissivity	0.84

Table D.10: Glazing Construction Details of the Glazing of the RDP House

Zone (Surface)			Kitchen	North Bedroom	South Bedroom	Lounge	Bathroom
Glazing Type			4 mm Clear Float Glass				
Reveal	Outside Reveal Depth (m)		0				
	Inside Reveal Depth (m)		0				
	Inside Sill Depth (m)		0				
Frame and Dividers	Construction		Wooden Window Frame				
	Frame	Frame Width (m)	0.04				
		Frame Inside Projection (m)	0				
		Frame Outside Projection (m)	0				
		Glass edge-centre conduction ratio	1				
Free Aperture	Opening Position		Top				
	% Glazing Area Opens		5				

Appendix E: Data Inputs for Chapter 5

The following data was used as input for the analysis of models simulated in Chapter 5.

E.1 Weather Data

Weather data used to analyse the thermal performance of the Alice House is presented in Figures E.1 to E.9.

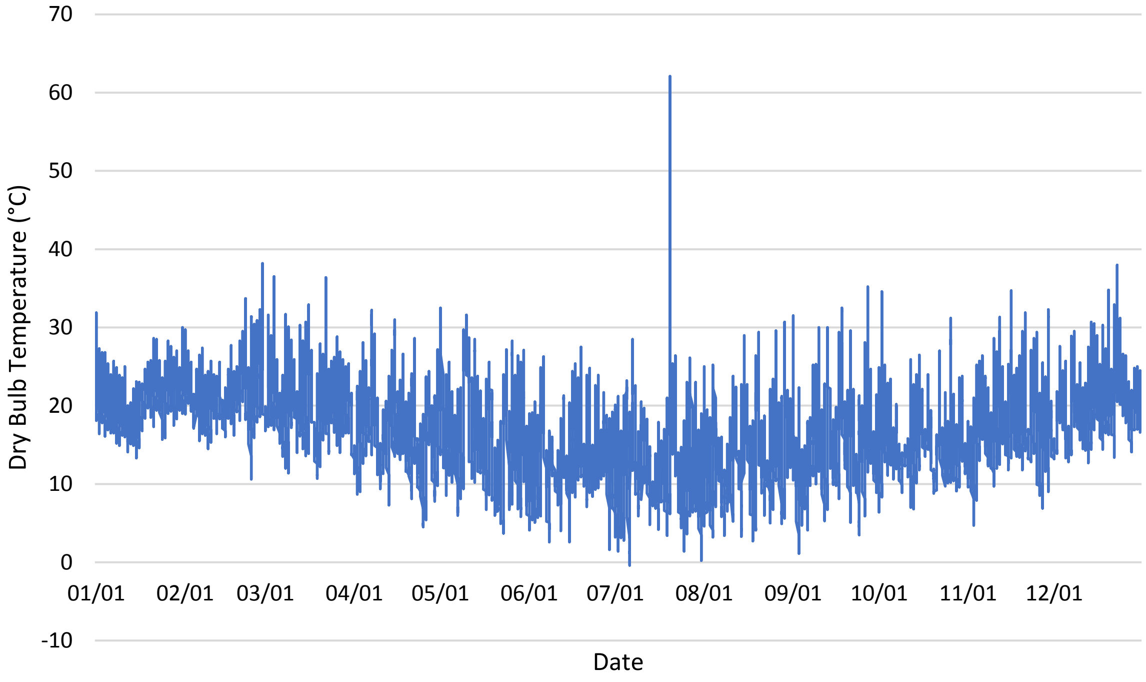


Figure E.1: Dry Bulb Temperature Data from Alice Meteonorm and on-site data

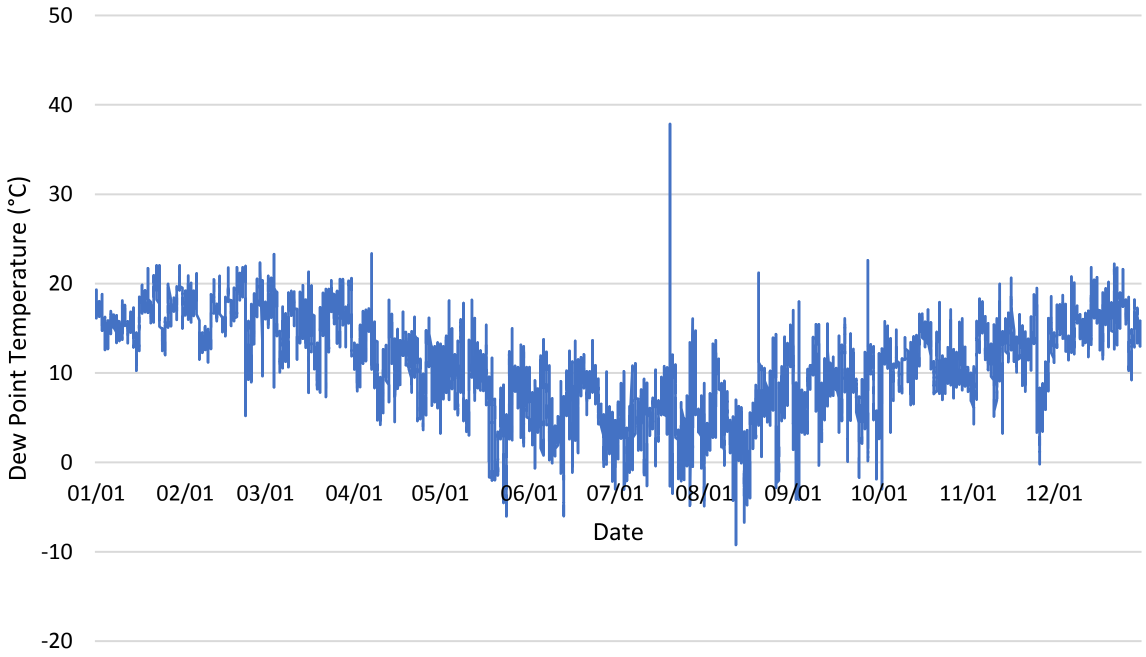


Figure E.2: Dew Point Temperature Data from Alice Meteonorm and on-site data

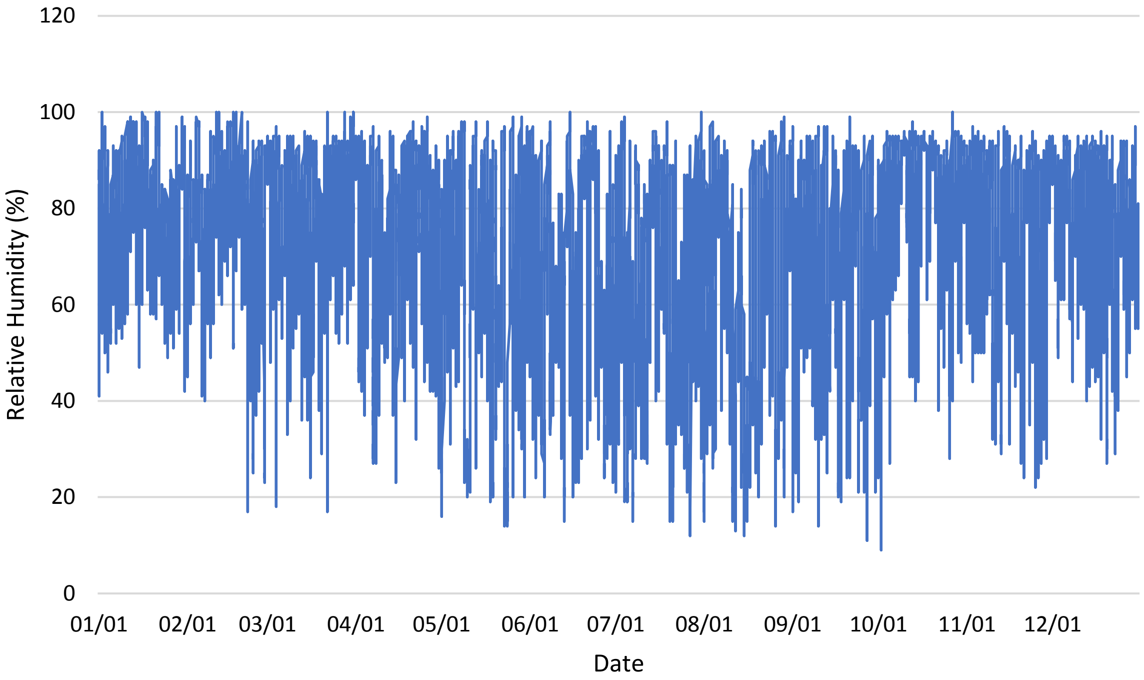


Figure E.3: Relative Humidity Data from Alice Meteonorm and on-site data

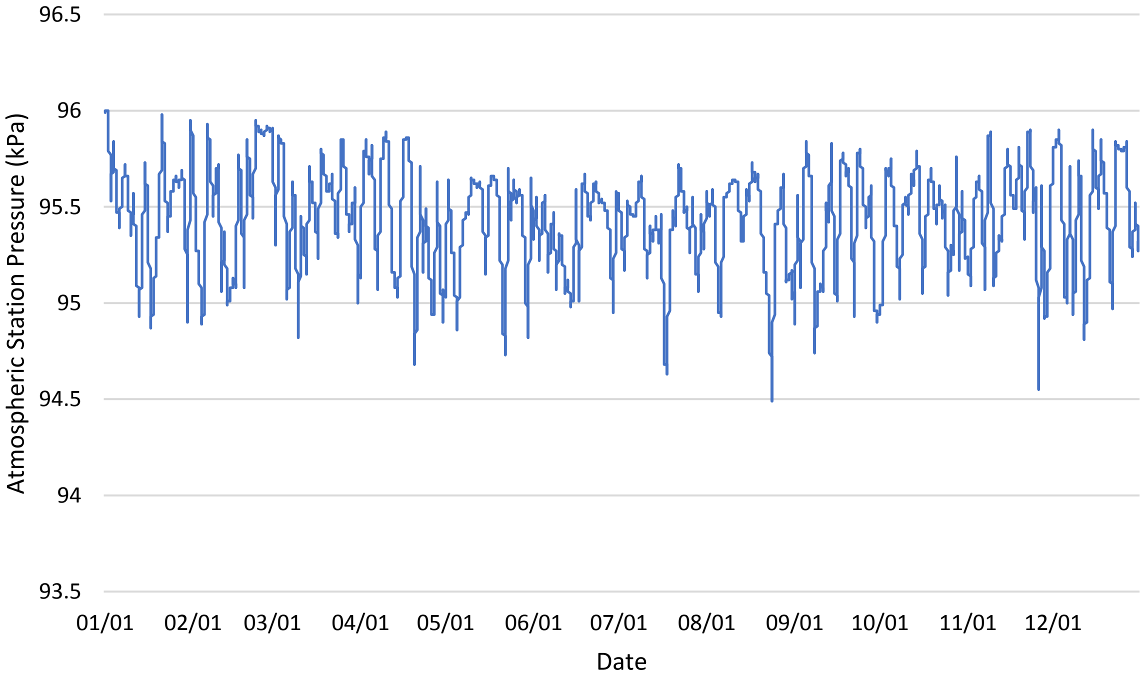


Figure E.4: Atmospheric Station Pressure Data from Alice Meteonorm and on-site data

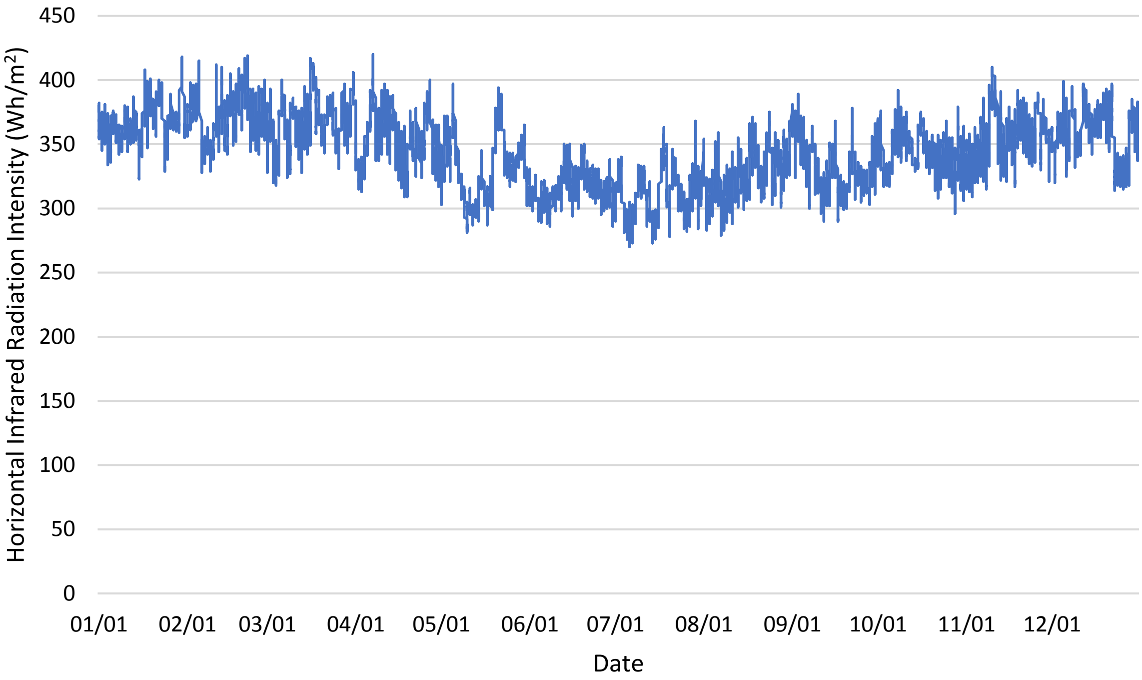


Figure E.5: Horizontal Infrared Radiation Intensity Data from Alice Meteonorm and on-site data

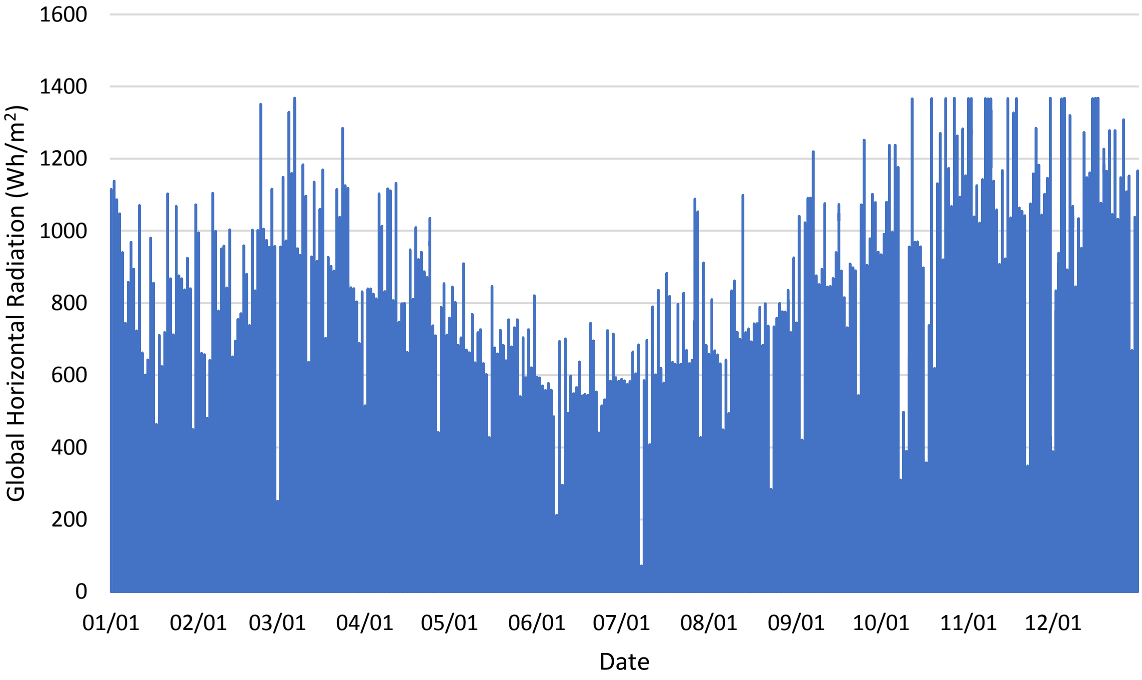


Figure E.6: Global Horizontal Irradiation Data from Alice Meteonorm and on-site data

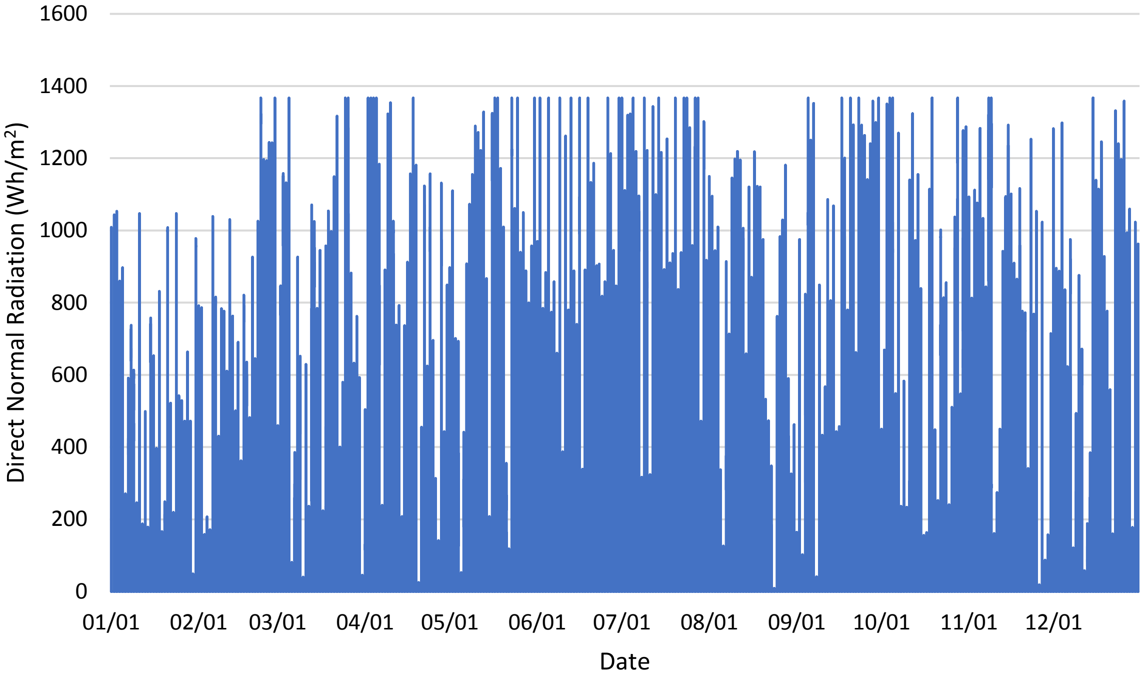


Figure E.7: Direct Normal Irradiation Data from Alice Meteonorm and on-site data

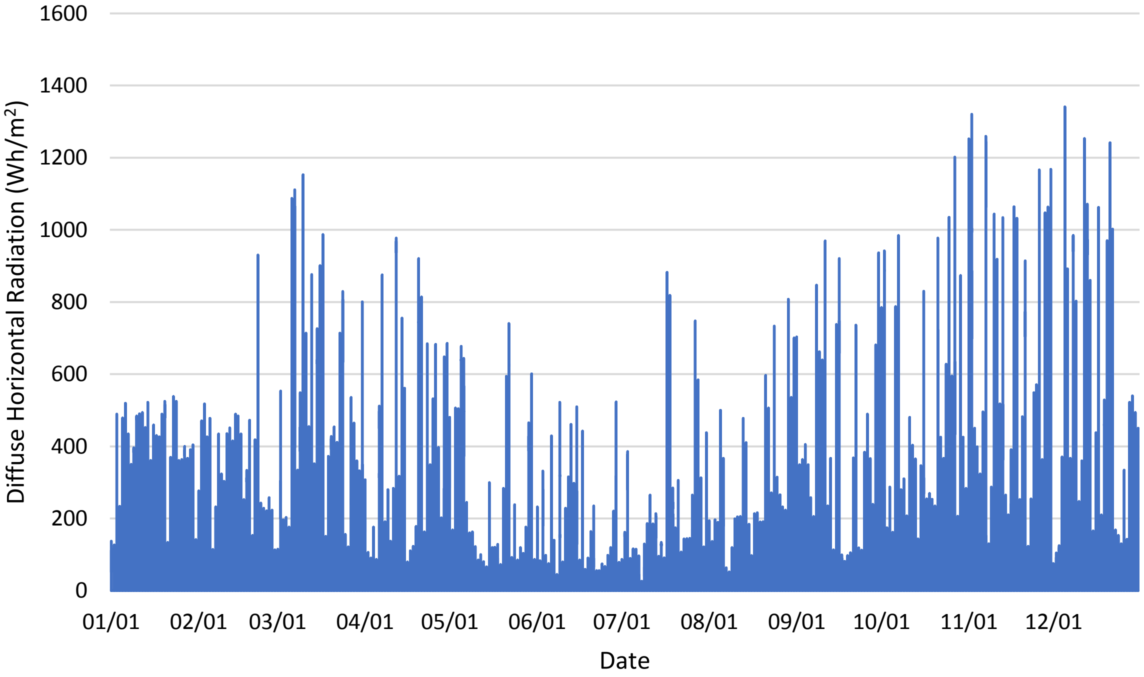


Figure E.8: Diffuse Horizontal Irradiation Data from Alice Meteonorm and on-site data

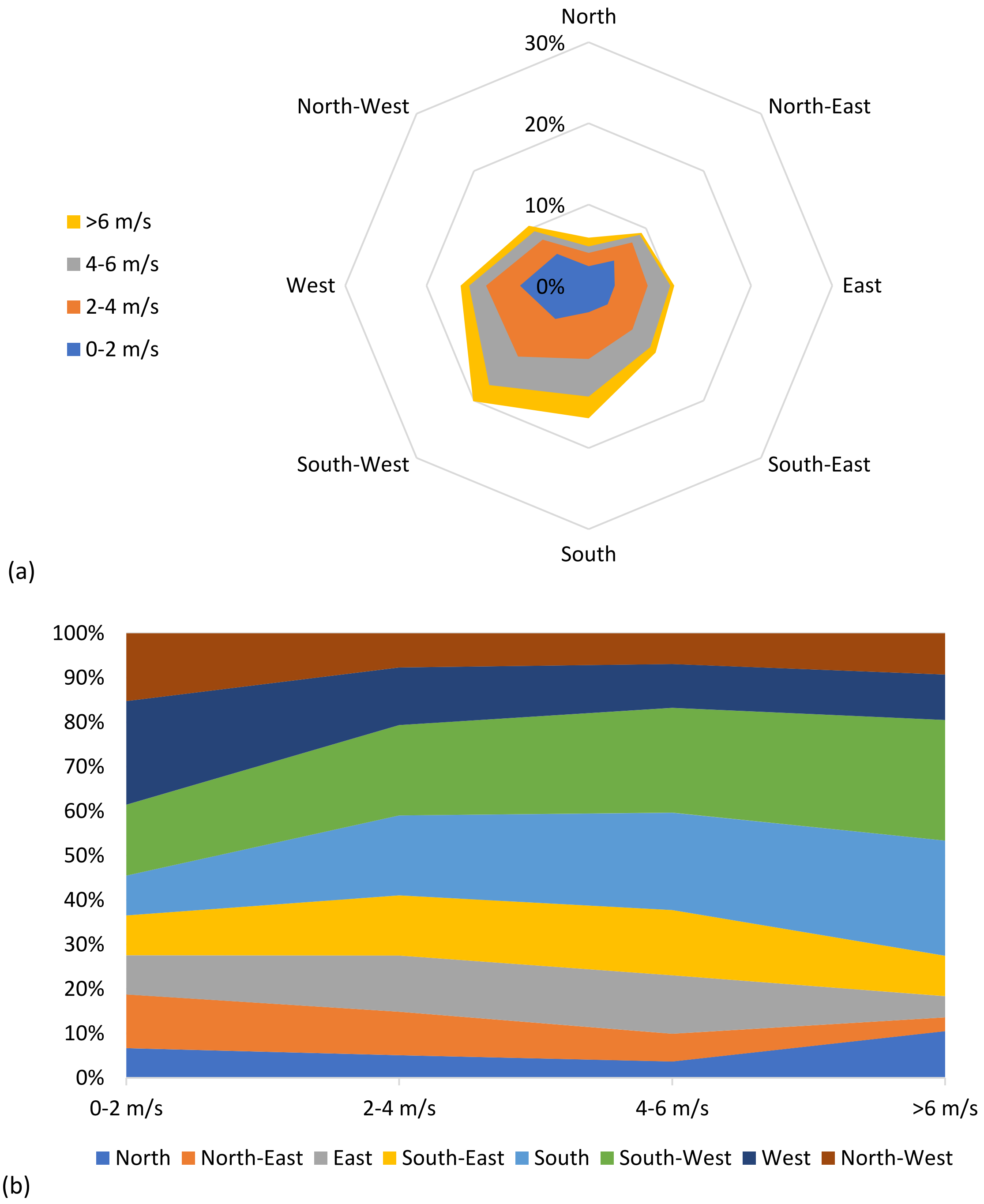


Figure E.9: (a) Wind Rose of Alice Meteonorm and on-site data (b) Wind Speed Within Wind Direction Distribution

E.2 Internal Heat Gains

The schedule of internal heat gains associated with kitchen appliances and miscellaneous heat gains for the Alice House is provided in Figure E.10. The graphs present a visualisation of times when kitchen appliances and miscellaneous heat gains are active during weekends/holidays and weekdays.

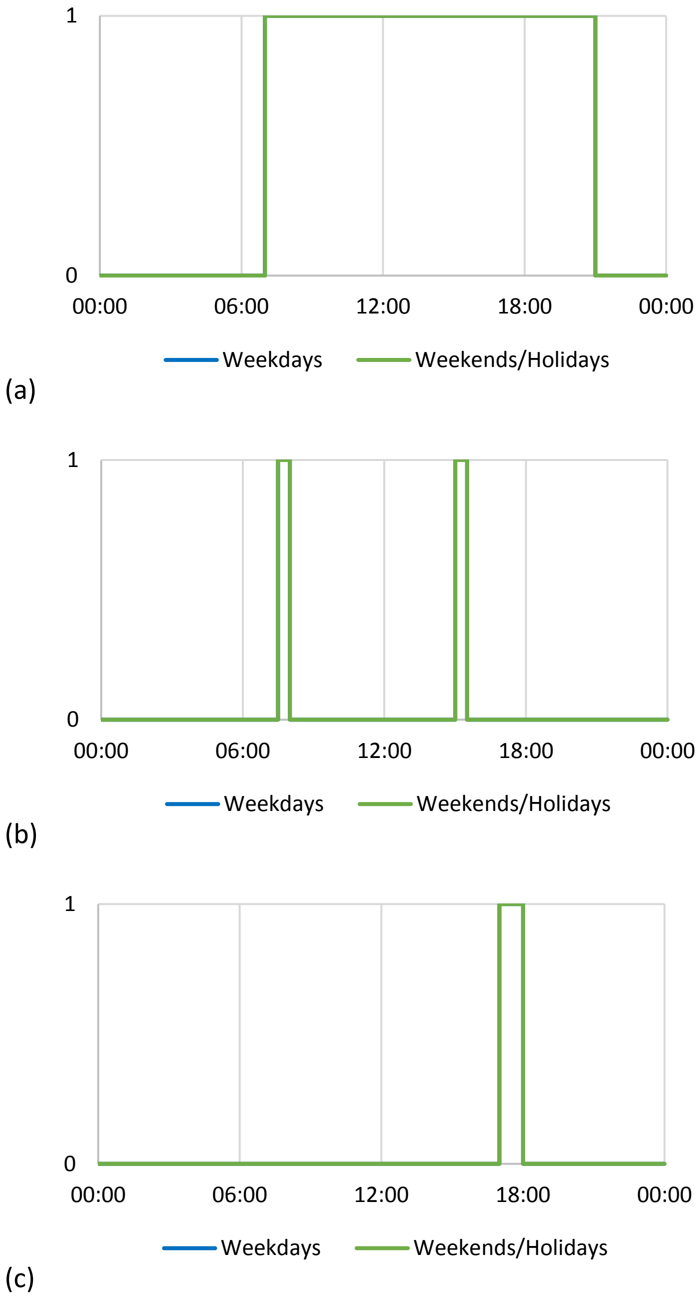
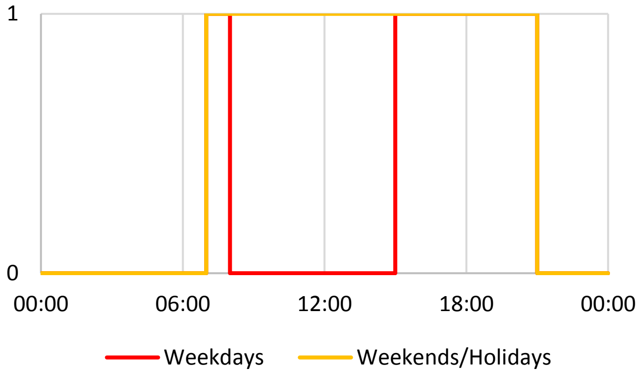


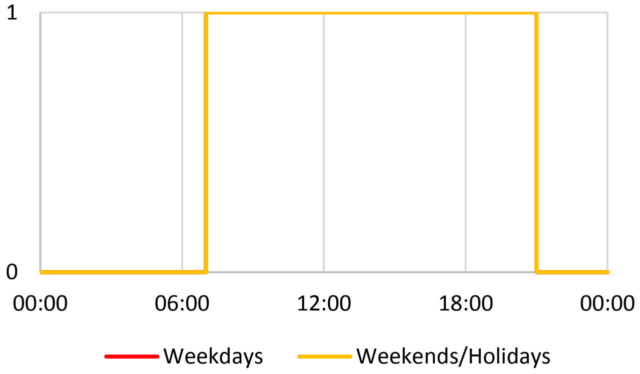
Figure E.10: (a) Schedule for heat gains associated with the TV and DVD player (b) Schedule for heat gains associated with the electric kettle (c) Schedule for heat gains associated with the electric cooker

E.3 Occupancy

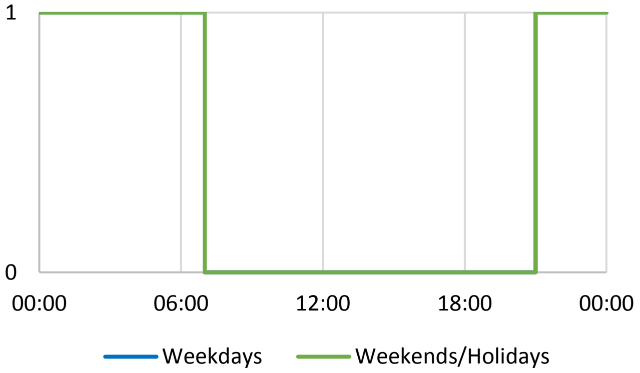
The schedule of zone occupancy is provided in Figure E.11. The graphs present a visualisation of times when zones are occupied during weekends/holidays and weekdays.



(a)



(b)



(c)

Figure E.11: (a) Occupancy Schedule for the daughter in the lounge (b) Occupancy Schedule for the mother and toddler in the lounge (c) Occupancy Schedule for the family in the bedroom

E.4 Lighting

The schedule of zone lighting data is provided in Figure E.12. Graphs should be read similarly to that of occupancy.

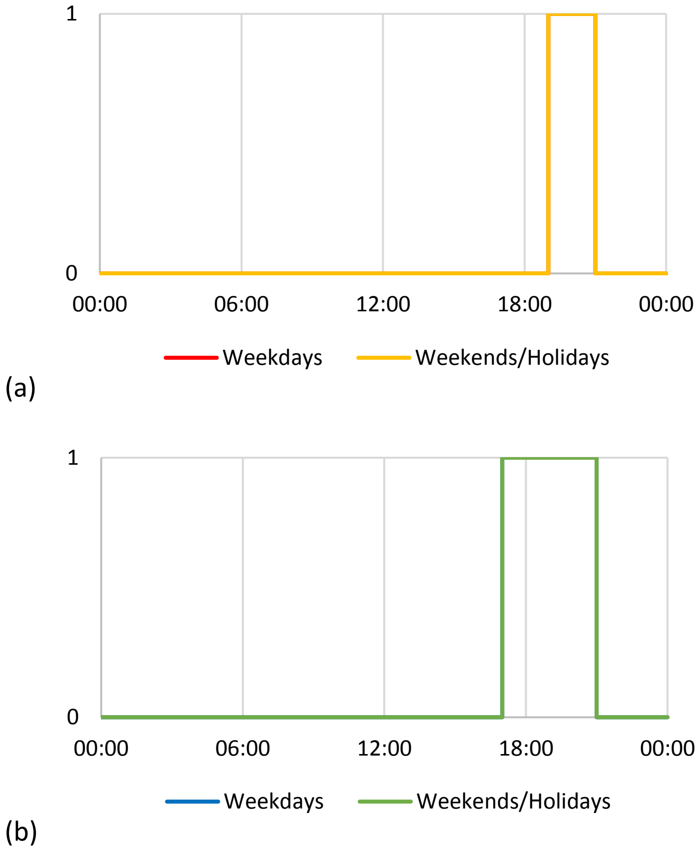
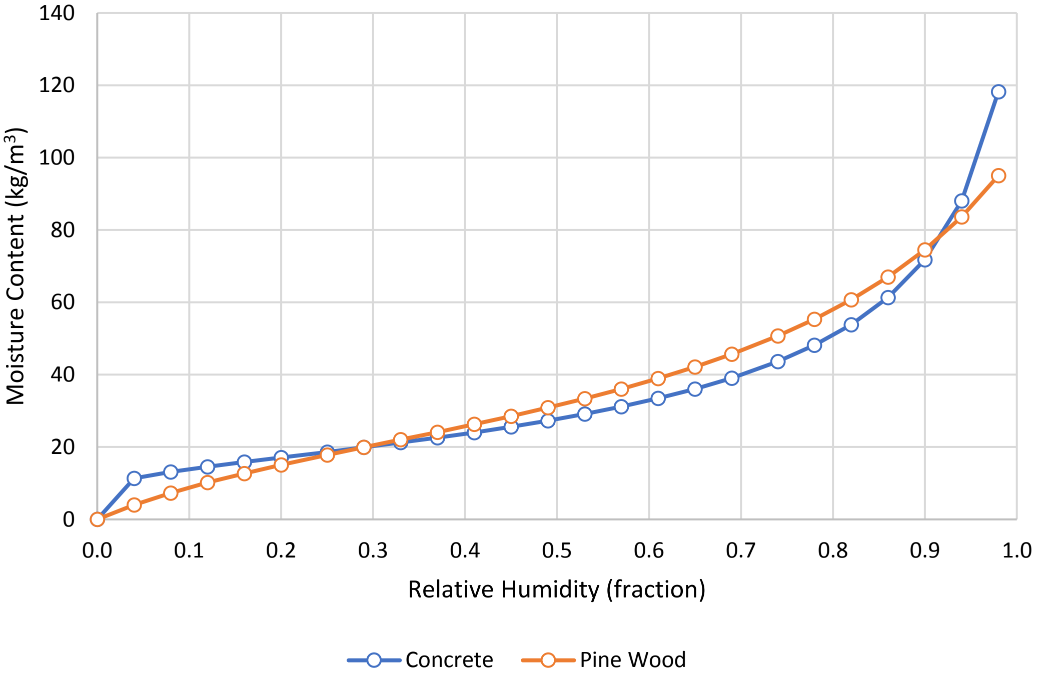


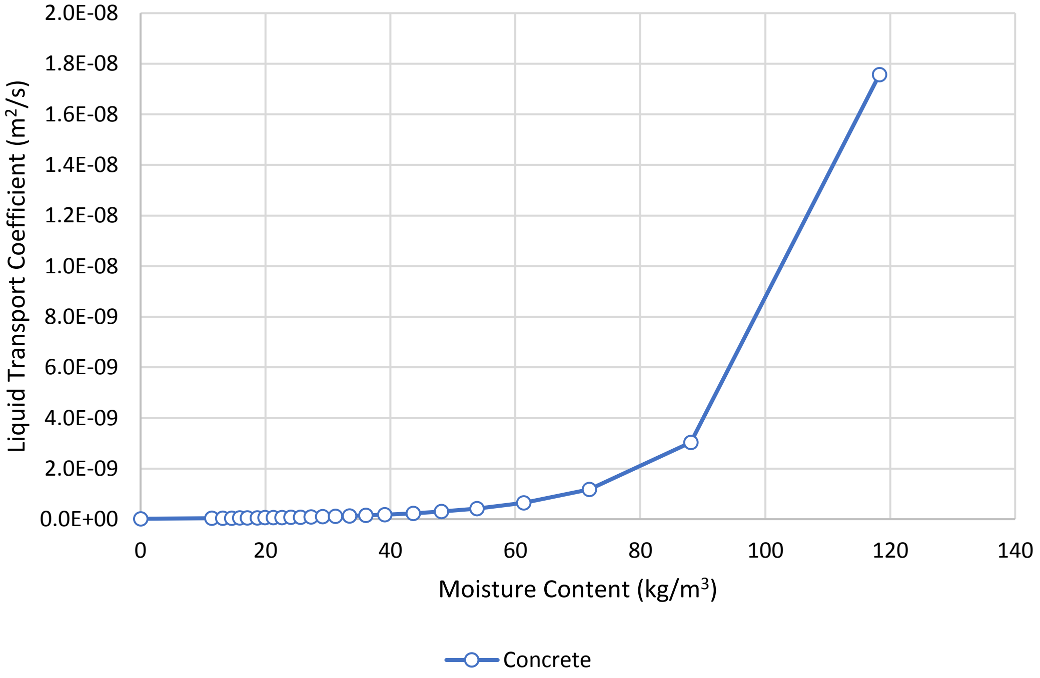
Figure E.12: (a) Schedule for zone lighting during the summer (b) Schedule for zone lighting during the winter

E.5 Material Properties

A visual representation of the moisture transfer properties of building materials is presented in Figure E.13. The moisture transfer properties of external walls and the floor were kept the same with the exception of the moisture dependent thermal conductivity. The initial thermal conductivity value was based on the dry thermal conductivity.



(a)



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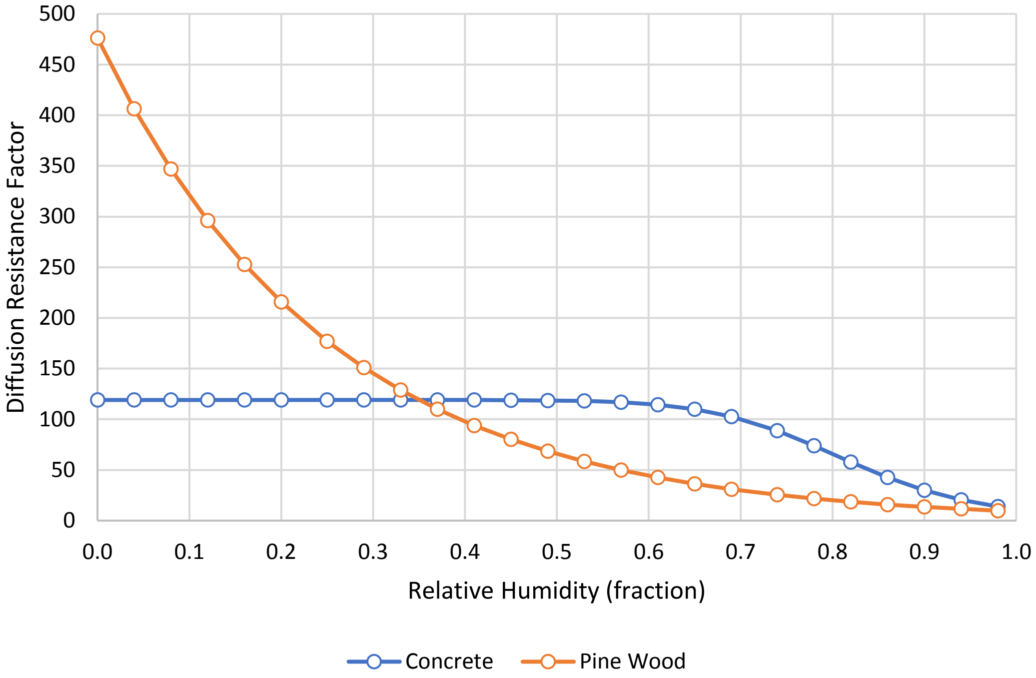
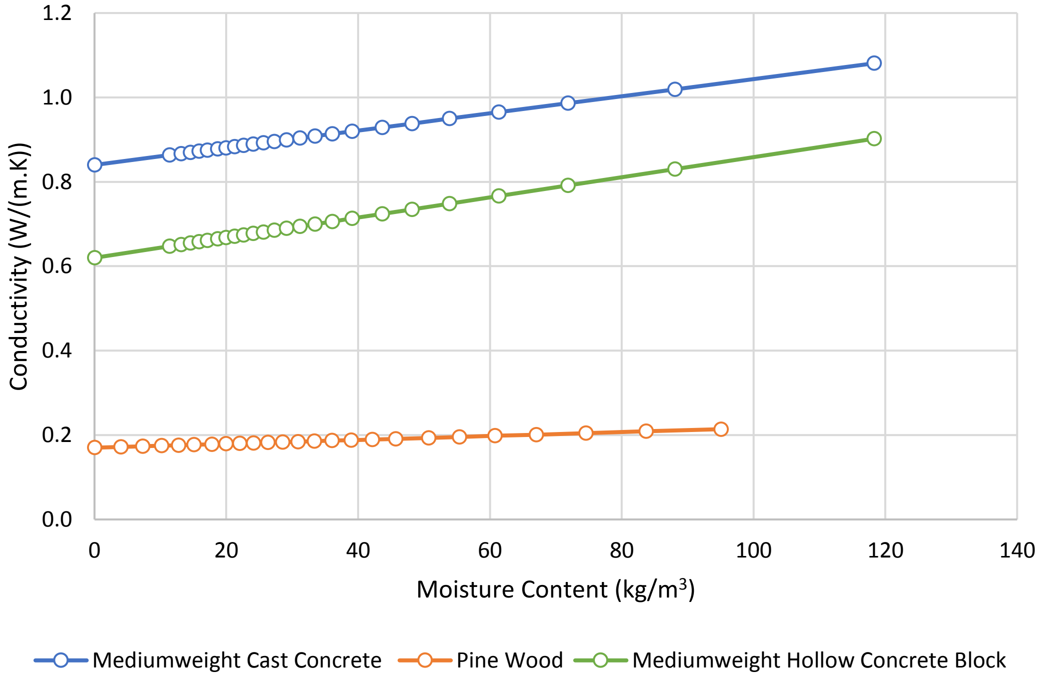


(c)



(d)

Figure E.13: (a) Sorption isotherm of Alice House Materials (b) Liquid Transport Coefficient Values of Alice House Materials (c) Diffusion Resistance Factor Values of Alice House Materials (d) Moisture Dependent Thermal Conductivity Values of Alice House Materials

E.6 Validation Analyses Metrics

Metrics for the validation analyses performed on the simulations performed in Chapter 5 is presented below.

E.6.1 Living Room Air Temperature

E.6.1.1 Overall Validation Metrics

Table E.1 contains the validation metrics for the living room air temperature for the summer and winter weeks combined.

Table E.1: Validation metrics for the living room air temperature for the summer and winter week combined

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.21	2.13	2.68	0.93	11.74	9.29	0.90	0.79	0.06
Reference Case (HAMT)	0.16	1.97	2.44	0.69	10.70	8.47	0.91	0.82	0.05
Scenario 1 - Low leakage	-0.03	2.04	2.53	-0.12	11.09	8.78	0.90	0.81	0.05
Scenario 2 - 75 mm floor	0.28	1.95	2.41	1.23	10.56	8.36	0.91	0.83	0.05
Scenario 3 - No cooker	0.24	1.90	2.33	1.04	10.20	8.08	0.92	0.84	0.05
Scenario 4 - No moisture	0.14	1.99	2.47	0.61	10.82	8.57	0.91	0.82	0.05
Scenario 5 - No ventilation	-0.99	2.01	2.57	-4.35	11.28	8.93	0.93	0.80	0.05

E.6.1.2 Weekly Validation Metrics

The validation metrics for the living room air temperature for the summer and winter weeks are presented in Tables E.2 and E.3.

Table E.2: Validation metrics for the living room air temperature for the summer week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.33	2.38	2.81	4.99	10.56	13.42	0.89	0.57	0.05
Reference Case (HAMT)	1.29	2.10	2.55	4.85	9.59	12.20	0.90	0.65	0.05
Scenario 1 - Low leakage	1.15	2.09	2.55	4.32	9.57	12.17	0.89	0.65	0.05
Scenario 2 - 75 mm floor	1.44	2.14	2.57	5.39	9.68	12.31	0.90	0.64	0.05
Scenario 3 - No cooker	1.32	2.10	2.55	4.95	9.59	12.20	0.90	0.65	0.05
Scenario 4 - No moisture	1.26	2.15	2.59	4.72	9.75	12.40	0.90	0.63	0.05
Scenario 5 - No ventilation	-0.52	2.04	2.65	-1.94	9.95	12.65	0.91	0.62	0.05

Table E.3: Validation metrics for the living room air temperature for the winter week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.90	1.88	2.54	-4.74	13.36	12.55	0.89	0.68	0.06
Reference Case (HAMT)	-0.97	1.83	2.33	-5.12	12.22	11.48	0.90	0.73	0.06
Scenario 1 - Low leakage	-1.20	1.98	2.51	-6.33	13.21	12.40	0.89	0.69	0.06
Scenario 2 - 75 mm floor	-0.87	1.75	2.23	-4.60	11.73	11.02	0.90	0.75	0.06
Scenario 3 - No cooker	-0.84	1.71	2.08	-4.44	10.93	10.27	0.91	0.78	0.05
Scenario 4 - No moisture	-0.98	1.83	2.34	-5.13	12.29	11.54	0.90	0.73	0.06
Scenario 5 - No ventilation	-1.47	1.99	2.50	-7.71	13.12	12.32	0.92	0.69	0.06

E.6.1.3 Daily Validation Metrics

The validation metrics for the living room air temperature for the summer days are presented in Tables E.4 to E.10.

Table E.4: Validation metrics for the living room air temperature for 23 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.66	2.84	3.20	6.52	12.55	32.19	0.57	-0.51	0.06
Reference Case (HAMT)	1.69	2.64	3.04	6.62	11.93	30.62	0.56	-0.37	0.06
Scenario 1 - Low leakage	1.47	2.57	3.02	5.78	11.84	30.38	0.52	-0.35	0.06
Scenario 2 - 75 mm floor	1.82	2.68	3.06	7.15	12.00	30.80	0.58	-0.38	0.06
Scenario 3 - No cooker	1.71	2.66	3.05	6.72	11.95	30.67	0.56	-0.37	0.06
Scenario 4 - No moisture	1.67	2.69	3.08	6.55	12.07	30.97	0.57	-0.40	0.06
Scenario 5 - No ventilation	-1.29	2.46	3.08	-5.07	12.09	31.02	0.84	-0.40	0.06

Table E.5: Validation metrics for the living room air temperature for 24 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.35	1.47	1.85	1.35	7.19	11.16	0.95	0.89	0.04
Reference Case (HAMT)	0.45	1.29	1.67	1.75	6.47	10.04	0.96	0.91	0.03
Scenario 1 - Low leakage	0.23	1.38	1.72	0.87	6.68	10.36	0.95	0.90	0.03
Scenario 2 - 75 mm floor	0.59	1.26	1.63	2.29	6.34	9.84	0.96	0.91	0.03
Scenario 3 - No cooker	0.48	1.26	1.65	1.86	6.42	9.97	0.96	0.91	0.03
Scenario 4 - No moisture	0.39	1.31	1.70	1.52	6.59	10.22	0.96	0.91	0.03
Scenario 5 - No ventilation	-1.37	1.51	2.11	-5.33	8.21	12.73	0.98	0.86	0.04

Table E.6: Validation metrics for the living room air temperature for 25 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.88	2.25	2.79	3.39	10.72	25.87	0.86	0.40	0.05
Reference Case (HAMT)	0.87	1.92	2.51	3.36	9.67	23.34	0.86	0.51	0.05
Scenario 1 - Low leakage	0.70	1.90	2.50	2.69	9.62	23.24	0.85	0.51	0.05
Scenario 2 - 75 mm floor	1.02	1.92	2.50	3.94	9.62	23.23	0.86	0.51	0.05
Scenario 3 - No cooker	0.90	1.89	2.49	3.46	9.59	23.15	0.86	0.52	0.05
Scenario 4 - No moisture	0.83	2.00	2.58	3.20	9.91	23.92	0.86	0.49	0.05
Scenario 5 - No ventilation	-1.26	2.11	2.83	-4.84	10.87	26.24	0.94	0.38	0.05

Table E.7: Validation metrics for the living room air temperature for 26 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.10	2.21	2.46	4.03	9.04	23.71	0.92	0.50	0.05
Reference Case (HAMT)	1.06	1.79	2.08	3.89	7.63	20.02	0.92	0.64	0.04
Scenario 1 - Low leakage	0.93	1.77	2.06	3.43	7.58	19.89	0.91	0.65	0.04
Scenario 2 - 75 mm floor	1.22	1.84	2.12	4.46	7.77	20.39	0.93	0.63	0.04
Scenario 3 - No cooker	1.08	1.79	2.08	3.97	7.63	20.01	0.92	0.64	0.04
Scenario 4 - No moisture	1.02	1.89	2.15	3.74	7.89	20.69	0.92	0.62	0.04
Scenario 5 - No ventilation	-0.96	2.25	2.89	-3.54	10.61	27.82	0.94	0.31	0.05

Table E.8: Validation metrics for the living room air temperature for 27 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.78	2.37	2.71	6.24	9.52	22.88	0.93	0.48	0.05
Reference Case (HAMT)	1.72	2.06	2.44	6.03	8.59	20.65	0.93	0.57	0.04
Scenario 1 - Low leakage	1.63	2.01	2.39	5.73	8.41	20.22	0.93	0.59	0.04
Scenario 2 - 75 mm floor	1.88	2.16	2.53	6.62	8.88	21.35	0.93	0.54	0.05
Scenario 3 - No cooker	1.75	2.04	2.43	6.15	8.55	20.54	0.93	0.58	0.04
Scenario 4 - No moisture	1.68	2.11	2.48	5.91	8.70	20.91	0.93	0.56	0.04
Scenario 5 - No ventilation	-0.24	1.89	2.20	-0.84	7.75	18.62	0.96	0.65	0.04

Table E.9: Validation metrics for the living room air temperature for 28 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.45	2.44	3.04	1.50	10.04	21.74	0.81	0.49	0.05
Reference Case (HAMT)	0.57	2.35	2.84	1.89	9.37	20.28	0.81	0.56	0.05
Scenario 1 - Low leakage	0.51	2.44	2.92	1.67	9.63	20.85	0.80	0.53	0.05
Scenario 2 - 75 mm floor	0.78	2.42	2.85	2.57	9.39	20.33	0.82	0.55	0.05
Scenario 3 - No cooker	0.59	2.34	2.81	1.96	9.28	20.09	0.82	0.56	0.05
Scenario 4 - No moisture	0.49	2.34	2.88	1.63	9.52	20.60	0.81	0.54	0.05
Scenario 5 - No ventilation	-0.06	2.38	3.23	-0.19	10.66	23.08	0.78	0.43	0.05

Table E.10: Validation metrics for the living room air temperature for 29 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.08	3.08	3.33	13.41	14.50	92.07	0.56	-11.27	0.08
Reference Case (HAMT)	2.66	2.66	2.98	11.59	12.96	82.26	0.50	-8.79	0.07
Scenario 1 - Low leakage	2.57	2.57	2.92	11.20	12.73	80.79	0.49	-8.45	0.07
Scenario 2 - 75 mm floor	2.73	2.73	3.02	11.88	13.14	83.41	0.51	-9.07	0.07
Scenario 3 - No cooker	2.71	2.71	3.03	11.78	13.19	83.73	0.46	-9.15	0.07
Scenario 4 - No moisture	2.70	2.70	3.01	11.76	13.10	83.18	0.51	-9.01	0.07
Scenario 5 - No ventilation	1.56	1.64	1.86	6.80	8.07	51.25	0.74	-2.80	0.04

The validation metrics for the living room air temperature for the winter days are presented in Tables E.11 to E.17.

Table E.11: Validation metrics for the living room air temperature for 25 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.00	1.99	2.48	-5.23	12.95	24.93	0.78	0.27	0.06
Reference Case (HAMT)	-1.06	1.95	2.30	-5.53	12.01	23.14	0.79	0.37	0.06
Scenario 1 - Low leakage	-1.17	2.12	2.61	-6.11	13.62	26.23	0.74	0.19	0.07
Scenario 2 - 75 mm floor	-0.96	1.88	2.23	-5.02	11.64	22.42	0.79	0.41	0.06
Scenario 3 - No cooker	-0.94	1.84	2.10	-4.92	10.94	21.08	0.81	0.48	0.05
Scenario 4 - No moisture	-1.06	1.95	2.31	-5.51	12.06	23.22	0.79	0.37	0.06
Scenario 5 - No ventilation	-1.68	2.29	2.66	-8.73	13.88	26.73	0.83	0.16	0.07

Table E.12: Validation metrics for the living room air temperature for 26 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.08	1.76	2.68	-6.07	15.08	23.93	0.82	0.48	0.07
Reference Case (HAMT)	-1.04	1.74	2.50	-5.86	14.06	22.31	0.83	0.55	0.07
Scenario 1 - Low leakage	-1.47	2.03	2.77	-8.28	15.57	24.71	0.82	0.45	0.07
Scenario 2 - 75 mm floor	-0.97	1.68	2.42	-5.45	13.60	21.57	0.83	0.58	0.06
Scenario 3 - No cooker	-0.92	1.62	2.23	-5.15	12.54	19.90	0.85	0.64	0.06
Scenario 4 - No moisture	-1.05	1.74	2.51	-5.90	14.13	22.42	0.83	0.55	0.07
Scenario 5 - No ventilation	-1.78	1.89	2.62	-10.01	14.75	23.40	0.92	0.51	0.07

Table E.13: Validation metrics for the living room air temperature for 27 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.18	1.74	2.48	-6.82	14.36	16.48	0.92	0.76	0.07
Reference Case (HAMT)	-1.30	1.80	2.34	-7.53	13.51	15.50	0.93	0.79	0.06
Scenario 1 - Low leakage	-1.60	2.00	2.59	-9.25	14.95	17.16	0.92	0.74	0.07
Scenario 2 - 75 mm floor	-1.23	1.73	2.24	-7.09	12.93	14.84	0.93	0.81	0.06
Scenario 3 - No cooker	-1.18	1.68	2.06	-6.81	11.90	13.65	0.94	0.84	0.06
Scenario 4 - No moisture	-1.30	1.80	2.35	-7.53	13.56	15.56	0.93	0.79	0.06
Scenario 5 - No ventilation	-1.96	2.19	2.70	-11.35	15.61	17.91	0.95	0.72	0.07

Table E.14: Validation metrics for the living room air temperature for 28 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.36	1.94	2.44	-7.38	13.24	14.60	0.97	0.83	0.06
Reference Case (HAMT)	-1.45	1.96	2.22	-7.87	12.05	13.30	0.97	0.86	0.06
Scenario 1 - Low leakage	-1.63	2.08	2.29	-8.87	12.44	13.72	0.97	0.85	0.06
Scenario 2 - 75 mm floor	-1.37	1.88	2.13	-7.44	11.53	12.72	0.97	0.87	0.05
Scenario 3 - No cooker	-1.31	1.83	2.03	-7.13	10.99	12.12	0.97	0.88	0.05
Scenario 4 - No moisture	-1.46	1.97	2.24	-7.89	12.14	13.39	0.97	0.86	0.06
Scenario 5 - No ventilation	-1.36	1.87	2.11	-7.38	11.44	12.62	0.97	0.87	0.05

Table E.15: Validation metrics for the living room air temperature for 29 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.93	1.53	2.18	-4.66	10.98	19.65	0.85	0.57	0.05
Reference Case (HAMT)	-0.98	1.53	2.04	-4.95	10.25	18.33	0.86	0.63	0.05
Scenario 1 - Low leakage	-1.20	1.67	2.23	-6.04	11.21	20.06	0.85	0.55	0.05
Scenario 2 - 75 mm floor	-0.85	1.43	1.93	-4.26	9.71	17.37	0.87	0.66	0.05
Scenario 3 - No cooker	-0.85	1.40	1.73	-4.28	8.70	15.57	0.90	0.73	0.04
Scenario 4 - No moisture	-0.99	1.53	2.05	-4.96	10.30	18.43	0.86	0.62	0.05
Scenario 5 - No ventilation	-1.62	1.86	2.45	-8.17	12.31	22.03	0.90	0.46	0.06

Table E.16: Validation metrics for the living room air temperature for 30 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.53	2.18	2.57	2.73	13.29	24.20	0.82	0.37	0.07
Reference Case (HAMT)	0.31	1.88	2.26	1.59	11.68	21.26	0.82	0.52	0.06
Scenario 1 - Low leakage	0.13	1.89	2.32	0.69	12.00	21.84	0.81	0.49	0.06
Scenario 2 - 75 mm floor	0.39	1.85	2.21	2.02	11.45	20.83	0.83	0.54	0.06
Scenario 3 - No cooker	0.44	1.76	2.03	2.30	10.49	19.09	0.85	0.61	0.05
Scenario 4 - No moisture	0.31	1.89	2.28	1.60	11.77	21.42	0.82	0.51	0.06
Scenario 5 - No ventilation	-0.38	1.84	2.23	-1.96	11.55	21.02	0.90	0.53	0.06

Table E.17: Validation metrics for the living room air temperature for 31 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.29	2.02	2.91	-6.05	13.62	18.16	0.90	0.66	0.06
Reference Case (HAMT)	-1.29	1.94	2.58	-6.04	12.12	16.15	0.91	0.73	0.06
Scenario 1 - Low leakage	-1.49	2.06	2.73	-6.98	12.81	17.07	0.90	0.70	0.06
Scenario 2 - 75 mm floor	-1.14	1.83	2.44	-5.33	11.43	15.24	0.92	0.76	0.05
Scenario 3 - No cooker	-1.15	1.81	2.34	-5.41	10.98	14.64	0.92	0.78	0.05
Scenario 4 - No moisture	-1.30	1.94	2.60	-6.08	12.20	16.26	0.91	0.73	0.06
Scenario 5 - No ventilation	-1.49	1.96	2.65	-6.98	12.41	16.54	0.92	0.72	0.06

E.6.1.4 Overall Hourly Validation Metrics

The first hourly-based validation analysis considered results from the summer and winter week. The validation metrics for the living room air temperature are presented in Tables E.18 to E.41.

Table E.18: Validation metrics for the living room air temperature for 00:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.15	1.16	1.35	-0.75	6.57	9.04	0.99	0.92	0.03
Reference Case (HAMT)	-0.40	1.23	1.42	-1.96	6.89	9.50	0.99	0.92	0.03
Scenario 1 - Low leakage	-0.67	1.34	1.55	-3.26	7.56	10.41	0.99	0.90	0.04
Scenario 2 - 75 mm floor	-0.20	1.22	1.42	-0.99	6.89	9.50	0.99	0.92	0.03
Scenario 3 - No cooker	-0.38	1.21	1.40	-1.84	6.79	9.35	0.99	0.92	0.03
Scenario 4 - No moisture	-0.36	1.23	1.42	-1.76	6.91	9.52	0.99	0.92	0.03
Scenario 5 - No ventilation	-0.71	1.21	1.41	-3.45	6.88	9.47	0.99	0.92	0.03

Table E.19: Validation metrics for the living room air temperature for 01:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.23	1.13	1.29	1.14	6.43	8.53	0.98	0.93	0.03
Reference Case (HAMT)	-0.14	1.13	1.26	-0.71	6.32	8.38	0.99	0.93	0.03
Scenario 1 - Low leakage	-0.39	1.22	1.36	-1.93	6.82	9.04	0.99	0.92	0.03
Scenario 2 - 75 mm floor	0.04	1.13	1.29	0.19	6.47	8.58	0.99	0.93	0.03
Scenario 3 - No cooker	-0.12	1.11	1.25	-0.60	6.24	8.28	0.99	0.93	0.03
Scenario 4 - No moisture	-0.08	1.14	1.28	-0.42	6.42	8.51	0.99	0.93	0.03
Scenario 5 - No ventilation	-0.38	1.11	1.22	-1.90	6.11	8.10	0.99	0.94	0.03

Table E.20: Validation metrics for the living room air temperature for 02:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.67	1.32	1.49	3.40	7.59	9.46	0.99	0.91	0.04
Reference Case (HAMT)	0.20	1.17	1.32	1.00	6.74	8.39	0.99	0.93	0.03
Scenario 1 - Low leakage	-0.05	1.22	1.36	-0.26	6.96	8.68	0.99	0.92	0.03
Scenario 2 - 75 mm floor	0.35	1.24	1.39	1.81	7.09	8.84	0.99	0.92	0.03
Scenario 3 - No cooker	0.21	1.17	1.31	1.10	6.69	8.34	0.99	0.93	0.03
Scenario 4 - No moisture	0.26	1.21	1.36	1.34	6.93	8.64	0.99	0.93	0.03
Scenario 5 - No ventilation	0.01	1.12	1.24	0.03	6.34	7.90	0.99	0.94	0.03

Table E.21: Validation metrics for the living room air temperature for 03:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	0.94	1.45	1.73	4.92	9.05	10.66	0.98	0.88	0.05
Reference Case (HAMT)	0.39	1.34	1.48	2.05	7.72	9.09	0.99	0.92	0.04
Scenario 1 - Low leakage	0.17	1.39	1.50	0.89	7.85	9.25	0.99	0.91	0.04
Scenario 2 - 75 mm floor	0.53	1.40	1.56	2.76	8.14	9.59	0.99	0.91	0.04
Scenario 3 - No cooker	0.41	1.33	1.47	2.13	7.69	9.05	0.99	0.92	0.04
Scenario 4 - No moisture	0.46	1.39	1.53	2.42	7.99	9.41	0.99	0.91	0.04
Scenario 5 - No ventilation	0.23	1.29	1.39	1.22	7.28	8.57	0.99	0.93	0.04

Table E.22: Validation metrics for the living room air temperature for 04:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.50	1.84	2.26	7.89	11.89	13.36	0.96	0.79	0.06
Reference Case (HAMT)	0.89	1.62	1.87	4.67	9.82	11.03	0.96	0.86	0.05
Scenario 1 - Low leakage	0.68	1.66	1.87	3.59	9.81	11.03	0.96	0.86	0.05
Scenario 2 - 75 mm floor	1.00	1.68	1.95	5.28	10.25	11.52	0.96	0.85	0.05
Scenario 3 - No cooker	0.90	1.61	1.87	4.75	9.83	11.04	0.96	0.86	0.05
Scenario 4 - No moisture	0.96	1.67	1.93	5.07	10.12	11.38	0.96	0.85	0.05
Scenario 5 - No ventilation	0.76	1.56	1.79	4.00	9.40	10.56	0.96	0.87	0.05

Table E.23: Validation metrics for the living room air temperature for 05:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.55	1.80	2.23	8.29	11.90	13.07	0.97	0.80	0.06
Reference Case (HAMT)	0.90	1.55	1.79	4.83	9.59	10.53	0.98	0.87	0.05
Scenario 1 - Low leakage	0.75	1.65	1.88	4.03	10.02	11.00	0.97	0.86	0.05
Scenario 2 - 75 mm floor	1.00	1.60	1.87	5.34	10.01	10.99	0.98	0.86	0.05
Scenario 3 - No cooker	0.92	1.54	1.80	4.90	9.60	10.54	0.98	0.87	0.05
Scenario 4 - No moisture	0.98	1.60	1.86	5.24	9.94	10.91	0.97	0.86	0.05
Scenario 5 - No ventilation	0.81	1.51	1.74	4.32	9.29	10.20	0.98	0.88	0.05

Table E.24: Validation metrics for the living room air temperature for 06:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.34	1.63	2.08	7.31	11.31	12.57	0.96	0.82	0.06
Reference Case (HAMT)	0.68	1.44	1.65	3.72	9.01	10.00	0.97	0.89	0.04
Scenario 1 - Low leakage	0.62	1.42	1.60	3.37	8.74	9.71	0.98	0.89	0.04
Scenario 2 - 75 mm floor	0.76	1.49	1.73	4.14	9.40	10.44	0.97	0.88	0.05
Scenario 3 - No cooker	0.69	1.44	1.65	3.78	9.00	10.00	0.97	0.89	0.04
Scenario 4 - No moisture	0.76	1.49	1.73	4.15	9.41	10.45	0.97	0.88	0.05
Scenario 5 - No ventilation	0.62	1.43	1.63	3.38	8.87	9.85	0.97	0.89	0.04

Table E.25: Validation metrics for the living room air temperature for 07:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.39	1.86	2.30	7.72	12.78	13.97	0.95	0.78	0.06
Reference Case (HAMT)	0.73	1.67	1.89	4.03	10.46	11.43	0.96	0.86	0.05
Scenario 1 - Low leakage	0.61	1.59	1.84	3.38	10.20	11.14	0.97	0.86	0.05
Scenario 2 - 75 mm floor	0.79	1.71	1.95	4.36	10.79	11.80	0.96	0.85	0.05
Scenario 3 - No cooker	0.73	1.66	1.88	4.08	10.46	11.43	0.96	0.86	0.05
Scenario 4 - No moisture	0.80	1.72	1.95	4.45	10.84	11.84	0.96	0.84	0.05
Scenario 5 - No ventilation	0.69	1.66	1.87	3.83	10.39	11.35	0.96	0.86	0.05

Table E.26: Validation metrics for the living room air temperature for 08:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.66	1.88	2.28	8.59	11.75	13.76	0.96	0.78	0.06
Reference Case (HAMT)	1.06	1.50	1.82	5.49	9.40	11.01	0.97	0.86	0.05
Scenario 1 - Low leakage	0.88	1.39	1.70	4.52	8.80	10.31	0.98	0.88	0.04
Scenario 2 - 75 mm floor	1.11	1.54	1.88	5.74	9.72	11.39	0.97	0.85	0.05
Scenario 3 - No cooker	1.07	1.50	1.82	5.53	9.40	11.02	0.97	0.86	0.05
Scenario 4 - No moisture	1.13	1.56	1.89	5.85	9.74	11.41	0.97	0.85	0.05
Scenario 5 - No ventilation	0.88	1.34	1.62	4.54	8.38	9.82	0.97	0.89	0.04

Table E.27: Validation metrics for the living room air temperature for 09:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	2.88	3.03	3.38	13.49	15.80	19.88	0.92	0.40	0.08
Reference Case (HAMT)	2.60	2.75	3.18	12.16	14.88	18.71	0.92	0.47	0.08
Scenario 1 - Low leakage	2.48	2.56	3.10	11.59	14.49	18.23	0.92	0.50	0.08
Scenario 2 - 75 mm floor	2.61	2.75	3.20	12.23	14.96	18.82	0.92	0.46	0.08
Scenario 3 - No cooker	2.60	2.75	3.18	12.18	14.89	18.73	0.92	0.47	0.08
Scenario 4 - No moisture	2.61	2.76	3.19	12.21	14.93	18.78	0.92	0.47	0.08
Scenario 5 - No ventilation	1.12	1.32	1.57	5.22	7.37	9.27	0.97	0.87	0.04

Table E.28: Validation metrics for the living room air temperature for 10:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	2.38	2.61	3.07	10.26	13.26	16.01	0.91	0.55	0.07
Reference Case (HAMT)	2.22	2.53	2.97	9.57	12.82	15.48	0.91	0.57	0.07
Scenario 1 - Low leakage	2.09	2.47	2.92	9.01	12.62	15.24	0.90	0.59	0.06
Scenario 2 - 75 mm floor	2.24	2.54	2.99	9.65	12.89	15.57	0.91	0.57	0.07
Scenario 3 - No cooker	2.22	2.53	2.97	9.59	12.82	15.49	0.91	0.57	0.07
Scenario 4 - No moisture	2.21	2.52	2.96	9.52	12.76	15.41	0.91	0.58	0.07
Scenario 5 - No ventilation	0.47	1.33	1.81	2.03	7.81	9.44	0.93	0.84	0.04

Table E.29: Validation metrics for the living room air temperature for 11:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	2.06	2.14	2.85	8.25	11.43	14.49	0.91	0.65	0.06
Reference Case (HAMT)	2.04	2.17	2.83	8.19	11.36	14.40	0.91	0.65	0.06
Scenario 1 - Low leakage	1.91	2.17	2.82	7.68	11.33	14.36	0.90	0.65	0.06
Scenario 2 - 75 mm floor	2.07	2.20	2.85	8.31	11.44	14.50	0.92	0.65	0.06
Scenario 3 - No cooker	2.04	2.17	2.83	8.20	11.36	14.40	0.91	0.65	0.06
Scenario 4 - No moisture	2.00	2.14	2.80	8.04	11.25	14.26	0.91	0.66	0.06
Scenario 5 - No ventilation	0.02	1.14	1.37	0.08	5.51	6.99	0.96	0.92	0.03

Table E.30: Validation metrics for the living room air temperature for 12:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.93	2.52	3.15	7.23	11.77	21.68	0.84	0.48	0.06
Reference Case (HAMT)	2.08	2.47	3.13	7.76	11.70	21.54	0.85	0.48	0.06
Scenario 1 - Low leakage	1.92	2.52	3.12	7.19	11.67	21.49	0.84	0.49	0.06
Scenario 2 - 75 mm floor	2.12	2.47	3.14	7.94	11.75	21.63	0.86	0.48	0.06
Scenario 3 - No cooker	2.08	2.47	3.13	7.77	11.71	21.55	0.85	0.48	0.06
Scenario 4 - No moisture	2.02	2.44	3.10	7.55	11.58	21.31	0.85	0.50	0.06
Scenario 5 - No ventilation	0.03	1.09	1.41	0.10	5.29	9.73	0.97	0.89	0.03

Table E.31: Validation metrics for the living room air temperature for 13:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.66	2.56	2.88	2.40	10.43	20.63	0.79	0.59	0.05
Reference Case (HAMT)	0.97	2.42	2.80	3.51	10.14	20.05	0.82	0.62	0.05
Scenario 1 - Low leakage	0.78	2.57	2.90	2.81	10.50	20.77	0.79	0.59	0.05
Scenario 2 - 75 mm floor	1.04	2.40	2.79	3.78	10.12	20.01	0.82	0.62	0.05
Scenario 3 - No cooker	0.97	2.42	2.80	3.51	10.14	20.05	0.82	0.62	0.05
Scenario 4 - No moisture	0.90	2.40	2.77	3.25	10.05	19.87	0.82	0.62	0.05
Scenario 5 - No ventilation	-0.97	1.62	1.75	-3.50	6.36	12.57	0.95	0.85	0.03

Table E.32: Validation metrics for the living room air temperature for 14:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.42	1.12	1.65	1.48	5.85	10.14	0.95	0.89	0.03
Reference Case (HAMT)	0.83	1.27	1.75	2.95	6.21	10.76	0.95	0.88	0.03
Scenario 1 - Low leakage	0.70	1.21	1.75	2.48	6.19	10.73	0.95	0.88	0.03
Scenario 2 - 75 mm floor	0.92	1.33	1.79	3.28	6.35	11.01	0.95	0.87	0.03
Scenario 3 - No cooker	0.83	1.27	1.75	2.95	6.21	10.76	0.95	0.88	0.03
Scenario 4 - No moisture	0.72	1.24	1.70	2.55	6.04	10.47	0.95	0.88	0.03
Scenario 5 - No ventilation	-1.45	1.80	1.98	-5.14	7.04	12.20	0.96	0.84	0.03

Table E.33: Validation metrics for the living room air temperature for 15:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.15	1.85	2.16	4.02	7.54	14.26	0.95	0.81	0.04
Reference Case (HAMT)	1.46	2.01	2.27	5.12	7.92	14.99	0.95	0.79	0.04
Scenario 1 - Low leakage	1.45	1.99	2.25	5.06	7.85	14.86	0.95	0.79	0.04
Scenario 2 - 75 mm floor	1.54	2.08	2.31	5.38	8.06	15.26	0.95	0.78	0.04
Scenario 3 - No cooker	1.46	2.01	2.27	5.12	7.92	14.99	0.95	0.79	0.04
Scenario 4 - No moisture	1.38	1.96	2.23	4.82	7.79	14.74	0.95	0.80	0.04
Scenario 5 - No ventilation	-1.74	2.05	2.34	-6.07	8.17	15.46	0.95	0.78	0.04

Table E.34: Validation metrics for the living room air temperature for 16:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.64	1.68	2.09	2.23	7.29	13.01	0.95	0.80	0.04
Reference Case (HAMT)	0.96	1.73	2.12	3.35	7.42	13.23	0.94	0.79	0.04
Scenario 1 - Low leakage	0.95	1.72	2.11	3.31	7.37	13.16	0.95	0.79	0.04
Scenario 2 - 75 mm floor	1.04	1.78	2.15	3.64	7.50	13.39	0.94	0.78	0.04
Scenario 3 - No cooker	0.96	1.73	2.12	3.35	7.42	13.23	0.94	0.79	0.04
Scenario 4 - No moisture	0.87	1.71	2.09	3.04	7.31	13.04	0.95	0.80	0.04
Scenario 5 - No ventilation	-2.02	2.36	2.64	-7.06	9.22	16.45	0.94	0.67	0.04

Table E.35: Validation metrics for the living room air temperature for 17:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.43	2.30	3.02	-5.25	11.13	22.58	0.86	0.39	0.05
Reference Case (HAMT)	-0.93	2.07	2.71	-3.41	9.99	20.26	0.86	0.51	0.05
Scenario 1 - Low leakage	-0.99	2.06	2.72	-3.63	10.01	20.29	0.86	0.51	0.05
Scenario 2 - 75 mm floor	-0.78	2.00	2.62	-2.88	9.65	19.58	0.86	0.54	0.05
Scenario 3 - No cooker	-0.93	2.07	2.71	-3.42	9.99	20.26	0.86	0.51	0.05
Scenario 4 - No moisture	-1.05	2.10	2.79	-3.88	10.26	20.82	0.87	0.48	0.05
Scenario 5 - No ventilation	-3.11	3.48	3.91	-11.43	14.38	29.17	0.87	-0.01	0.07

Table E.36: Validation metrics for the living room air temperature for 18:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.83	4.44	5.13	-15.01	20.13	45.32	0.58	-0.64	0.09
Reference Case (HAMT)	-3.29	3.94	4.55	-12.91	17.85	40.20	0.64	-0.29	0.08
Scenario 1 - Low leakage	-3.51	4.16	4.85	-13.78	19.01	42.81	0.59	-0.47	0.09
Scenario 2 - 75 mm floor	-3.14	3.80	4.39	-12.32	17.22	38.77	0.66	-0.20	0.08
Scenario 3 - No cooker	-1.85	2.72	3.12	-7.25	12.22	27.52	0.79	0.39	0.06
Scenario 4 - No moisture	-3.37	4.00	4.61	-13.23	18.07	40.69	0.65	-0.32	0.08
Scenario 5 - No ventilation	-6.38	6.38	6.64	-25.01	26.05	58.65	0.92	-1.75	0.11

Table E.37: Validation metrics for the living room air temperature for 19:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.98	4.19	4.39	-16.52	18.24	35.96	0.89	-0.26	0.08
Reference Case (HAMT)	-3.30	3.49	3.70	-13.70	15.39	30.33	0.90	0.10	0.07
Scenario 1 - Low leakage	-3.56	3.75	3.98	-14.81	16.54	32.60	0.89	-0.04	0.08
Scenario 2 - 75 mm floor	-3.05	3.24	3.47	-12.67	14.41	28.40	0.91	0.21	0.07
Scenario 3 - No cooker	-3.14	3.34	3.54	-13.04	14.73	29.03	0.91	0.18	0.07
Scenario 4 - No moisture	-3.47	3.64	3.85	-14.41	15.99	31.52	0.91	0.03	0.07
Scenario 5 - No ventilation	-4.26	4.27	4.55	-17.72	18.90	37.25	0.93	-0.35	0.09

Table E.38: Validation metrics for the living room air temperature for 20:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.18	3.39	3.59	-13.65	15.37	29.60	0.91	0.18	0.07
Reference Case (HAMT)	-2.67	2.86	3.08	-11.45	13.21	25.43	0.92	0.40	0.06
Scenario 1 - Low leakage	-3.00	3.18	3.42	-12.86	14.66	28.22	0.91	0.26	0.07
Scenario 2 - 75 mm floor	-2.43	2.62	2.86	-10.42	12.26	23.61	0.93	0.48	0.06
Scenario 3 - No cooker	-2.62	2.81	3.03	-11.23	12.97	24.97	0.92	0.42	0.06
Scenario 4 - No moisture	-2.80	2.98	3.18	-12.01	13.62	26.22	0.93	0.36	0.06
Scenario 5 - No ventilation	-3.41	3.46	3.68	-14.63	15.77	30.35	0.94	0.14	0.07

Table E.39: Validation metrics for the living room air temperature for 21:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.24	2.42	2.68	-9.87	11.85	20.10	0.94	0.60	0.06
Reference Case (HAMT)	-1.94	2.12	2.42	-8.58	10.68	18.12	0.95	0.67	0.05
Scenario 1 - Low leakage	-2.31	2.46	2.79	-10.19	12.30	20.87	0.94	0.57	0.06
Scenario 2 - 75 mm floor	-1.71	1.94	2.24	-7.57	9.87	16.75	0.95	0.72	0.05
Scenario 3 - No cooker	-1.90	2.08	2.37	-8.41	10.48	17.79	0.95	0.69	0.05
Scenario 4 - No moisture	-2.02	2.17	2.46	-8.91	10.85	18.42	0.95	0.66	0.05
Scenario 5 - No ventilation	-2.63	2.66	2.92	-11.62	12.87	21.84	0.96	0.53	0.06

Table E.40: Validation metrics for the living room air temperature for 22:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.08	1.46	1.68	-4.94	7.68	12.67	0.96	0.84	0.04
Reference Case (HAMT)	-1.02	1.41	1.62	-4.68	7.42	12.23	0.96	0.85	0.04
Scenario 1 - Low leakage	-1.35	1.69	1.91	-6.19	8.76	14.44	0.96	0.79	0.04
Scenario 2 - 75 mm floor	-0.80	1.31	1.49	-3.68	6.82	11.25	0.97	0.87	0.03
Scenario 3 - No cooker	-0.99	1.38	1.58	-4.53	7.26	11.97	0.96	0.86	0.03
Scenario 4 - No moisture	-1.05	1.41	1.62	-4.79	7.41	12.22	0.96	0.85	0.04
Scenario 5 - No ventilation	-1.50	1.67	1.87	-6.88	8.54	14.09	0.97	0.80	0.04

Table E.41: Validation metrics for the living room air temperature for 23:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	-0.40	1.31	1.48	-1.91	7.01	10.39	0.96	0.89	0.03
Reference Case (HAMT)	-0.53	1.31	1.49	-2.49	7.04	10.43	0.97	0.88	0.03
Scenario 1 - Low leakage	-0.82	1.46	1.68	-3.87	7.92	11.74	0.96	0.85	0.04
Scenario 2 - 75 mm floor	-0.32	1.28	1.45	-1.53	6.83	10.12	0.97	0.89	0.03
Scenario 3 - No cooker	-0.50	1.29	1.46	-2.36	6.92	10.25	0.97	0.89	0.03
Scenario 4 - No moisture	-0.51	1.31	1.48	-2.42	7.01	10.39	0.97	0.89	0.03
Scenario 5 - No ventilation	-0.89	1.38	1.54	-4.18	7.27	10.78	0.97	0.88	0.04

E.6.1.5 Summer Hourly Validation Metrics

The second hourly-based validation analysis considered only results from the summer week. The validation metrics for the living room air temperature are presented in Tables E.42 to E.65.

Table E.42: Validation metrics for the living room air temperature for 00:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	0.91	1.10	1.28	3.62	5.12	17.20	0.97	0.66	0.03
Reference Case (HAMT)	0.70	0.96	1.13	2.78	4.51	15.12	0.98	0.73	0.02
Scenario 1 - Low leakage	0.43	0.91	1.08	1.73	4.30	14.44	0.97	0.76	0.02
Scenario 2 - 75 mm floor	0.94	1.08	1.31	3.78	5.24	17.60	0.98	0.64	0.03
Scenario 3 - No cooker	0.70	0.96	1.13	2.80	4.52	15.17	0.98	0.73	0.02
Scenario 4 - No moisture	0.76	0.99	1.17	3.03	4.67	15.66	0.98	0.72	0.02
Scenario 5 - No ventilation	0.19	0.82	0.96	0.75	3.83	12.85	0.98	0.81	0.02

Table E.43: Validation metrics for the living room air temperature for 01:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.25	1.25	1.45	5.10	5.95	19.53	0.95	0.56	0.03
Reference Case (HAMT)	0.89	1.01	1.15	3.64	4.69	15.39	0.96	0.73	0.02
Scenario 1 - Low leakage	0.66	1.00	1.06	2.72	4.32	14.17	0.96	0.77	0.02
Scenario 2 - 75 mm floor	1.11	1.12	1.34	4.54	5.46	17.93	0.96	0.63	0.03
Scenario 3 - No cooker	0.89	1.01	1.15	3.66	4.71	15.44	0.96	0.73	0.02
Scenario 4 - No moisture	0.98	1.04	1.21	3.99	4.97	16.31	0.96	0.69	0.03
Scenario 5 - No ventilation	0.50	0.92	0.94	2.06	3.83	12.57	0.96	0.82	0.02

Table E.44: Validation metrics for the living room air temperature for 02:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.74	1.74	1.86	7.23	7.76	22.86	0.97	0.36	0.04
Reference Case (HAMT)	1.26	1.28	1.43	5.27	5.94	17.51	0.98	0.62	0.03
Scenario 1 - Low leakage	1.04	1.17	1.29	4.31	5.36	15.81	0.98	0.69	0.03
Scenario 2 - 75 mm floor	1.46	1.46	1.62	6.09	6.72	19.82	0.98	0.52	0.03
Scenario 3 - No cooker	1.27	1.28	1.43	5.29	5.96	17.56	0.98	0.62	0.03
Scenario 4 - No moisture	1.37	1.37	1.51	5.69	6.30	18.58	0.98	0.58	0.03
Scenario 5 - No ventilation	0.97	1.13	1.23	4.02	5.11	15.05	0.97	0.72	0.03

Table E.45: Validation metrics for the living room air temperature for 03:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.16	2.16	2.28	9.12	9.63	26.87	0.96	0.09	0.05
Reference Case (HAMT)	1.60	1.60	1.74	6.76	7.36	20.54	0.97	0.47	0.04
Scenario 1 - Low leakage	1.41	1.49	1.62	5.96	6.82	19.04	0.97	0.54	0.04
Scenario 2 - 75 mm floor	1.78	1.78	1.92	7.52	8.09	22.60	0.97	0.36	0.04
Scenario 3 - No cooker	1.61	1.61	1.75	6.78	7.37	20.59	0.97	0.47	0.04
Scenario 4 - No moisture	1.71	1.71	1.85	7.23	7.79	21.74	0.97	0.41	0.04
Scenario 5 - No ventilation	1.36	1.45	1.56	5.73	6.59	18.39	0.97	0.57	0.03

Table E.46: Validation metrics for the living room air temperature for 04:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.42	2.42	2.53	10.37	10.87	27.57	0.96	0.01	0.06
Reference Case (HAMT)	1.79	1.79	1.93	7.67	8.28	21.02	0.98	0.42	0.04
Scenario 1 - Low leakage	1.62	1.69	1.83	6.97	7.87	19.96	0.97	0.48	0.04
Scenario 2 - 75 mm floor	1.95	1.95	2.09	8.35	8.95	22.72	0.98	0.33	0.05
Scenario 3 - No cooker	1.79	1.79	1.93	7.69	8.30	21.05	0.98	0.42	0.04
Scenario 4 - No moisture	1.91	1.91	2.04	8.18	8.75	22.19	0.97	0.36	0.05
Scenario 5 - No ventilation	1.60	1.65	1.78	6.85	7.65	19.40	0.97	0.51	0.04

Table E.47: Validation metrics for the living room air temperature for 05:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.51	2.51	2.66	10.99	11.65	28.58	0.94	-0.09	0.06
Reference Case (HAMT)	1.84	1.84	2.00	8.04	8.77	21.51	0.96	0.38	0.05
Scenario 1 - Low leakage	1.69	1.77	1.92	7.38	8.41	20.62	0.95	0.43	0.04
Scenario 2 - 75 mm floor	1.98	1.98	2.14	8.64	9.36	22.95	0.96	0.30	0.05
Scenario 3 - No cooker	1.84	1.84	2.01	8.05	8.78	21.54	0.96	0.38	0.05
Scenario 4 - No moisture	1.96	1.96	2.12	8.57	9.26	22.72	0.96	0.31	0.05
Scenario 5 - No ventilation	1.70	1.75	1.90	7.44	8.32	20.42	0.96	0.44	0.04

Table E.48: Validation metrics for the living room air temperature for 06:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.65	2.65	2.80	11.78	12.44	30.89	0.93	-0.27	0.07
Reference Case (HAMT)	1.94	1.94	2.10	8.64	9.36	23.24	0.95	0.28	0.05
Scenario 1 - Low leakage	1.78	1.86	2.00	7.92	8.88	22.06	0.95	0.35	0.05
Scenario 2 - 75 mm floor	2.06	2.06	2.22	9.17	9.88	24.54	0.95	0.20	0.05
Scenario 3 - No cooker	1.94	1.94	2.11	8.65	9.37	23.27	0.95	0.28	0.05
Scenario 4 - No moisture	2.07	2.07	2.23	9.20	9.90	24.59	0.95	0.19	0.05
Scenario 5 - No ventilation	1.86	1.89	2.05	8.29	9.12	22.65	0.95	0.32	0.05

Table E.49: Validation metrics for the living room air temperature for 07:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.85	2.85	3.03	12.80	13.63	39.19	0.89	-0.77	0.07
Reference Case (HAMT)	2.13	2.13	2.33	9.55	10.47	30.12	0.92	-0.04	0.05
Scenario 1 - Low leakage	1.94	1.96	2.23	8.70	10.02	28.81	0.89	0.05	0.05
Scenario 2 - 75 mm floor	2.23	2.23	2.43	10.02	10.93	31.42	0.92	-0.14	0.06
Scenario 3 - No cooker	2.13	2.13	2.33	9.56	10.49	30.15	0.92	-0.05	0.05
Scenario 4 - No moisture	2.25	2.25	2.44	10.11	10.99	31.59	0.92	-0.15	0.06
Scenario 5 - No ventilation	2.10	2.10	2.30	9.42	10.31	29.66	0.92	-0.01	0.05

Table E.50: Validation metrics for the living room air temperature for 08:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.88	2.88	3.01	12.24	12.77	39.24	0.96	-0.73	0.07
Reference Case (HAMT)	2.24	2.24	2.41	9.49	10.21	31.37	0.97	-0.11	0.05
Scenario 1 - Low leakage	2.00	2.00	2.25	8.47	9.56	29.39	0.94	0.03	0.05
Scenario 2 - 75 mm floor	2.33	2.33	2.50	9.87	10.62	32.64	0.97	-0.20	0.06
Scenario 3 - No cooker	2.24	2.24	2.41	9.49	10.22	31.39	0.97	-0.11	0.05
Scenario 4 - No moisture	2.35	2.35	2.50	9.96	10.62	32.64	0.97	-0.20	0.06
Scenario 5 - No ventilation	1.90	1.90	2.10	8.06	8.91	27.38	0.97	0.16	0.05

Table E.51: Validation metrics for the living room air temperature for 09:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	4.24	4.24	4.36	16.98	17.43	51.06	0.94	-1.89	0.09
Reference Case (HAMT)	4.12	4.12	4.23	16.47	16.93	49.57	0.94	-1.72	0.09
Scenario 1 - Low leakage	4.08	4.08	4.19	16.34	16.79	49.18	0.94	-1.68	0.09
Scenario 2 - 75 mm floor	4.14	4.14	4.25	16.58	17.03	49.87	0.94	-1.76	0.09
Scenario 3 - No cooker	4.12	4.12	4.23	16.47	16.93	49.58	0.94	-1.72	0.09
Scenario 4 - No moisture	4.12	4.12	4.24	16.49	16.96	49.67	0.94	-1.73	0.09
Scenario 5 - No ventilation	1.18	1.29	1.64	4.72	6.56	19.20	0.90	0.59	0.03

Table E.52: Validation metrics for the living room air temperature for 10:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.57	3.57	3.71	13.46	13.98	30.36	0.96	-0.17	0.07
Reference Case (HAMT)	3.54	3.54	3.68	13.35	13.87	30.12	0.96	-0.15	0.07
Scenario 1 - Low leakage	3.52	3.52	3.66	13.27	13.79	29.96	0.96	-0.14	0.07
Scenario 2 - 75 mm floor	3.57	3.57	3.70	13.45	13.96	30.31	0.96	-0.17	0.07
Scenario 3 - No cooker	3.54	3.54	3.68	13.35	13.86	30.10	0.96	-0.15	0.07
Scenario 4 - No moisture	3.51	3.51	3.65	13.24	13.77	29.90	0.96	-0.13	0.07
Scenario 5 - No ventilation	0.06	1.15	1.57	0.23	5.94	12.90	0.89	0.79	0.03

Table E.53: Validation metrics for the living room air temperature for 11:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.64	3.64	3.89	12.77	13.63	31.79	0.97	-0.20	0.07
Reference Case (HAMT)	3.69	3.69	3.90	12.94	13.66	31.86	0.97	-0.21	0.07
Scenario 1 - Low leakage	3.68	3.68	3.88	12.89	13.61	31.75	0.97	-0.20	0.07
Scenario 2 - 75 mm floor	3.73	3.73	3.92	13.06	13.76	32.08	0.97	-0.23	0.07
Scenario 3 - No cooker	3.69	3.69	3.90	12.95	13.66	31.86	0.97	-0.21	0.07
Scenario 4 - No moisture	3.63	3.63	3.86	12.74	13.53	31.54	0.97	-0.19	0.07
Scenario 5 - No ventilation	-0.34	1.63	1.72	-1.18	6.02	14.04	0.90	0.77	0.03

Table E.54: Validation metrics for the living room air temperature for 12:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.70	3.70	4.09	12.27	13.56	33.87	0.97	-0.34	0.07
Reference Case (HAMT)	3.82	3.82	4.15	12.67	13.75	34.35	0.97	-0.37	0.07
Scenario 1 - Low leakage	3.81	3.81	4.13	12.62	13.70	34.20	0.97	-0.36	0.07
Scenario 2 - 75 mm floor	3.86	3.86	4.18	12.81	13.85	34.59	0.97	-0.39	0.07
Scenario 3 - No cooker	3.82	3.82	4.15	12.67	13.76	34.35	0.97	-0.38	0.07
Scenario 4 - No moisture	3.74	3.74	4.09	12.41	13.58	33.90	0.97	-0.34	0.07
Scenario 5 - No ventilation	-0.27	1.07	1.28	-0.90	4.25	10.61	0.97	0.87	0.02

Table E.55: Validation metrics for the living room air temperature for 13:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.87	2.92	3.36	9.25	10.84	26.08	0.97	0.23	0.06
Reference Case (HAMT)	3.05	3.05	3.45	9.83	11.13	26.78	0.97	0.19	0.06
Scenario 1 - Low leakage	3.04	3.04	3.44	9.79	11.08	26.65	0.97	0.19	0.06
Scenario 2 - 75 mm floor	3.10	3.10	3.49	10.01	11.25	27.05	0.97	0.17	0.06
Scenario 3 - No cooker	3.05	3.05	3.45	9.83	11.13	26.78	0.97	0.19	0.06
Scenario 4 - No moisture	2.95	2.95	3.39	9.53	10.94	26.32	0.97	0.21	0.06
Scenario 5 - No ventilation	-0.83	1.45	1.56	-2.67	5.03	12.11	0.98	0.83	0.02

Table E.56: Validation metrics for the living room air temperature for 14:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.18	1.57	2.11	3.73	6.63	13.62	0.96	0.76	0.03
Reference Case (HAMT)	1.64	1.68	2.27	5.17	7.15	14.67	0.96	0.72	0.04
Scenario 1 - Low leakage	1.60	1.65	2.24	5.05	7.06	14.48	0.96	0.73	0.04
Scenario 2 - 75 mm floor	1.75	1.75	2.32	5.52	7.31	15.01	0.96	0.71	0.04
Scenario 3 - No cooker	1.64	1.68	2.27	5.18	7.15	14.67	0.96	0.72	0.04
Scenario 4 - No moisture	1.46	1.64	2.20	4.59	6.92	14.21	0.96	0.74	0.04
Scenario 5 - No ventilation	-1.16	1.86	1.96	-3.66	6.17	12.66	0.95	0.79	0.03

Table E.57: Validation metrics for the living room air temperature for 15:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.29	1.49	1.82	4.02	5.68	12.52	0.99	0.82	0.03
Reference Case (HAMT)	1.74	1.74	2.06	5.40	6.41	14.14	0.99	0.77	0.03
Scenario 1 - Low leakage	1.70	1.70	2.02	5.28	6.29	13.88	0.99	0.78	0.03
Scenario 2 - 75 mm floor	1.85	1.85	2.13	5.75	6.63	14.62	0.99	0.76	0.03
Scenario 3 - No cooker	1.74	1.74	2.06	5.40	6.41	14.14	0.99	0.77	0.03
Scenario 4 - No moisture	1.59	1.64	1.98	4.93	6.15	13.57	0.99	0.79	0.03
Scenario 5 - No ventilation	-1.22	1.85	2.22	-3.79	6.91	15.24	0.94	0.74	0.03

Table E.58: Validation metrics for the living room air temperature for 16:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.61	1.35	1.86	1.90	5.83	12.97	0.96	0.79	0.03
Reference Case (HAMT)	1.06	1.40	1.93	3.31	6.03	13.41	0.96	0.77	0.03
Scenario 1 - Low leakage	1.03	1.40	1.91	3.21	5.97	13.28	0.96	0.77	0.03
Scenario 2 - 75 mm floor	1.18	1.50	1.97	3.69	6.16	13.70	0.96	0.76	0.03
Scenario 3 - No cooker	1.06	1.40	1.93	3.31	6.03	13.41	0.96	0.77	0.03
Scenario 4 - No moisture	0.90	1.37	1.86	2.80	5.82	12.96	0.96	0.79	0.03
Scenario 5 - No ventilation	-1.70	2.38	2.68	-5.32	8.38	18.65	0.91	0.56	0.04

Table E.59: Validation metrics for the living room air temperature for 17:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.34	2.80	3.77	-4.46	12.53	38.40	0.81	-0.75	0.06
Reference Case (HAMT)	-0.81	2.61	3.45	-2.69	11.49	35.22	0.80	-0.47	0.06
Scenario 1 - Low leakage	-0.84	2.60	3.45	-2.79	11.46	35.12	0.80	-0.46	0.06
Scenario 2 - 75 mm floor	-0.65	2.55	3.35	-2.15	11.15	34.16	0.80	-0.39	0.05
Scenario 3 - No cooker	-0.81	2.61	3.45	-2.69	11.49	35.22	0.80	-0.47	0.06
Scenario 4 - No moisture	-1.02	2.65	3.56	-3.40	11.84	36.29	0.80	-0.56	0.06
Scenario 5 - No ventilation	-3.33	4.09	4.56	-11.08	15.16	46.46	0.80	-1.56	0.07

Table E.60: Validation metrics for the living room air temperature for 18:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.90	2.12	2.54	-3.11	8.80	37.92	0.92	-0.40	0.04
Reference Case (HAMT)	-0.65	1.94	2.39	-2.25	8.27	35.61	0.91	-0.24	0.04
Scenario 1 - Low leakage	-0.66	1.95	2.39	-2.28	8.27	35.62	0.91	-0.24	0.04
Scenario 2 - 75 mm floor	-0.58	1.89	2.35	-2.01	8.13	35.02	0.91	-0.20	0.04
Scenario 3 - No cooker	-0.09	1.82	2.41	-0.30	8.35	35.98	0.91	-0.26	0.04
Scenario 4 - No moisture	-0.75	2.01	2.43	-2.59	8.44	36.34	0.92	-0.29	0.04
Scenario 5 - No ventilation	-6.55	6.55	7.00	-22.71	24.26	104.51	0.85	-9.65	0.11

Table E.61: Validation metrics for the living room air temperature for 19:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.17	3.59	3.82	-11.58	13.95	48.09	0.86	-1.52	0.07
Reference Case (HAMT)	-2.42	2.80	3.02	-8.84	11.02	38.02	0.87	-0.57	0.05
Scenario 1 - Low leakage	-2.61	2.97	3.21	-9.52	11.73	40.47	0.86	-0.78	0.06
Scenario 2 - 75 mm floor	-2.15	2.53	2.75	-7.84	10.04	34.61	0.87	-0.30	0.05
Scenario 3 - No cooker	-2.37	2.77	2.99	-8.64	10.90	37.61	0.87	-0.54	0.05
Scenario 4 - No moisture	-2.71	3.07	3.30	-9.91	12.04	41.51	0.87	-0.87	0.06
Scenario 5 - No ventilation	-4.17	4.18	4.63	-15.24	16.91	58.32	0.84	-2.70	0.08

Table E.62: Validation metrics for the living room air temperature for 20:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.33	2.74	2.89	-8.69	10.81	37.88	0.88	-0.66	0.05
Reference Case (HAMT)	-1.73	2.10	2.25	-6.45	8.40	29.43	0.89	0.00	0.04
Scenario 1 - Low leakage	-1.98	2.34	2.51	-7.40	9.37	32.84	0.88	-0.25	0.04
Scenario 2 - 75 mm floor	-1.46	1.84	1.99	-5.44	7.44	26.07	0.90	0.21	0.04
Scenario 3 - No cooker	-1.71	2.09	2.24	-6.39	8.36	29.30	0.89	0.01	0.04
Scenario 4 - No moisture	-1.96	2.30	2.46	-7.32	9.18	32.19	0.89	-0.20	0.04
Scenario 5 - No ventilation	-3.06	3.17	3.47	-11.45	12.96	45.43	0.87	-1.39	0.06

Table E.63: Validation metrics for the living room air temperature for 21:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.30	1.67	1.87	-4.95	7.13	23.96	0.88	0.37	0.03
Reference Case (HAMT)	-0.94	1.29	1.48	-3.58	5.65	18.97	0.90	0.60	0.03
Scenario 1 - Low leakage	-1.24	1.55	1.79	-4.73	6.81	22.87	0.88	0.43	0.03
Scenario 2 - 75 mm floor	-0.68	1.14	1.29	-2.60	4.93	16.55	0.90	0.70	0.02
Scenario 3 - No cooker	-0.93	1.29	1.48	-3.53	5.62	18.89	0.90	0.61	0.03
Scenario 4 - No moisture	-1.08	1.37	1.59	-4.11	6.06	20.34	0.90	0.55	0.03
Scenario 5 - No ventilation	-2.19	2.25	2.58	-8.33	9.82	33.00	0.87	-0.20	0.05

Table E.64: Validation metrics for the living room air temperature for 22:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.23	1.00	1.16	-0.91	4.58	14.86	0.89	0.76	0.02
Reference Case (HAMT)	-0.13	0.90	1.04	-0.50	4.09	13.28	0.91	0.81	0.02
Scenario 1 - Low leakage	-0.42	1.11	1.27	-1.66	4.99	16.19	0.88	0.72	0.02
Scenario 2 - 75 mm floor	0.12	0.89	1.01	0.47	3.96	12.87	0.91	0.82	0.02
Scenario 3 - No cooker	-0.12	0.90	1.04	-0.47	4.09	13.28	0.91	0.81	0.02
Scenario 4 - No moisture	-0.18	0.91	1.05	-0.71	4.11	13.35	0.91	0.81	0.02
Scenario 5 - No ventilation	-0.97	1.31	1.53	-3.81	6.01	19.50	0.89	0.59	0.03

Table E.65: Validation metrics for the living room air temperature for 23:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.68	1.14	1.29	2.71	5.14	16.52	0.89	0.72	0.03
Reference Case (HAMT)	0.58	1.00	1.16	2.31	4.63	14.87	0.91	0.77	0.02
Scenario 1 - Low leakage	0.31	0.97	1.16	1.24	4.66	14.97	0.89	0.77	0.02
Scenario 2 - 75 mm floor	0.81	1.09	1.28	3.24	5.14	16.50	0.92	0.72	0.03
Scenario 3 - No cooker	0.59	1.00	1.16	2.34	4.65	14.93	0.91	0.77	0.02
Scenario 4 - No moisture	0.59	1.01	1.16	2.37	4.66	14.95	0.91	0.77	0.02
Scenario 5 - No ventilation	-0.04	1.02	1.15	-0.14	4.58	14.72	0.88	0.78	0.02

E.6.1.6 Winter Hourly Validation Metrics

The final hourly-based validation analysis considered only results from the winter week. The validation metrics for the living room air temperature are presented in Tables E.66 to E.89.

Table E.66: Validation metrics for the living room air temperature for 00:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.21	1.21	1.41	-7.55	8.79	24.25	0.93	0.45	0.04
Reference Case (HAMT)	-1.50	1.50	1.66	-9.33	10.30	28.42	0.93	0.24	0.05
Scenario 1 - Low leakage	-1.77	1.77	1.92	-11.03	11.91	32.86	0.93	-0.02	0.06
Scenario 2 - 75 mm floor	-1.35	1.35	1.52	-8.39	9.42	25.99	0.93	0.36	0.04
Scenario 3 - No cooker	-1.46	1.46	1.62	-9.07	10.05	27.74	0.93	0.28	0.05
Scenario 4 - No moisture	-1.48	1.48	1.64	-9.19	10.16	28.06	0.93	0.26	0.05
Scenario 5 - No ventilation	-1.61	1.61	1.75	-9.98	10.90	30.09	0.93	0.15	0.05

Table E.67: Validation metrics for the living room air temperature for 01:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.79	1.02	1.09	-5.07	7.03	19.09	0.92	0.67	0.03
Reference Case (HAMT)	-1.17	1.25	1.37	-7.53	8.82	23.96	0.93	0.47	0.04
Scenario 1 - Low leakage	-1.44	1.45	1.62	-9.23	10.38	28.19	0.92	0.27	0.05
Scenario 2 - 75 mm floor	-1.03	1.15	1.25	-6.65	8.04	21.84	0.93	0.56	0.04
Scenario 3 - No cooker	-1.14	1.22	1.34	-7.30	8.62	23.39	0.93	0.50	0.04
Scenario 4 - No moisture	-1.15	1.23	1.35	-7.36	8.68	23.56	0.93	0.49	0.04
Scenario 5 - No ventilation	-1.26	1.31	1.45	-8.13	9.34	25.35	0.93	0.41	0.04

Table E.68: Validation metrics for the living room air temperature for 02:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.41	0.91	0.97	-2.68	6.42	18.10	0.90	0.77	0.03
Reference Case (HAMT)	-0.87	1.06	1.20	-5.77	7.93	22.37	0.91	0.64	0.04
Scenario 1 - Low leakage	-1.14	1.27	1.43	-7.51	9.48	26.75	0.91	0.49	0.05
Scenario 2 - 75 mm floor	-0.75	1.01	1.11	-4.99	7.37	20.78	0.92	0.69	0.04
Scenario 3 - No cooker	-0.84	1.05	1.18	-5.56	7.78	21.94	0.91	0.66	0.04
Scenario 4 - No moisture	-0.84	1.05	1.18	-5.58	7.79	21.97	0.91	0.66	0.04
Scenario 5 - No ventilation	-0.95	1.11	1.25	-6.31	8.30	23.41	0.92	0.61	0.04

Table E.69: Validation metrics for the living room air temperature for 03:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.28	0.74	0.88	-1.93	6.08	16.17	0.91	0.81	0.03
Reference Case (HAMT)	-0.82	1.08	1.14	-5.64	7.87	20.96	0.92	0.67	0.04
Scenario 1 - Low leakage	-1.07	1.29	1.38	-7.37	9.46	25.19	0.91	0.53	0.05
Scenario 2 - 75 mm floor	-0.73	1.01	1.08	-4.99	7.43	19.77	0.92	0.71	0.04
Scenario 3 - No cooker	-0.79	1.06	1.12	-5.45	7.73	20.58	0.92	0.68	0.04
Scenario 4 - No moisture	-0.79	1.06	1.12	-5.43	7.72	20.54	0.92	0.69	0.04
Scenario 5 - No ventilation	-0.89	1.13	1.20	-6.14	8.24	21.92	0.92	0.64	0.04

Table E.70: Validation metrics for the living room air temperature for 04:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.59	1.26	1.96	3.97	13.25	26.53	0.67	0.39	0.07
Reference Case (HAMT)	-0.01	1.44	1.80	-0.07	12.22	24.47	0.69	0.48	0.06
Scenario 1 - Low leakage	-0.26	1.63	1.90	-1.74	12.89	25.80	0.66	0.42	0.06
Scenario 2 - 75 mm floor	0.06	1.41	1.81	0.42	12.24	24.51	0.69	0.48	0.06
Scenario 3 - No cooker	0.01	1.43	1.80	0.10	12.23	24.48	0.69	0.48	0.06
Scenario 4 - No moisture	0.02	1.44	1.81	0.15	12.26	24.54	0.69	0.48	0.06
Scenario 5 - No ventilation	-0.07	1.46	1.80	-0.50	12.17	24.36	0.70	0.48	0.06

Table E.71: Validation metrics for the living room air temperature for 05:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.59	1.09	1.68	4.06	11.54	18.40	0.88	0.67	0.06
Reference Case (HAMT)	-0.03	1.25	1.56	-0.20	10.69	17.06	0.89	0.71	0.05
Scenario 1 - Low leakage	-0.18	1.52	1.83	-1.22	12.54	20.01	0.83	0.60	0.06
Scenario 2 - 75 mm floor	0.02	1.23	1.56	0.14	10.72	17.10	0.89	0.71	0.05
Scenario 3 - No cooker	-0.01	1.24	1.56	-0.05	10.69	17.05	0.89	0.71	0.05
Scenario 4 - No moisture	0.00	1.24	1.56	0.03	10.70	17.08	0.89	0.71	0.05
Scenario 5 - No ventilation	-0.08	1.27	1.56	-0.58	10.68	17.04	0.89	0.71	0.05

Table E.72: Validation metrics for the living room air temperature for 06:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.04	0.62	0.90	0.26	6.33	10.12	0.95	0.90	0.03
Reference Case (HAMT)	-0.57	0.94	1.02	-4.02	7.18	11.47	0.96	0.87	0.03
Scenario 1 - Low leakage	-0.54	0.97	1.08	-3.79	7.57	12.10	0.96	0.86	0.04
Scenario 2 - 75 mm floor	-0.54	0.92	1.01	-3.80	7.10	11.35	0.96	0.88	0.03
Scenario 3 - No cooker	-0.56	0.93	1.01	-3.90	7.11	11.37	0.96	0.88	0.03
Scenario 4 - No moisture	-0.54	0.92	1.01	-3.81	7.06	11.29	0.96	0.88	0.03
Scenario 5 - No ventilation	-0.62	0.97	1.05	-4.36	7.38	11.79	0.96	0.87	0.04

Table E.73: Validation metrics for the living room air temperature for 07:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.07	0.86	1.19	-0.49	8.60	13.52	0.92	0.83	0.04
Reference Case (HAMT)	-0.67	1.21	1.29	-4.89	9.39	14.76	0.92	0.79	0.04
Scenario 1 - Low leakage	-0.72	1.23	1.34	-5.21	9.69	15.23	0.92	0.78	0.05
Scenario 2 - 75 mm floor	-0.66	1.19	1.28	-4.78	9.32	14.65	0.92	0.80	0.04
Scenario 3 - No cooker	-0.66	1.19	1.29	-4.78	9.34	14.67	0.92	0.79	0.04
Scenario 4 - No moisture	-0.65	1.19	1.28	-4.69	9.31	14.64	0.92	0.80	0.04
Scenario 5 - No ventilation	-0.72	1.23	1.32	-5.19	9.57	15.04	0.92	0.78	0.05

Table E.74: Validation metrics for the living room air temperature for 08:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	0.44	0.88	1.14	2.93	7.50	14.73	0.94	0.79	0.04
Reference Case (HAMT)	-0.11	0.76	0.91	-0.72	6.02	11.83	0.95	0.87	0.03
Scenario 1 - Low leakage	-0.25	0.77	0.85	-1.62	5.60	11.01	0.95	0.89	0.03
Scenario 2 - 75 mm floor	-0.10	0.76	0.91	-0.68	5.99	11.77	0.94	0.87	0.03
Scenario 3 - No cooker	-0.10	0.77	0.91	-0.64	6.02	11.82	0.95	0.87	0.03
Scenario 4 - No moisture	-0.08	0.77	0.92	-0.55	6.06	11.90	0.95	0.87	0.03
Scenario 5 - No ventilation	-0.14	0.77	0.92	-0.95	6.09	11.97	0.95	0.86	0.03

Table E.75: Validation metrics for the living room air temperature for 09:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.52	1.81	1.96	8.58	11.04	29.26	0.89	0.30	0.06
Reference Case (HAMT)	1.08	1.38	1.53	6.09	8.61	22.82	0.90	0.57	0.04
Scenario 1 - Low leakage	0.87	1.04	1.26	4.90	7.10	18.81	0.92	0.71	0.04
Scenario 2 - 75 mm floor	1.08	1.36	1.53	6.10	8.62	22.84	0.90	0.57	0.04
Scenario 3 - No cooker	1.09	1.39	1.54	6.14	8.66	22.94	0.90	0.57	0.04
Scenario 4 - No moisture	1.10	1.40	1.55	6.20	8.73	23.13	0.90	0.56	0.04
Scenario 5 - No ventilation	1.05	1.36	1.51	5.94	8.50	22.53	0.90	0.58	0.04

Table E.76: Validation metrics for the living room air temperature for 10:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	1.19	1.65	2.27	5.99	11.44	23.51	0.74	0.31	0.06
Reference Case (HAMT)	0.90	1.52	2.03	4.52	10.25	21.07	0.76	0.44	0.05
Scenario 1 - Low leakage	0.66	1.42	1.93	3.32	9.73	19.99	0.75	0.50	0.05
Scenario 2 - 75 mm floor	0.91	1.51	2.04	4.57	10.27	21.11	0.75	0.44	0.05
Scenario 3 - No cooker	0.90	1.52	2.04	4.56	10.27	21.11	0.76	0.44	0.05
Scenario 4 - No moisture	0.90	1.52	2.04	4.55	10.28	21.13	0.75	0.44	0.05
Scenario 5 - No ventilation	0.88	1.51	2.02	4.42	10.18	20.93	0.76	0.45	0.05

Table E.77: Validation metrics for the living room air temperature for 11:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	0.47	0.65	1.06	2.20	4.96	11.12	0.94	0.85	0.02
Reference Case (HAMT)	0.39	0.64	0.92	1.82	4.29	9.63	0.95	0.89	0.02
Scenario 1 - Low leakage	0.15	0.67	0.93	0.71	4.36	9.77	0.94	0.89	0.02
Scenario 2 - 75 mm floor	0.42	0.68	0.93	1.95	4.37	9.79	0.95	0.88	0.02
Scenario 3 - No cooker	0.39	0.65	0.92	1.85	4.31	9.66	0.95	0.89	0.02
Scenario 4 - No moisture	0.37	0.64	0.91	1.76	4.29	9.62	0.95	0.89	0.02
Scenario 5 - No ventilation	0.38	0.64	0.91	1.77	4.27	9.56	0.95	0.89	0.02

Table E.78: Validation metrics for the living room air temperature for 12:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	0.17	1.34	1.76	0.71	7.54	36.67	0.93	-0.45	0.04
Reference Case (HAMT)	0.33	1.12	1.54	1.41	6.62	32.18	0.94	-0.12	0.03
Scenario 1 - Low leakage	0.04	1.23	1.56	0.18	6.67	32.41	0.92	-0.13	0.03
Scenario 2 - 75 mm floor	0.38	1.07	1.51	1.64	6.49	31.55	0.94	-0.07	0.03
Scenario 3 - No cooker	0.33	1.12	1.55	1.43	6.63	32.21	0.94	-0.12	0.03
Scenario 4 - No moisture	0.30	1.13	1.55	1.27	6.65	32.35	0.94	-0.13	0.03
Scenario 5 - No ventilation	0.33	1.11	1.53	1.40	6.58	31.97	0.94	-0.10	0.03

Table E.79: Validation metrics for the living room air temperature for 13:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.54	2.20	2.30	-6.37	9.50	45.07	0.55	-0.77	0.05
Reference Case (HAMT)	-1.11	1.80	1.94	-4.58	8.00	37.96	0.57	-0.26	0.04
Scenario 1 - Low leakage	-1.48	2.11	2.24	-6.13	9.25	43.87	0.50	-0.68	0.04
Scenario 2 - 75 mm floor	-1.02	1.70	1.86	-4.21	7.67	36.40	0.58	-0.16	0.04
Scenario 3 - No cooker	-1.11	1.80	1.94	-4.58	8.00	37.97	0.57	-0.26	0.04
Scenario 4 - No moisture	-1.16	1.84	1.97	-4.80	8.14	38.62	0.57	-0.30	0.04
Scenario 5 - No ventilation	-1.10	1.79	1.93	-4.57	7.97	37.83	0.57	-0.25	0.04

Table E.80: Validation metrics for the living room air temperature for 14:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.35	0.66	1.00	-1.43	4.07	13.26	0.92	0.82	0.02
Reference Case (HAMT)	0.02	0.87	0.99	0.08	4.03	13.13	0.91	0.82	0.02
Scenario 1 - Low leakage	-0.21	0.77	1.04	-0.84	4.22	13.74	0.91	0.80	0.02
Scenario 2 - 75 mm floor	0.10	0.92	1.01	0.40	4.12	13.42	0.91	0.81	0.02
Scenario 3 - No cooker	0.02	0.87	0.99	0.07	4.03	13.13	0.91	0.82	0.02
Scenario 4 - No moisture	-0.02	0.84	0.99	-0.09	4.00	13.05	0.91	0.82	0.02
Scenario 5 - No ventilation	-1.74	1.74	2.01	-7.06	8.16	26.59	0.95	0.26	0.04

Table E.81: Validation metrics for the living room air temperature for 15:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.01	2.22	2.44	4.03	9.75	32.27	0.77	-0.13	0.05
Reference Case (HAMT)	1.19	2.29	2.46	4.75	9.80	32.44	0.78	-0.14	0.05
Scenario 1 - Low leakage	1.20	2.29	2.45	4.77	9.77	32.36	0.78	-0.13	0.05
Scenario 2 - 75 mm floor	1.23	2.32	2.47	4.91	9.86	32.63	0.78	-0.15	0.05
Scenario 3 - No cooker	1.19	2.29	2.46	4.75	9.80	32.43	0.78	-0.14	0.05
Scenario 4 - No moisture	1.17	2.28	2.45	4.68	9.79	32.42	0.78	-0.14	0.05
Scenario 5 - No ventilation	-2.25	2.25	2.45	-8.99	9.77	32.34	0.95	-0.13	0.05

Table E.82: Validation metrics for the living room air temperature for 16:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.67	2.01	2.29	2.66	9.06	39.07	0.88	-0.36	0.05
Reference Case (HAMT)	0.86	2.05	2.30	3.40	9.12	39.30	0.89	-0.38	0.05
Scenario 1 - Low leakage	0.87	2.05	2.29	3.44	9.09	39.18	0.89	-0.37	0.05
Scenario 2 - 75 mm floor	0.90	2.06	2.31	3.58	9.16	39.48	0.89	-0.39	0.05
Scenario 3 - No cooker	0.86	2.05	2.30	3.40	9.11	39.29	0.89	-0.38	0.05
Scenario 4 - No moisture	0.84	2.04	2.30	3.33	9.10	39.25	0.89	-0.37	0.05
Scenario 5 - No ventilation	-2.34	2.34	2.59	-9.26	10.28	44.33	0.82	-0.75	0.05

Table E.83: Validation metrics for the living room air temperature for 17:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.51	1.79	2.02	-6.24	8.34	28.80	0.88	0.22	0.04
Reference Case (HAMT)	-1.05	1.52	1.67	-4.31	6.88	23.73	0.88	0.47	0.03
Scenario 1 - Low leakage	-1.13	1.53	1.70	-4.67	7.01	24.21	0.87	0.45	0.03
Scenario 2 - 75 mm floor	-0.92	1.46	1.59	-3.79	6.54	22.57	0.88	0.52	0.03
Scenario 3 - No cooker	-1.05	1.53	1.67	-4.32	6.88	23.76	0.88	0.47	0.03
Scenario 4 - No moisture	-1.08	1.54	1.69	-4.47	6.98	24.11	0.88	0.45	0.03
Scenario 5 - No ventilation	-2.88	2.88	3.12	-11.88	12.86	44.40	0.87	-0.85	0.06

Table E.84: Validation metrics for the living room air temperature for 18:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-6.76	6.76	6.80	-30.55	30.73	127.51	0.94	-8.81	0.13
Reference Case (HAMT)	-5.93	5.93	5.98	-26.83	27.02	112.13	0.95	-6.59	0.12
Scenario 1 - Low leakage	-6.37	6.37	6.42	-28.79	29.05	120.54	0.93	-7.77	0.13
Scenario 2 - 75 mm floor	-5.70	5.70	5.75	-25.78	25.98	107.80	0.95	-6.01	0.11
Scenario 3 - No cooker	-3.61	3.61	3.69	-16.31	16.67	69.18	0.94	-1.89	0.08
Scenario 4 - No moisture	-6.00	6.00	6.04	-27.13	27.32	113.35	0.95	-6.76	0.12
Scenario 5 - No ventilation	-6.20	6.20	6.25	-28.02	28.28	117.34	0.93	-7.31	0.12

Table E.85: Validation metrics for the living room air temperature for 19:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-4.78	4.78	4.90	-23.04	23.60	93.81	0.85	-7.49	0.11
Reference Case (HAMT)	-4.17	4.17	4.28	-20.11	20.62	82.00	0.86	-5.49	0.09
Scenario 1 - Low leakage	-4.52	4.52	4.62	-21.79	22.27	88.53	0.84	-6.56	0.10
Scenario 2 - 75 mm floor	-3.95	3.95	4.06	-19.05	19.57	77.80	0.86	-4.84	0.09
Scenario 3 - No cooker	-3.91	3.91	4.03	-18.85	19.40	77.12	0.86	-4.74	0.09
Scenario 4 - No moisture	-4.22	4.22	4.33	-20.35	20.87	82.97	0.86	-5.65	0.09
Scenario 5 - No ventilation	-4.36	4.36	4.46	-20.99	21.51	85.52	0.84	-6.06	0.10

Table E.86: Validation metrics for the living room air temperature for 20:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-4.04	4.04	4.17	-20.32	20.95	85.91	0.85	-5.30	0.09
Reference Case (HAMT)	-3.62	3.62	3.74	-18.19	18.78	77.01	0.86	-4.06	0.09
Scenario 1 - Low leakage	-4.02	4.02	4.14	-20.22	20.80	85.29	0.83	-5.21	0.09
Scenario 2 - 75 mm floor	-3.41	3.41	3.52	-17.12	17.71	72.63	0.86	-3.50	0.08
Scenario 3 - No cooker	-3.53	3.53	3.65	-17.75	18.35	75.23	0.86	-3.83	0.08
Scenario 4 - No moisture	-3.65	3.65	3.76	-18.34	18.92	77.58	0.86	-4.14	0.09
Scenario 5 - No ventilation	-3.76	3.76	3.88	-18.92	19.49	79.92	0.85	-4.45	0.09

Table E.87: Validation metrics for the living room air temperature for 21:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.17	3.17	3.30	-16.66	17.34	50.71	0.90	-1.58	0.08
Reference Case (HAMT)	-2.95	2.95	3.08	-15.49	16.19	47.36	0.90	-1.25	0.07
Scenario 1 - Low leakage	-3.37	3.37	3.51	-17.72	18.44	53.94	0.89	-1.92	0.08
Scenario 2 - 75 mm floor	-2.75	2.75	2.89	-14.42	15.15	44.32	0.90	-0.97	0.07
Scenario 3 - No cooker	-2.88	2.88	3.02	-15.13	15.84	46.33	0.90	-1.16	0.07
Scenario 4 - No moisture	-2.96	2.96	3.09	-15.54	16.24	47.49	0.90	-1.27	0.08
Scenario 5 - No ventilation	-3.08	3.08	3.22	-16.17	16.89	49.40	0.89	-1.45	0.08

Table E.88: Validation metrics for the living room air temperature for 22:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.93	1.93	2.07	-10.57	11.34	35.44	0.94	-0.23	0.05
Reference Case (HAMT)	-1.92	1.92	2.04	-10.52	11.19	34.99	0.94	-0.20	0.05
Scenario 1 - Low leakage	-2.28	2.28	2.39	-12.50	13.10	40.96	0.92	-0.64	0.06
Scenario 2 - 75 mm floor	-1.73	1.73	1.85	-9.47	10.15	31.71	0.94	0.02	0.05
Scenario 3 - No cooker	-1.86	1.86	1.98	-10.20	10.89	34.03	0.94	-0.13	0.05
Scenario 4 - No moisture	-1.91	1.91	2.03	-10.49	11.17	34.90	0.94	-0.19	0.05
Scenario 5 - No ventilation	-2.03	2.03	2.15	-11.16	11.80	36.88	0.93	-0.33	0.06

Table E.89: Validation metrics for the living room air temperature for 23:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.48	1.48	1.66	-8.55	9.56	28.81	0.94	0.19	0.05
Reference Case (HAMT)	-1.63	1.63	1.76	-9.40	10.14	30.56	0.94	0.09	0.05
Scenario 1 - Low leakage	-1.95	1.95	2.07	-11.23	11.90	35.86	0.93	-0.25	0.06
Scenario 2 - 75 mm floor	-1.46	1.46	1.59	-8.41	9.17	27.63	0.95	0.26	0.04
Scenario 3 - No cooker	-1.58	1.58	1.71	-9.12	9.88	29.76	0.95	0.14	0.05
Scenario 4 - No moisture	-1.62	1.62	1.75	-9.31	10.06	30.32	0.95	0.11	0.05
Scenario 5 - No ventilation	-1.74	1.74	1.85	-10.00	10.67	32.15	0.94	0.00	0.05

E.6.2 Living Room Relative Humidity

E.6.2.1 Overall Validation Metrics

Table E.90 contains the validation metrics for the living room relative humidity for the summer and winter weeks combined.

Table E.90: Validation metrics for the living room relative humidity for the summer and winter week combined

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-5.21	8.81	11.34	-10.26	22.31	20.66	0.88	0.36	0.10
Reference Case (HAMT)	-6.06	7.94	9.85	-11.93	19.39	17.96	0.88	0.51	0.09
Scenario 1 - Low leakage	-11.41	12.37	14.19	-22.45	27.92	25.86	0.86	-0.01	0.12
Scenario 2 - 75 mm floor	-7.63	9.05	10.99	-15.01	21.62	20.02	0.88	0.40	0.10
Scenario 3 - No cooker	-5.69	7.90	9.82	-11.19	19.33	17.90	0.87	0.52	0.09
Scenario 4 - No moisture	-2.70	5.29	7.21	-5.30	14.19	13.14	0.89	0.74	0.07
Scenario 5 - No ventilation	-8.80	9.71	11.74	-17.32	23.10	21.40	0.85	0.31	0.10

E.6.2.2 Weekly Validation Metrics

The validation metrics for the living room relative humidity for the summer and winter weeks are presented in Tables E.91 and E.92.

Table E.91: Validation metrics for the living room relative humidity for the summer week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-9.00	11.15	13.42	-17.35	25.87	24.95	0.87	-0.20	0.11
Reference Case (HAMT)	-9.80	10.98	12.34	-18.88	23.80	22.95	0.89	-0.01	0.11
Scenario 1 - Low leakage	-12.12	13.24	14.89	-23.36	28.72	27.69	0.86	-0.47	0.12
Scenario 2 - 75 mm floor	-11.09	12.14	13.57	-21.37	26.17	25.23	0.88	-0.22	0.11
Scenario 3 - No cooker	-9.83	10.98	12.35	-18.95	23.80	22.95	0.89	-0.01	0.11
Scenario 4 - No moisture	-3.92	6.01	8.13	-7.55	15.67	15.11	0.86	0.56	0.07
Scenario 5 - No ventilation	-13.17	13.43	14.73	-25.39	28.40	27.38	0.85	-0.44	0.12

Table E.92: Validation metrics for the living room relative humidity for the winter week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.42	6.46	8.77	-2.86	17.64	16.85	0.90	0.69	0.08
Reference Case (HAMT)	-2.33	4.90	6.46	-4.69	12.99	12.41	0.93	0.83	0.06
Scenario 1 - Low leakage	-10.70	11.49	13.45	-21.50	27.03	25.82	0.87	0.27	0.12
Scenario 2 - 75 mm floor	-4.17	5.97	7.56	-8.37	15.19	14.52	0.92	0.77	0.07
Scenario 3 - No cooker	-1.55	4.83	6.37	-3.11	12.81	12.24	0.92	0.84	0.06
Scenario 4 - No moisture	-1.47	4.58	6.15	-2.96	12.37	11.82	0.93	0.85	0.06
Scenario 5 - No ventilation	-4.44	6.00	7.66	-8.92	15.40	14.71	0.92	0.76	0.07

E.6.2.3 Daily Validation Metrics

The validation metrics for the living room relative humidity for the summer days are presented in Tables E.93 to E.99.

Table E.93: Validation metrics for the living room relative humidity for 23 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-8.11	9.47	11.02	-18.96	25.77	42.96	0.82	-0.38	0.11
Reference Case (HAMT)	-12.37	12.37	13.56	-28.93	31.71	52.88	0.94	-1.10	0.13
Scenario 1 - Low leakage	-15.73	15.73	17.43	-36.79	40.76	67.95	0.96	-2.46	0.17
Scenario 2 - 75 mm floor	-13.69	13.69	14.86	-32.02	34.74	57.91	0.95	-1.51	0.15
Scenario 3 - No cooker	-12.38	12.38	13.56	-28.95	31.71	52.88	0.94	-1.10	0.13
Scenario 4 - No moisture	-6.35	6.92	8.36	-14.86	19.55	32.60	0.83	0.20	0.09
Scenario 5 - No ventilation	-16.01	16.01	16.40	-37.44	38.34	63.93	0.97	-2.06	0.16

Table E.94: Validation metrics for the living room relative humidity for 24 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-4.67	7.22	9.08	-10.40	20.24	28.83	0.92	0.14	0.09
Reference Case (HAMT)	-9.36	10.67	12.64	-20.85	28.15	40.10	0.95	-0.67	0.12
Scenario 1 - Low leakage	-12.63	13.91	16.33	-28.15	36.37	51.81	0.96	-1.78	0.15
Scenario 2 - 75 mm floor	-11.40	12.55	14.91	-25.40	33.21	47.32	0.95	-1.32	0.14
Scenario 3 - No cooker	-9.37	10.62	12.62	-20.87	28.11	40.05	0.95	-0.66	0.12
Scenario 4 - No moisture	-2.10	4.20	6.23	-4.67	13.87	19.77	0.89	0.60	0.07
Scenario 5 - No ventilation	-16.81	16.81	17.19	-37.45	38.30	54.56	0.96	-2.08	0.16

Table E.95: Validation metrics for the living room relative humidity for 25 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-8.56	11.47	12.76	-16.83	25.09	46.91	0.72	-1.37	0.11
Reference Case (HAMT)	-10.12	12.35	13.14	-19.89	25.83	48.29	0.75	-1.51	0.12
Scenario 1 - Low leakage	-12.43	14.62	15.69	-24.43	30.85	57.67	0.75	-2.58	0.13
Scenario 2 - 75 mm floor	-11.55	13.59	14.57	-22.70	28.64	53.53	0.75	-2.09	0.13
Scenario 3 - No cooker	-10.15	12.30	13.11	-19.95	25.77	48.18	0.75	-1.50	0.12
Scenario 4 - No moisture	-3.69	6.49	8.31	-7.26	16.33	30.53	0.67	0.00	0.08
Scenario 5 - No ventilation	-14.18	14.18	15.58	-27.88	30.63	57.26	0.76	-2.53	0.13

Table E.96: Validation metrics for the living room relative humidity for 26 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-11.22	13.06	15.59	-20.64	28.67	49.54	0.78	-2.41	0.13
Reference Case (HAMT)	-9.59	10.70	11.90	-17.64	21.88	37.81	0.82	-0.98	0.10
Scenario 1 - Low leakage	-10.94	12.04	13.35	-20.13	24.56	42.44	0.82	-1.50	0.11
Scenario 2 - 75 mm floor	-10.70	11.72	13.01	-19.67	23.92	41.34	0.82	-1.37	0.11
Scenario 3 - No cooker	-9.63	10.74	11.90	-17.71	21.89	37.84	0.82	-0.99	0.10
Scenario 4 - No moisture	-3.28	5.97	6.99	-6.03	12.85	22.21	0.74	0.32	0.06
Scenario 5 - No ventilation	-13.00	13.03	14.76	-23.91	27.14	46.91	0.74	-2.05	0.12

Table E.97: Validation metrics for the living room relative humidity for 27 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-11.08	11.49	13.74	-18.95	23.49	59.22	0.90	-2.58	0.11
Reference Case (HAMT)	-8.79	8.86	10.11	-15.03	17.28	43.55	0.89	-0.94	0.08
Scenario 1 - Low leakage	-9.94	10.01	11.22	-16.98	19.18	48.34	0.90	-1.39	0.09
Scenario 2 - 75 mm floor	-9.63	9.67	10.90	-16.46	18.63	46.97	0.89	-1.25	0.09
Scenario 3 - No cooker	-8.85	8.85	10.10	-15.12	17.27	43.53	0.89	-0.94	0.08
Scenario 4 - No moisture	-3.36	4.15	6.76	-5.74	11.55	29.12	0.70	0.13	0.06
Scenario 5 - No ventilation	-9.32	9.91	10.68	-15.94	18.26	46.02	0.88	-1.16	0.08

Table E.98: Validation metrics for the living room relative humidity for 28 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.78	7.79	11.32	-4.01	25.49	25.75	0.73	0.33	0.12
Reference Case (HAMT)	-5.62	9.21	11.21	-12.66	25.23	25.49	0.79	0.34	0.11
Scenario 1 - Low leakage	-9.71	12.95	15.28	-21.85	34.40	34.76	0.77	-0.22	0.15
Scenario 2 - 75 mm floor	-6.73	9.83	11.64	-15.14	26.20	26.47	0.81	0.29	0.12
Scenario 3 - No cooker	-5.65	9.18	11.17	-12.71	25.14	25.40	0.79	0.35	0.11
Scenario 4 - No moisture	-1.38	6.66	9.32	-3.10	20.98	21.20	0.77	0.55	0.10
Scenario 5 - No ventilation	-12.17	13.36	15.50	-27.40	34.90	35.26	0.72	-0.26	0.15

Table E.99: Validation metrics for the living room relative humidity for 29 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-17.59	17.59	18.26	-26.14	27.15	142.35	0.35	-29.32	0.12
Reference Case (HAMT)	-12.72	12.72	13.46	-18.90	20.00	104.89	0.47	-15.46	0.09
Scenario 1 - Low leakage	-13.45	13.45	14.10	-19.99	20.96	109.91	0.39	-17.08	0.10
Scenario 2 - 75 mm floor	-13.91	13.91	14.52	-20.68	21.59	113.20	0.46	-18.17	0.10
Scenario 3 - No cooker	-12.79	12.79	13.54	-19.00	20.12	105.53	0.46	-15.66	0.09
Scenario 4 - No moisture	-7.27	7.66	10.16	-10.81	15.11	79.21	0.42	-8.39	0.07
Scenario 5 - No ventilation	-10.68	10.68	11.81	-15.87	17.55	92.03	0.07	-11.67	0.08

The validation metrics for the living room relative humidity for the winter days are presented in Tables E.100 to E.106.

Table E.100: Validation metrics for the living room relative humidity for 25 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.93	7.72	12.51	-8.25	35.22	26.84	0.89	0.31	0.15
Reference Case (HAMT)	-4.92	5.86	9.69	-13.85	27.28	20.79	0.90	0.59	0.12
Scenario 1 - Low leakage	-15.99	16.55	18.56	-45.03	52.28	39.85	0.87	-0.51	0.20
Scenario 2 - 75 mm floor	-6.32	7.02	10.92	-17.79	30.75	23.44	0.90	0.48	0.13
Scenario 3 - No cooker	-4.40	5.75	9.44	-12.39	26.57	20.25	0.90	0.61	0.11
Scenario 4 - No moisture	-4.33	5.42	9.20	-12.20	25.91	19.75	0.90	0.63	0.11
Scenario 5 - No ventilation	-6.54	6.66	10.62	-18.42	29.91	22.80	0.91	0.51	0.13

Table E.101: Validation metrics for the living room relative humidity for 26 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.88	4.64	7.21	10.57	19.63	22.45	0.81	0.51	0.10
Reference Case (HAMT)	-1.39	4.02	5.16	-3.79	14.07	16.08	0.88	0.75	0.07
Scenario 1 - Low leakage	-14.28	14.54	16.05	-38.88	43.71	49.98	0.79	-1.41	0.18
Scenario 2 - 75 mm floor	-2.92	5.06	5.68	-7.96	15.47	17.69	0.88	0.70	0.07
Scenario 3 - No cooker	-0.47	4.04	5.41	-1.27	14.73	16.85	0.86	0.73	0.07
Scenario 4 - No moisture	-0.65	3.67	5.17	-1.77	14.08	16.10	0.88	0.75	0.07
Scenario 5 - No ventilation	-2.67	4.89	5.55	-7.28	15.11	17.28	0.89	0.71	0.07

Table E.102: Validation metrics for the living room relative humidity for 27 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.71	7.95	8.93	-3.34	17.49	25.37	0.80	0.49	0.08
Reference Case (HAMT)	-2.89	6.69	7.11	-5.67	13.93	20.20	0.86	0.68	0.07
Scenario 1 - Low leakage	-11.37	11.53	13.42	-22.26	26.28	38.12	0.89	-0.15	0.11
Scenario 2 - 75 mm floor	-5.19	8.07	8.76	-10.17	17.15	24.87	0.84	0.51	0.08
Scenario 3 - No cooker	-2.00	6.79	7.45	-3.91	14.59	21.16	0.83	0.64	0.07
Scenario 4 - No moisture	-1.88	6.24	6.73	-3.69	13.17	19.10	0.86	0.71	0.06
Scenario 5 - No ventilation	-5.65	7.80	8.40	-11.06	16.46	23.86	0.87	0.55	0.08

Table E.103: Validation metrics for the living room relative humidity for 28 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.14	3.89	4.49	2.17	8.53	10.27	0.96	0.92	0.04
Reference Case (HAMT)	-0.71	3.88	4.96	-1.34	9.43	11.35	0.95	0.90	0.05
Scenario 1 - Low leakage	-9.07	10.06	11.97	-17.23	22.75	27.38	0.89	0.42	0.10
Scenario 2 - 75 mm floor	-2.94	4.50	5.63	-5.58	10.69	12.87	0.95	0.87	0.05
Scenario 3 - No cooker	0.23	3.41	4.19	0.44	7.96	9.58	0.97	0.93	0.04
Scenario 4 - No moisture	0.21	3.83	4.91	0.40	9.33	11.23	0.95	0.90	0.04
Scenario 5 - No ventilation	-4.43	5.66	7.33	-8.42	13.93	16.76	0.96	0.78	0.06

Table E.104: Validation metrics for the living room relative humidity for 29 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.66	3.60	4.45	-1.25	8.43	15.60	0.91	0.74	0.04
Reference Case (HAMT)	-2.93	3.98	4.57	-5.55	8.67	16.05	0.92	0.72	0.04
Scenario 1 - Low leakage	-10.98	11.41	12.28	-20.82	23.26	43.07	0.88	-0.98	0.10
Scenario 2 - 75 mm floor	-4.72	5.56	6.15	-8.95	11.65	21.58	0.90	0.50	0.06
Scenario 3 - No cooker	-2.20	3.61	4.23	-4.17	8.01	14.83	0.91	0.77	0.04
Scenario 4 - No moisture	-1.99	3.33	3.92	-3.78	7.43	13.76	0.92	0.80	0.04
Scenario 5 - No ventilation	-4.77	5.15	5.73	-9.04	10.87	20.12	0.94	0.57	0.05

Table E.105: Validation metrics for the living room relative humidity for 30 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-6.56	9.08	11.09	-10.17	17.19	58.82	0.51	-3.80	0.08
Reference Case (HAMT)	-1.77	5.87	6.86	-2.74	10.63	36.37	0.44	-0.84	0.05
Scenario 1 - Low leakage	-6.45	8.82	10.42	-10.00	16.16	55.28	0.45	-3.24	0.08
Scenario 2 - 75 mm floor	-3.75	6.69	8.04	-5.81	12.46	42.63	0.44	-1.52	0.06
Scenario 3 - No cooker	-1.01	6.08	6.80	-1.56	10.54	36.06	0.40	-0.80	0.05
Scenario 4 - No moisture	-0.82	5.79	6.55	-1.27	10.16	34.76	0.43	-0.68	0.05
Scenario 5 - No ventilation	-1.87	5.93	7.30	-2.90	11.32	38.71	0.61	-1.08	0.06

Table E.106: Validation metrics for the living room relative humidity for 31 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.12	8.36	9.38	-5.67	17.01	21.49	0.93	0.64	0.08
Reference Case (HAMT)	-1.71	3.98	5.35	-3.11	9.70	12.26	0.95	0.88	0.05
Scenario 1 - Low leakage	-6.75	7.50	8.99	-12.24	16.31	20.60	0.93	0.67	0.07
Scenario 2 - 75 mm floor	-3.32	4.87	6.15	-6.02	11.15	14.08	0.95	0.85	0.05
Scenario 3 - No cooker	-0.97	4.10	5.37	-1.76	9.74	12.31	0.94	0.88	0.05
Scenario 4 - No moisture	-0.84	3.78	5.11	-1.52	9.26	11.70	0.95	0.89	0.04
Scenario 5 - No ventilation	-5.11	5.94	7.54	-9.28	13.67	17.27	0.95	0.77	0.06

E.6.2.4 Overall Hourly Validation Metrics

The first hourly-based validation analysis considered results from the summer and winter week. The validation metrics for the living room relative humidity are presented in Tables E.107 to E.130.

Table E.107: Validation metrics for the living room relative humidity for 00:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-7.51	9.41	11.51	-13.13	20.13	29.60	0.80	-0.46	0.09
Reference Case (HAMT)	-7.65	7.98	10.17	-13.38	17.78	26.15	0.77	-0.14	0.08
Scenario 1 - Low leakage	-14.98	14.98	15.83	-26.19	27.69	40.72	0.86	-1.76	0.12
Scenario 2 - 75 mm floor	-9.42	9.43	11.45	-16.47	20.02	29.44	0.79	-0.44	0.09
Scenario 3 - No cooker	-7.30	7.74	10.10	-12.77	17.67	25.98	0.76	-0.12	0.08
Scenario 4 - No moisture	-2.65	3.19	5.16	-4.64	9.02	13.26	0.89	0.71	0.04
Scenario 5 - No ventilation	-9.89	9.92	12.10	-17.29	21.16	31.13	0.77	-0.61	0.10

Table E.108: Validation metrics for the living room relative humidity for 01:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-9.23	10.50	11.96	-16.16	20.93	31.61	0.84	-0.59	0.10
Reference Case (HAMT)	-8.85	8.90	10.68	-15.49	18.69	28.22	0.80	-0.27	0.09
Scenario 1 - Low leakage	-16.21	16.21	17.01	-28.37	29.77	44.95	0.88	-2.21	0.13
Scenario 2 - 75 mm floor	-10.86	10.86	12.30	-19.01	21.53	32.51	0.82	-0.68	0.10
Scenario 3 - No cooker	-8.50	8.66	10.56	-14.88	18.49	27.92	0.78	-0.24	0.09
Scenario 4 - No moisture	-3.72	3.98	5.71	-6.51	10.00	15.10	0.89	0.64	0.05
Scenario 5 - No ventilation	-11.16	11.16	12.80	-19.53	22.40	33.83	0.80	-0.82	0.10

Table E.109: Validation metrics for the living room relative humidity for 02:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-9.85	10.48	11.85	-17.09	20.56	31.65	0.91	-0.58	0.09
Reference Case (HAMT)	-9.07	9.07	10.45	-15.73	18.13	27.91	0.86	-0.23	0.08
Scenario 1 - Low leakage	-16.58	16.58	17.30	-28.77	30.02	46.22	0.89	-2.38	0.13
Scenario 2 - 75 mm floor	-11.24	11.24	12.33	-19.50	21.41	32.95	0.86	-0.72	0.10
Scenario 3 - No cooker	-8.72	8.72	10.30	-15.13	17.88	27.52	0.84	-0.20	0.08
Scenario 4 - No moisture	-3.65	3.76	4.37	-6.34	7.59	11.68	0.97	0.78	0.04
Scenario 5 - No ventilation	-11.24	11.24	12.65	-19.50	21.96	33.81	0.84	-0.81	0.10

Table E.110: Validation metrics for the living room relative humidity for 03:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-11.34	11.42	13.64	-19.57	23.54	36.74	0.89	-1.24	0.11
Reference Case (HAMT)	-9.91	9.91	11.37	-17.11	19.62	30.62	0.83	-0.56	0.09
Scenario 1 - Low leakage	-17.24	17.24	17.90	-29.76	30.89	48.22	0.87	-2.86	0.13
Scenario 2 - 75 mm floor	-12.30	12.30	13.50	-21.22	23.29	36.36	0.84	-1.19	0.10
Scenario 3 - No cooker	-9.57	9.57	11.21	-16.52	19.35	30.20	0.81	-0.51	0.09
Scenario 4 - No moisture	-4.05	4.07	4.78	-6.99	8.25	12.88	0.96	0.72	0.04
Scenario 5 - No ventilation	-12.14	12.14	13.78	-20.95	23.78	37.12	0.80	-1.29	0.11

Table E.111: Validation metrics for the living room relative humidity for 04:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-14.12	14.31	17.44	-24.76	30.59	49.86	0.75	-2.75	0.13
Reference Case (HAMT)	-12.04	12.04	14.05	-21.11	24.64	40.17	0.71	-1.43	0.11
Scenario 1 - Low leakage	-19.19	19.19	20.20	-33.65	35.42	57.75	0.71	-4.02	0.15
Scenario 2 - 75 mm floor	-14.59	14.59	16.35	-25.58	28.68	46.75	0.71	-2.29	0.13
Scenario 3 - No cooker	-11.70	11.70	13.84	-20.52	24.28	39.58	0.70	-1.36	0.11
Scenario 4 - No moisture	-5.79	5.79	8.33	-10.16	14.60	23.80	0.78	0.15	0.07
Scenario 5 - No ventilation	-14.33	14.33	16.44	-25.13	28.83	46.99	0.70	-2.33	0.13

Table E.112: Validation metrics for the living room relative humidity for 05:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-14.93	16.25	19.23	-26.42	34.02	49.07	0.61	-2.23	0.15
Reference Case (HAMT)	-12.47	12.47	15.25	-22.06	26.98	38.92	0.64	-1.03	0.12
Scenario 1 - Low leakage	-19.70	19.70	21.27	-34.86	37.64	54.29	0.67	-2.95	0.16
Scenario 2 - 75 mm floor	-15.02	15.02	17.41	-26.56	30.80	44.43	0.64	-1.65	0.13
Scenario 3 - No cooker	-12.16	12.16	15.07	-21.51	26.66	38.46	0.63	-0.98	0.12
Scenario 4 - No moisture	-5.97	6.37	10.20	-10.55	18.04	26.03	0.65	0.09	0.08
Scenario 5 - No ventilation	-14.70	14.70	17.47	-26.01	30.90	44.57	0.63	-1.66	0.13

Table E.113: Validation metrics for the living room relative humidity for 06:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-11.96	13.81	16.26	-20.83	28.30	43.85	0.88	-1.54	0.12
Reference Case (HAMT)	-10.27	10.27	12.22	-17.88	21.28	32.98	0.86	-0.44	0.10
Scenario 1 - Low leakage	-18.08	18.08	18.73	-31.47	32.61	50.53	0.88	-2.38	0.14
Scenario 2 - 75 mm floor	-12.91	12.91	14.63	-22.47	25.47	39.47	0.86	-1.06	0.11
Scenario 3 - No cooker	-9.98	9.99	12.09	-17.38	21.06	32.63	0.86	-0.41	0.10
Scenario 4 - No moisture	-3.59	3.80	4.80	-6.25	8.36	12.96	0.96	0.78	0.04
Scenario 5 - No ventilation	-12.46	12.46	14.65	-21.69	25.51	39.53	0.85	-1.07	0.11

Table E.114: Validation metrics for the living room relative humidity for 07:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-10.67	13.23	15.13	-17.98	25.49	45.12	0.90	-1.37	0.11
Reference Case (HAMT)	-9.39	9.62	11.33	-15.81	19.09	33.79	0.85	-0.33	0.09
Scenario 1 - Low leakage	-16.90	16.90	17.68	-28.47	29.79	52.72	0.85	-2.23	0.13
Scenario 2 - 75 mm floor	-12.19	12.19	13.84	-20.53	23.31	41.26	0.85	-0.98	0.10
Scenario 3 - No cooker	-9.09	9.37	11.21	-15.32	18.88	33.42	0.85	-0.30	0.09
Scenario 4 - No moisture	-2.49	3.45	4.28	-4.19	7.21	12.76	0.94	0.81	0.03
Scenario 5 - No ventilation	-11.78	11.86	13.85	-19.85	23.34	41.30	0.84	-0.98	0.10

Table E.115: Validation metrics for the living room relative humidity for 08:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-7.20	8.67	10.46	-12.42	18.04	26.71	0.91	0.25	0.08
Reference Case (HAMT)	-6.31	7.08	8.77	-10.88	15.12	22.39	0.86	0.47	0.07
Scenario 1 - Low leakage	-12.75	12.75	14.54	-21.98	25.07	37.13	0.87	-0.45	0.11
Scenario 2 - 75 mm floor	-8.92	8.98	10.72	-15.38	18.48	27.37	0.87	0.21	0.08
Scenario 3 - No cooker	-6.03	7.05	8.73	-10.39	15.05	22.28	0.85	0.48	0.07
Scenario 4 - No moisture	0.02	3.94	4.97	0.03	8.57	12.69	0.93	0.83	0.04
Scenario 5 - No ventilation	-7.94	8.29	9.92	-13.69	17.11	25.33	0.87	0.33	0.08

Table E.116: Validation metrics for the living room relative humidity for 09:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-8.52	12.94	15.25	-15.38	27.51	37.01	0.68	-0.49	0.12
Reference Case (HAMT)	-8.30	12.34	14.19	-14.98	25.61	34.45	0.64	-0.29	0.12
Scenario 1 - Low leakage	-12.49	13.35	15.20	-22.55	27.43	36.89	0.73	-0.48	0.12
Scenario 2 - 75 mm floor	-9.80	12.56	14.46	-17.69	26.09	35.09	0.68	-0.34	0.12
Scenario 3 - No cooker	-8.06	12.40	14.23	-14.55	25.68	34.55	0.63	-0.30	0.12
Scenario 4 - No moisture	-7.11	11.74	13.35	-12.83	24.10	32.41	0.65	-0.14	0.11
Scenario 5 - No ventilation	-5.13	8.45	10.40	-9.26	18.78	25.25	0.70	0.31	0.09

Table E.117: Validation metrics for the living room relative humidity for 10:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-6.99	8.70	10.44	-14.14	21.10	20.89	0.90	0.51	0.09
Reference Case (HAMT)	-7.50	9.03	10.53	-15.16	21.29	21.08	0.88	0.50	0.10
Scenario 1 - Low leakage	-11.00	11.29	12.75	-22.24	25.79	25.53	0.91	0.27	0.11
Scenario 2 - 75 mm floor	-8.74	9.37	10.88	-17.67	22.00	21.78	0.90	0.47	0.10
Scenario 3 - No cooker	-7.29	9.01	10.51	-14.74	21.26	21.05	0.87	0.50	0.10
Scenario 4 - No moisture	-6.73	8.65	10.09	-13.61	20.40	20.20	0.87	0.54	0.09
Scenario 5 - No ventilation	-5.41	7.26	9.61	-10.94	19.43	19.23	0.85	0.58	0.09

Table E.118: Validation metrics for the living room relative humidity for 11:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-6.09	6.86	9.60	-13.65	21.52	22.25	0.92	0.47	0.10
Reference Case (HAMT)	-7.27	8.35	9.98	-16.31	22.37	23.13	0.90	0.43	0.10
Scenario 1 - Low leakage	-10.73	11.23	12.47	-24.06	27.95	28.90	0.88	0.11	0.12
Scenario 2 - 75 mm floor	-8.47	9.02	10.43	-19.00	23.40	24.19	0.92	0.38	0.10
Scenario 3 - No cooker	-7.09	8.29	9.94	-15.89	22.29	23.05	0.89	0.43	0.10
Scenario 4 - No moisture	-6.51	7.87	9.55	-14.59	21.42	22.15	0.89	0.48	0.10
Scenario 5 - No ventilation	-6.72	7.63	9.47	-15.06	21.23	21.96	0.86	0.49	0.10

Table E.119: Validation metrics for the living room relative humidity for 12:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-5.87	8.31	10.62	-14.34	25.96	27.47	0.86	0.32	0.11
Reference Case (HAMT)	-7.63	9.54	11.15	-18.66	27.25	28.82	0.84	0.25	0.12
Scenario 1 - Low leakage	-11.13	12.05	13.33	-27.21	32.58	34.47	0.84	-0.07	0.14
Scenario 2 - 75 mm floor	-8.73	9.92	11.52	-21.34	28.16	29.79	0.87	0.20	0.12
Scenario 3 - No cooker	-7.46	9.49	11.12	-18.23	27.18	28.75	0.84	0.25	0.12
Scenario 4 - No moisture	-6.86	9.06	10.67	-16.78	26.09	27.60	0.84	0.31	0.11
Scenario 5 - No ventilation	-8.52	10.05	11.38	-20.82	27.82	29.43	0.81	0.22	0.12

Table E.120: Validation metrics for the living room relative humidity for 13:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-5.36	7.07	9.23	-14.47	24.91	21.45	0.90	0.38	0.11
Reference Case (HAMT)	-7.83	9.15	10.33	-21.11	27.88	24.01	0.89	0.22	0.12
Scenario 1 - Low leakage	-11.45	12.55	13.63	-30.88	36.78	31.68	0.82	-0.36	0.15
Scenario 2 - 75 mm floor	-8.79	9.87	10.93	-23.71	29.50	25.40	0.89	0.13	0.13
Scenario 3 - No cooker	-7.67	9.04	10.26	-20.70	27.68	23.84	0.88	0.23	0.12
Scenario 4 - No moisture	-7.09	8.52	9.75	-19.13	26.31	22.66	0.89	0.31	0.11
Scenario 5 - No ventilation	-10.19	11.38	12.34	-27.48	33.30	28.68	0.81	-0.11	0.14

Table E.121: Validation metrics for the living room relative humidity for 14:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.90	4.31	5.24	-10.87	14.61	10.73	0.98	0.83	0.06
Reference Case (HAMT)	-6.35	6.35	7.05	-17.70	19.65	14.44	0.98	0.69	0.09
Scenario 1 - Low leakage	-8.60	8.60	9.38	-23.98	26.16	19.22	0.96	0.46	0.11
Scenario 2 - 75 mm floor	-7.09	7.09	7.74	-19.77	21.59	15.86	0.98	0.63	0.09
Scenario 3 - No cooker	-6.26	6.26	6.97	-17.46	19.43	14.28	0.98	0.70	0.08
Scenario 4 - No moisture	-5.38	5.54	6.12	-15.00	17.07	12.54	0.98	0.77	0.08
Scenario 5 - No ventilation	-10.66	11.23	12.54	-29.73	34.97	25.70	0.86	0.03	0.15

Table E.122: Validation metrics for the living room relative humidity for 15:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.79	4.55	5.42	-7.80	15.15	11.51	0.97	0.82	0.07
Reference Case (HAMT)	-4.07	5.27	5.89	-11.38	16.46	12.51	0.97	0.79	0.07
Scenario 1 - Low leakage	-4.36	5.41	6.05	-12.19	16.92	12.85	0.97	0.78	0.07
Scenario 2 - 75 mm floor	-4.43	5.52	6.18	-12.37	17.28	13.13	0.97	0.77	0.08
Scenario 3 - No cooker	-4.06	5.27	5.88	-11.35	16.44	12.49	0.97	0.79	0.07
Scenario 4 - No moisture	-3.33	4.70	5.19	-9.31	14.49	11.01	0.97	0.84	0.06
Scenario 5 - No ventilation	-9.92	10.46	11.80	-27.73	32.98	25.06	0.87	0.17	0.14

Table E.123: Validation metrics for the living room relative humidity for 16:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.64	4.18	5.85	-1.74	15.99	12.84	0.95	0.81	0.07
Reference Case (HAMT)	-1.95	4.66	5.74	-5.34	15.70	12.60	0.95	0.81	0.07
Scenario 1 - Low leakage	-2.21	4.77	5.82	-6.04	15.90	12.76	0.95	0.81	0.07
Scenario 2 - 75 mm floor	-2.31	4.90	5.93	-6.31	16.21	13.01	0.95	0.80	0.07
Scenario 3 - No cooker	-1.94	4.65	5.74	-5.31	15.69	12.59	0.95	0.81	0.07
Scenario 4 - No moisture	-1.27	4.22	5.30	-3.48	14.49	11.63	0.95	0.84	0.07
Scenario 5 - No ventilation	-9.53	9.53	11.59	-26.06	31.69	25.43	0.87	0.24	0.13

Table E.124: Validation metrics for the living room relative humidity for 17:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	6.55	8.67	10.46	15.28	24.38	23.46	0.88	0.44	0.12
Reference Case (HAMT)	4.18	6.56	8.44	9.74	19.67	18.93	0.89	0.64	0.10
Scenario 1 - Low leakage	3.37	6.18	8.08	7.86	18.84	18.13	0.88	0.67	0.09
Scenario 2 - 75 mm floor	3.43	6.06	7.67	8.01	17.88	17.20	0.90	0.70	0.09
Scenario 3 - No cooker	4.21	6.59	8.46	9.82	19.72	18.97	0.89	0.64	0.10
Scenario 4 - No moisture	5.04	6.98	9.06	11.75	21.13	20.33	0.88	0.58	0.11
Scenario 5 - No ventilation	-4.75	7.47	8.72	-11.09	20.34	19.57	0.85	0.61	0.09

Table E.125: Validation metrics for the living room relative humidity for 18:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	4.81	7.64	9.21	10.08	19.28	23.37	0.84	0.47	0.10
Reference Case (HAMT)	2.07	6.26	7.57	4.32	15.84	19.20	0.83	0.64	0.08
Scenario 1 - Low leakage	-1.77	6.68	8.85	-3.70	18.52	22.45	0.74	0.51	0.09
Scenario 2 - 75 mm floor	1.37	5.98	7.34	2.86	15.36	18.62	0.84	0.66	0.08
Scenario 3 - No cooker	2.45	6.73	7.89	5.14	16.51	20.01	0.85	0.61	0.08
Scenario 4 - No moisture	2.70	6.46	7.78	5.65	16.28	19.73	0.83	0.62	0.08
Scenario 5 - No ventilation	-2.08	5.18	7.11	-4.36	14.89	18.05	0.85	0.68	0.07

Table E.126: Validation metrics for the living room relative humidity for 19:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.97	5.84	7.35	5.79	14.30	19.50	0.87	0.61	0.07
Reference Case (HAMT)	-1.08	4.08	5.56	-2.11	10.82	14.75	0.89	0.78	0.05
Scenario 1 - Low leakage	-7.49	8.64	11.34	-14.57	22.05	30.07	0.70	0.07	0.10
Scenario 2 - 75 mm floor	-2.27	4.62	5.85	-4.42	11.38	15.52	0.89	0.75	0.05
Scenario 3 - No cooker	1.39	4.60	6.07	2.71	11.82	16.11	0.87	0.73	0.06
Scenario 4 - No moisture	1.21	4.30	5.81	2.36	11.31	15.42	0.88	0.76	0.06
Scenario 5 - No ventilation	-7.46	8.64	10.43	-14.52	20.29	27.67	0.80	0.21	0.09

Table E.127: Validation metrics for the living room relative humidity for 20:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.28	5.37	7.71	6.07	14.28	19.63	0.87	0.48	0.07
Reference Case (HAMT)	-1.22	5.14	5.92	-2.26	10.95	15.06	0.85	0.69	0.05
Scenario 1 - Low leakage	-8.55	8.63	10.24	-15.82	18.95	26.06	0.87	0.09	0.09
Scenario 2 - 75 mm floor	-2.56	5.53	6.36	-4.74	11.78	16.20	0.85	0.65	0.06
Scenario 3 - No cooker	-0.33	5.56	6.38	-0.61	11.80	16.23	0.83	0.65	0.06
Scenario 4 - No moisture	2.27	3.73	5.25	4.19	9.71	13.35	0.90	0.76	0.05
Scenario 5 - No ventilation	-4.89	7.34	8.90	-9.06	16.47	22.64	0.77	0.31	0.08

Table E.128: Validation metrics for the living room relative humidity for 21:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.90	5.14	6.35	1.63	11.54	15.56	0.91	0.64	0.06
Reference Case (HAMT)	-2.78	5.06	5.65	-5.05	10.26	13.84	0.89	0.72	0.05
Scenario 1 - Low leakage	-10.57	10.57	11.60	-19.22	21.08	28.43	0.95	-0.19	0.10
Scenario 2 - 75 mm floor	-4.18	5.71	6.40	-7.60	11.64	15.70	0.90	0.64	0.06
Scenario 3 - No cooker	-2.25	5.32	5.80	-4.10	10.55	14.23	0.88	0.70	0.05
Scenario 4 - No moisture	1.15	2.43	3.42	2.08	6.23	8.39	0.95	0.90	0.03
Scenario 5 - No ventilation	-5.70	7.19	8.35	-10.37	15.17	20.46	0.85	0.38	0.07

Table E.129: Validation metrics for the living room relative humidity for 22:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.53	6.26	7.43	-2.68	13.02	18.14	0.91	0.48	0.06
Reference Case (HAMT)	-4.02	4.87	6.26	-7.04	10.97	15.29	0.91	0.63	0.05
Scenario 1 - Low leakage	-11.99	11.99	12.59	-21.00	22.05	30.73	0.96	-0.49	0.10
Scenario 2 - 75 mm floor	-5.59	6.01	7.31	-9.80	12.80	17.83	0.91	0.50	0.06
Scenario 3 - No cooker	-3.61	5.09	6.31	-6.33	11.05	15.40	0.90	0.63	0.05
Scenario 4 - No moisture	0.31	1.83	2.31	0.54	4.04	5.63	0.98	0.95	0.02
Scenario 5 - No ventilation	-6.61	7.03	8.79	-11.58	15.39	21.45	0.88	0.28	0.07

Table E.130: Validation metrics for the living room relative humidity for 23:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-5.09	7.49	8.95	-8.87	15.58	22.87	0.92	0.22	0.07
Reference Case (HAMT)	-5.80	6.53	7.95	-10.09	13.84	20.32	0.89	0.38	0.06
Scenario 1 - Low leakage	-13.21	13.21	13.99	-23.00	24.36	35.76	0.90	-0.91	0.11
Scenario 2 - 75 mm floor	-7.44	7.63	9.23	-12.95	16.06	23.58	0.89	0.17	0.07
Scenario 3 - No cooker	-5.46	6.41	7.87	-9.51	13.70	20.11	0.88	0.40	0.06
Scenario 4 - No moisture	-1.18	2.63	3.54	-2.06	6.17	9.06	0.95	0.88	0.03
Scenario 5 - No ventilation	-8.01	8.22	10.14	-13.95	17.67	25.93	0.86	0.00	0.08

E.6.2.5 Summer Hourly Validation Metrics

The second hourly-based validation analysis considered only results from the summer week. The validation metrics for the living room relative humidity are presented in Tables E.131 to E.154.

Table E.131: Validation metrics for the living room relative humidity for 00:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-12.40	12.40	14.74	-22.10	26.27	108.07	0.37	-7.38	0.12
Reference Case (HAMT)	-13.27	13.27	14.06	-23.65	25.07	103.11	0.43	-6.62	0.11
Scenario 1 - Low leakage	-17.73	17.73	18.31	-31.59	32.64	134.25	0.48	-11.93	0.14
Scenario 2 - 75 mm floor	-14.93	14.93	15.55	-26.60	27.71	114.00	0.52	-8.32	0.12
Scenario 3 - No cooker	-13.26	13.26	14.06	-23.64	25.06	103.08	0.43	-6.62	0.11
Scenario 4 - No moisture	-4.34	4.34	6.91	-7.74	12.31	50.64	0.40	-0.84	0.06
Scenario 5 - No ventilation	-16.06	16.06	16.56	-28.63	29.52	121.42	0.63	-9.57	0.13

Table E.132: Validation metrics for the living room relative humidity for 01:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-13.58	13.58	14.60	-24.39	26.22	77.48	0.68	-4.93	0.12
Reference Case (HAMT)	-13.99	13.99	14.39	-25.13	25.85	76.38	0.90	-4.76	0.11
Scenario 1 - Low leakage	-18.61	18.61	19.08	-33.42	34.27	101.25	0.91	-9.13	0.15
Scenario 2 - 75 mm floor	-15.81	15.81	16.14	-28.41	28.99	85.66	0.93	-6.25	0.13
Scenario 3 - No cooker	-13.99	13.99	14.39	-25.12	25.84	76.37	0.90	-4.76	0.11
Scenario 4 - No moisture	-4.86	4.86	7.19	-8.72	12.91	38.15	0.49	-0.44	0.06
Scenario 5 - No ventilation	-16.87	16.87	17.06	-30.31	30.64	90.53	0.95	-7.10	0.13

Table E.133: Validation metrics for the living room relative humidity for 02:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-13.21	13.21	13.93	-23.55	24.83	69.21	0.97	-3.68	0.11
Reference Case (HAMT)	-13.58	13.58	13.73	-24.21	24.49	68.26	0.95	-3.56	0.11
Scenario 1 - Low leakage	-18.63	18.63	18.97	-33.22	33.82	94.28	0.91	-7.69	0.14
Scenario 2 - 75 mm floor	-15.46	15.46	15.66	-27.56	27.92	77.82	0.93	-4.92	0.12
Scenario 3 - No cooker	-13.57	13.57	13.73	-24.20	24.48	68.25	0.95	-3.56	0.11
Scenario 4 - No moisture	-3.90	3.90	4.25	-6.96	7.57	21.11	0.97	0.56	0.04
Scenario 5 - No ventilation	-16.15	16.15	16.45	-28.80	29.34	81.77	0.92	-5.54	0.13

Table E.134: Validation metrics for the living room relative humidity for 03:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-14.42	14.58	16.23	-25.58	28.80	87.15	0.97	-6.90	0.13
Reference Case (HAMT)	-14.39	14.39	14.79	-25.54	26.25	79.42	0.91	-5.56	0.12
Scenario 1 - Low leakage	-19.25	19.25	19.49	-34.16	34.59	104.68	0.86	-10.40	0.15
Scenario 2 - 75 mm floor	-16.51	16.51	16.95	-29.30	30.07	91.01	0.88	-7.62	0.13
Scenario 3 - No cooker	-14.39	14.39	14.79	-25.54	26.24	79.41	0.91	-5.56	0.12
Scenario 4 - No moisture	-3.84	3.84	4.20	-6.82	7.45	22.55	0.97	0.47	0.04
Scenario 5 - No ventilation	-17.08	17.08	17.80	-30.30	31.59	95.59	0.88	-8.51	0.14

Table E.135: Validation metrics for the living room relative humidity for 04:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-16.30	16.68	18.39	-29.01	32.72	85.16	0.95	-6.94	0.14
Reference Case (HAMT)	-15.79	15.79	16.20	-28.09	28.82	75.03	0.89	-5.16	0.13
Scenario 1 - Low leakage	-20.38	20.38	20.73	-36.27	36.89	96.03	0.84	-9.09	0.16
Scenario 2 - 75 mm floor	-18.11	18.11	18.54	-32.23	32.99	85.88	0.87	-7.07	0.14
Scenario 3 - No cooker	-15.78	15.78	16.19	-28.08	28.82	75.01	0.89	-5.16	0.13
Scenario 4 - No moisture	-4.51	4.51	5.12	-8.02	9.10	23.69	0.93	0.39	0.04
Scenario 5 - No ventilation	-18.61	18.61	19.27	-33.11	34.28	89.24	0.88	-7.72	0.15

Table E.136: Validation metrics for the living room relative humidity for 05:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-16.73	18.93	20.03	-29.23	34.99	122.22	0.82	-10.63	0.15
Reference Case (HAMT)	-15.51	15.51	16.41	-27.09	28.66	100.11	0.71	-6.80	0.13
Scenario 1 - Low leakage	-19.99	19.99	20.52	-34.92	35.84	125.17	0.63	-11.20	0.15
Scenario 2 - 75 mm floor	-17.89	17.89	18.77	-31.26	32.79	114.51	0.68	-9.21	0.14
Scenario 3 - No cooker	-15.50	15.50	16.40	-27.08	28.65	100.08	0.71	-6.80	0.13
Scenario 4 - No moisture	-3.65	4.46	5.59	-6.37	9.77	34.12	0.77	0.09	0.05
Scenario 5 - No ventilation	-18.32	18.32	19.47	-31.99	34.02	118.82	0.73	-9.99	0.15

Table E.137: Validation metrics for the living room relative humidity for 06:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-17.08	18.80	20.24	-29.49	34.95	141.33	0.85	-12.88	0.15
Reference Case (HAMT)	-15.68	15.68	16.19	-27.09	27.96	113.06	0.78	-7.88	0.12
Scenario 1 - Low leakage	-20.04	20.04	20.50	-34.60	35.40	143.16	0.60	-13.24	0.15
Scenario 2 - 75 mm floor	-18.23	18.23	18.77	-31.47	32.42	131.11	0.73	-10.94	0.14
Scenario 3 - No cooker	-15.68	15.68	16.19	-27.08	27.95	113.03	0.78	-7.88	0.12
Scenario 4 - No moisture	-3.42	3.78	4.56	-5.90	7.87	31.81	0.84	0.30	0.04
Scenario 5 - No ventilation	-18.52	18.52	19.29	-31.98	33.32	134.73	0.79	-11.61	0.14

Table E.138: Validation metrics for the living room relative humidity for 07:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-15.88	16.80	18.28	-26.46	30.47	100.18	0.87	-6.45	0.13
Reference Case (HAMT)	-14.56	14.56	15.03	-24.28	25.05	82.34	0.85	-4.03	0.11
Scenario 1 - Low leakage	-18.45	18.45	19.27	-30.75	32.12	105.60	0.67	-7.28	0.14
Scenario 2 - 75 mm floor	-17.17	17.17	17.73	-28.62	29.55	97.15	0.75	-6.00	0.13
Scenario 3 - No cooker	-14.56	14.56	15.02	-24.26	25.04	82.31	0.85	-4.03	0.11
Scenario 4 - No moisture	-1.90	3.20	3.94	-3.16	6.56	21.57	0.91	0.65	0.03
Scenario 5 - No ventilation	-17.75	17.75	18.28	-29.59	30.47	100.15	0.78	-6.44	0.13

Table E.139: Validation metrics for the living room relative humidity for 08:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-11.99	12.21	13.66	-20.76	23.65	54.39	0.91	-1.50	0.11
Reference Case (HAMT)	-10.95	10.95	11.88	-18.96	20.56	47.29	0.89	-0.89	0.09
Scenario 1 - Low leakage	-14.10	14.10	15.71	-24.40	27.19	62.53	0.64	-2.30	0.12
Scenario 2 - 75 mm floor	-13.31	13.31	14.14	-23.04	24.48	56.29	0.87	-1.68	0.11
Scenario 3 - No cooker	-10.94	10.94	11.87	-18.94	20.55	47.25	0.89	-0.89	0.09
Scenario 4 - No moisture	0.62	4.77	6.22	1.07	10.76	24.76	0.72	0.48	0.05
Scenario 5 - No ventilation	-12.69	12.69	13.31	-21.97	23.05	53.00	0.91	-1.37	0.10

Table E.140: Validation metrics for the living room relative humidity for 09:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-18.60	18.60	18.86	-34.38	34.88	59.92	0.97	-1.79	0.15
Reference Case (HAMT)	-18.22	18.22	18.50	-33.69	34.21	58.77	0.96	-1.69	0.14
Scenario 1 - Low leakage	-18.39	18.39	18.69	-34.01	34.56	59.38	0.96	-1.74	0.15
Scenario 2 - 75 mm floor	-18.67	18.67	18.97	-34.52	35.08	60.27	0.96	-1.82	0.15
Scenario 3 - No cooker	-18.22	18.22	18.50	-33.69	34.21	58.76	0.96	-1.69	0.14
Scenario 4 - No moisture	-16.78	16.78	17.05	-31.04	31.52	54.16	0.97	-1.28	0.13
Scenario 5 - No ventilation	-10.56	10.56	12.56	-19.53	23.22	39.90	0.85	-0.24	0.10

Table E.141: Validation metrics for the living room relative humidity for 10:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-13.76	13.76	14.11	-27.06	27.76	31.96	0.98	0.03	0.12
Reference Case (HAMT)	-13.82	13.82	14.15	-27.19	27.83	32.04	0.98	0.03	0.12
Scenario 1 - Low leakage	-13.83	13.83	14.15	-27.20	27.83	32.05	0.98	0.03	0.12
Scenario 2 - 75 mm floor	-14.07	14.07	14.39	-27.68	28.30	32.59	0.98	-0.01	0.12
Scenario 3 - No cooker	-13.82	13.82	14.14	-27.18	27.81	32.02	0.98	0.03	0.12
Scenario 4 - No moisture	-13.15	13.15	13.51	-25.87	26.58	30.61	0.98	0.11	0.11
Scenario 5 - No ventilation	-8.52	10.14	12.64	-16.76	24.87	28.64	0.82	0.22	0.11

Table E.142: Validation metrics for the living room relative humidity for 11:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-11.75	11.75	13.30	-25.55	28.93	33.11	0.97	-0.11	0.12
Reference Case (HAMT)	-12.18	12.18	13.29	-26.50	28.90	33.08	0.97	-0.11	0.12
Scenario 1 - Low leakage	-12.22	12.22	13.30	-26.58	28.94	33.12	0.97	-0.11	0.12
Scenario 2 - 75 mm floor	-12.46	12.46	13.51	-27.10	29.39	33.64	0.98	-0.14	0.12
Scenario 3 - No cooker	-12.18	12.18	13.29	-26.50	28.91	33.09	0.97	-0.11	0.12
Scenario 4 - No moisture	-11.48	11.48	12.75	-24.98	27.73	31.74	0.97	-0.02	0.12
Scenario 5 - No ventilation	-10.02	10.41	12.32	-21.80	26.79	30.67	0.84	0.05	0.12

Table E.143: Validation metrics for the living room relative humidity for 12:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-12.26	12.26	14.05	-29.67	33.99	37.13	0.99	-0.44	0.14
Reference Case (HAMT)	-12.86	12.86	14.20	-31.11	34.35	37.52	0.99	-0.47	0.14
Scenario 1 - Low leakage	-12.90	12.90	14.21	-31.22	34.39	37.56	0.99	-0.47	0.14
Scenario 2 - 75 mm floor	-13.15	13.15	14.45	-31.81	34.95	38.18	0.99	-0.52	0.14
Scenario 3 - No cooker	-12.86	12.86	14.20	-31.12	34.35	37.52	0.99	-0.47	0.14
Scenario 4 - No moisture	-12.12	12.12	13.53	-29.34	32.75	35.77	0.98	-0.34	0.14
Scenario 5 - No ventilation	-13.64	13.64	14.42	-32.99	34.90	38.12	0.93	-0.52	0.15

Table E.144: Validation metrics for the living room relative humidity for 13:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-10.11	10.11	12.14	-25.82	31.02	31.74	0.99	-0.05	0.13
Reference Case (HAMT)	-10.85	10.85	12.37	-27.71	31.61	32.35	0.99	-0.09	0.13
Scenario 1 - Low leakage	-10.88	10.88	12.38	-27.80	31.63	32.36	0.99	-0.09	0.13
Scenario 2 - 75 mm floor	-11.14	11.14	12.64	-28.46	32.29	33.04	0.99	-0.13	0.13
Scenario 3 - No cooker	-10.85	10.85	12.37	-27.71	31.61	32.35	0.99	-0.09	0.13
Scenario 4 - No moisture	-10.11	10.11	11.68	-25.82	29.85	30.54	0.99	0.03	0.13
Scenario 5 - No ventilation	-14.68	14.68	15.33	-37.51	39.16	40.07	0.94	-0.67	0.16

Table E.145: Validation metrics for the living room relative humidity for 14:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-4.80	5.52	6.44	-12.70	17.01	14.06	0.99	0.79	0.07
Reference Case (HAMT)	-6.61	6.61	7.40	-17.46	19.55	16.16	0.99	0.73	0.08
Scenario 1 - Low leakage	-6.76	6.76	7.50	-17.85	19.83	16.39	0.99	0.72	0.09
Scenario 2 - 75 mm floor	-7.17	7.17	7.90	-18.94	20.88	17.26	0.99	0.69	0.09
Scenario 3 - No cooker	-6.61	6.61	7.40	-17.46	19.55	16.16	0.99	0.73	0.08
Scenario 4 - No moisture	-5.10	5.44	5.99	-13.49	15.82	13.08	0.99	0.82	0.07
Scenario 5 - No ventilation	-14.25	14.25	15.21	-37.65	40.20	33.23	0.94	-0.15	0.16

Table E.146: Validation metrics for the living room relative humidity for 15:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.59	4.78	6.04	-9.49	15.99	13.00	0.98	0.83	0.07
Reference Case (HAMT)	-5.25	5.82	6.56	-13.90	17.36	14.11	0.98	0.79	0.08
Scenario 1 - Low leakage	-5.36	5.90	6.64	-14.19	17.58	14.29	0.98	0.79	0.08
Scenario 2 - 75 mm floor	-5.76	6.20	6.97	-15.24	18.45	15.01	0.98	0.77	0.08
Scenario 3 - No cooker	-5.25	5.82	6.56	-13.90	17.36	14.11	0.98	0.79	0.08
Scenario 4 - No moisture	-3.86	4.73	5.30	-10.23	14.03	11.41	0.98	0.87	0.06
Scenario 5 - No ventilation	-13.35	13.35	14.29	-35.34	37.82	30.75	0.95	0.02	0.15

Table E.147: Validation metrics for the living room relative humidity for 16:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.40	4.80	6.95	-3.59	17.82	15.24	0.93	0.79	0.08
Reference Case (HAMT)	-3.14	5.56	6.71	-8.05	17.22	14.73	0.94	0.80	0.08
Scenario 1 - Low leakage	-3.24	5.65	6.76	-8.32	17.35	14.84	0.94	0.80	0.08
Scenario 2 - 75 mm floor	-3.66	5.95	6.97	-9.38	17.89	15.30	0.94	0.79	0.08
Scenario 3 - No cooker	-3.14	5.55	6.71	-8.05	17.22	14.73	0.94	0.80	0.08
Scenario 4 - No moisture	-1.87	4.71	5.97	-4.79	15.30	13.09	0.94	0.85	0.07
Scenario 5 - No ventilation	-12.43	12.43	14.02	-31.90	35.97	30.76	0.96	0.15	0.15

Table E.148: Validation metrics for the living room relative humidity for 17:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	6.50	10.74	12.92	13.60	27.02	32.33	0.84	-0.22	0.14
Reference Case (HAMT)	4.38	9.02	10.91	9.15	22.82	27.30	0.84	0.13	0.11
Scenario 1 - Low leakage	4.25	8.91	10.75	8.88	22.48	26.89	0.84	0.16	0.11
Scenario 2 - 75 mm floor	3.43	8.45	9.93	7.16	20.76	24.84	0.85	0.28	0.10
Scenario 3 - No cooker	4.38	9.02	10.92	9.16	22.82	27.30	0.84	0.13	0.11
Scenario 4 - No moisture	5.86	9.67	11.79	12.25	24.64	29.48	0.84	-0.01	0.12
Scenario 5 - No ventilation	-5.72	7.72	8.91	-11.96	18.64	22.30	0.81	0.42	0.09

Table E.149: Validation metrics for the living room relative humidity for 18:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.65	7.12	8.97	5.12	17.32	28.60	0.82	0.25	0.09
Reference Case (HAMT)	1.76	6.73	8.41	3.41	16.24	26.82	0.82	0.34	0.08
Scenario 1 - Low leakage	1.72	6.71	8.38	3.33	16.19	26.73	0.82	0.34	0.08
Scenario 2 - 75 mm floor	1.47	6.64	8.31	2.83	16.04	26.48	0.82	0.35	0.08
Scenario 3 - No cooker	0.62	6.99	8.72	1.21	16.84	27.81	0.82	0.29	0.08
Scenario 4 - No moisture	2.39	6.84	8.55	4.61	16.50	27.24	0.82	0.32	0.08
Scenario 5 - No ventilation	-3.51	5.68	7.75	-6.77	14.97	24.72	0.76	0.44	0.07

Table E.150: Validation metrics for the living room relative humidity for 19:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.42	5.78	6.98	4.50	12.96	23.72	0.91	0.44	0.06
Reference Case (HAMT)	-1.23	3.81	4.66	-2.28	8.66	15.85	0.91	0.75	0.04
Scenario 1 - Low leakage	-1.85	4.15	4.88	-3.43	9.07	16.60	0.90	0.73	0.04
Scenario 2 - 75 mm floor	-2.45	4.35	5.04	-4.55	9.36	17.12	0.91	0.71	0.05
Scenario 3 - No cooker	-1.11	3.69	4.52	-2.05	8.40	15.37	0.91	0.76	0.04
Scenario 4 - No moisture	2.49	4.29	5.27	4.62	9.79	17.90	0.91	0.68	0.05
Scenario 5 - No ventilation	-11.88	11.88	12.96	-22.07	24.09	44.07	0.84	-0.94	0.11

Table E.151: Validation metrics for the living room relative humidity for 20:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.20	3.98	5.69	-0.35	10.17	22.41	0.94	0.51	0.05
Reference Case (HAMT)	-4.53	5.56	5.71	-8.11	10.21	22.51	0.91	0.50	0.05
Scenario 1 - Low leakage	-7.20	7.37	7.96	-12.87	14.24	31.37	0.91	0.03	0.07
Scenario 2 - 75 mm floor	-5.93	6.60	6.97	-10.60	12.47	27.48	0.89	0.26	0.06
Scenario 3 - No cooker	-4.45	5.48	5.61	-7.96	10.04	22.12	0.91	0.52	0.05
Scenario 4 - No moisture	1.51	2.23	3.46	2.70	6.19	13.63	0.93	0.82	0.03
Scenario 5 - No ventilation	-10.02	10.02	11.16	-17.92	19.95	43.95	0.80	-0.89	0.09

Table E.152: Validation metrics for the living room relative humidity for 21:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.42	4.82	5.81	-5.99	10.16	25.99	1.00	0.26	0.05
Reference Case (HAMT)	-6.70	6.70	6.75	-11.74	11.81	30.20	0.99	0.01	0.06
Scenario 1 - Low leakage	-10.59	10.59	10.81	-18.54	18.93	48.39	0.99	-1.55	0.09
Scenario 2 - 75 mm floor	-8.05	8.05	8.13	-14.10	14.23	36.38	0.99	-0.44	0.07
Scenario 3 - No cooker	-6.67	6.67	6.71	-11.67	11.74	30.03	0.99	0.02	0.06
Scenario 4 - No moisture	0.18	0.89	1.10	0.32	1.92	4.91	0.99	0.97	0.01
Scenario 5 - No ventilation	-10.85	10.85	11.04	-18.99	19.32	49.40	0.98	-1.66	0.09

Table E.153: Validation metrics for the living room relative humidity for 22:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-6.43	6.81	8.52	-10.87	14.41	42.26	0.96	-0.73	0.07
Reference Case (HAMT)	-8.26	8.26	8.57	-13.97	14.50	42.52	0.94	-0.75	0.07
Scenario 1 - Low leakage	-12.58	12.58	13.02	-21.28	22.02	64.59	0.91	-3.03	0.10
Scenario 2 - 75 mm floor	-9.71	9.71	10.02	-16.42	16.95	49.70	0.92	-1.39	0.08
Scenario 3 - No cooker	-8.24	8.24	8.55	-13.94	14.46	42.43	0.94	-0.74	0.07
Scenario 4 - No moisture	-0.60	1.67	1.92	-1.01	3.25	9.52	0.97	0.91	0.02
Scenario 5 - No ventilation	-11.79	11.79	12.18	-19.94	20.60	60.43	0.88	-2.53	0.09

Table E.154: Validation metrics for the living room relative humidity for 23:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-9.72	9.72	11.24	-16.21	18.74	59.53	0.93	-2.09	0.09
Reference Case (HAMT)	-9.86	9.86	10.23	-16.44	17.06	54.20	0.90	-1.57	0.08
Scenario 1 - Low leakage	-13.84	13.84	14.45	-23.08	24.10	76.55	0.82	-4.12	0.11
Scenario 2 - 75 mm floor	-11.36	11.36	11.76	-18.95	19.61	62.28	0.89	-2.39	0.09
Scenario 3 - No cooker	-9.85	9.85	10.22	-16.42	17.05	54.15	0.90	-1.56	0.08
Scenario 4 - No moisture	-1.59	2.37	2.53	-2.65	4.23	13.42	0.95	0.84	0.02
Scenario 5 - No ventilation	-12.74	12.74	13.18	-21.25	21.99	69.84	0.85	-3.26	0.10

E.6.2.6 Winter Hourly Validation Metrics

The final hourly-based validation analysis considered only results from the winter week. The validation metrics for the living room relative humidity are presented in Tables E.155 to E.178.

Table E.155: Validation metrics for the living room relative humidity for 00:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.62	6.41	6.90	-4.49	11.85	17.76	0.97	0.69	0.06
Reference Case (HAMT)	-2.04	2.70	3.00	-3.50	5.15	7.71	0.98	0.94	0.02
Scenario 1 - Low leakage	-12.23	12.23	12.88	-20.98	22.11	33.14	0.98	-0.08	0.10
Scenario 2 - 75 mm floor	-3.91	3.93	4.51	-6.70	7.74	11.60	0.99	0.87	0.04
Scenario 3 - No cooker	-1.34	2.22	2.54	-2.31	4.36	6.53	0.99	0.96	0.02
Scenario 4 - No moisture	-0.96	2.04	2.34	-1.65	4.02	6.03	0.99	0.96	0.02
Scenario 5 - No ventilation	-3.71	3.78	4.32	-6.37	7.41	11.10	0.99	0.88	0.04

Table E.156: Validation metrics for the living room relative humidity for 01:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-4.88	7.41	8.54	-8.33	14.57	22.57	0.96	0.48	0.07
Reference Case (HAMT)	-3.71	3.81	4.58	-6.33	7.81	12.10	0.97	0.85	0.04
Scenario 1 - Low leakage	-13.81	13.81	14.65	-23.57	25.00	38.71	0.96	-0.53	0.11
Scenario 2 - 75 mm floor	-5.91	5.91	6.49	-10.08	11.09	17.17	0.97	0.70	0.05
Scenario 3 - No cooker	-3.02	3.33	4.02	-5.15	6.87	10.63	0.97	0.88	0.03
Scenario 4 - No moisture	-2.58	3.10	3.69	-4.41	6.30	9.76	0.98	0.90	0.03
Scenario 5 - No ventilation	-5.44	5.44	6.05	-9.29	10.34	16.00	0.98	0.74	0.05

Table E.157: Validation metrics for the living room relative humidity for 02:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-6.49	7.75	9.31	-10.97	15.74	24.88	0.95	0.34	0.07
Reference Case (HAMT)	-4.56	4.56	5.45	-7.70	9.20	14.55	0.97	0.77	0.04
Scenario 1 - Low leakage	-14.53	14.53	15.45	-24.56	26.12	41.28	0.92	-0.82	0.12
Scenario 2 - 75 mm floor	-7.02	7.02	7.69	-11.86	13.00	20.54	0.96	0.55	0.06
Scenario 3 - No cooker	-3.87	3.87	4.87	-6.54	8.24	13.02	0.97	0.82	0.04
Scenario 4 - No moisture	-3.40	3.62	4.50	-5.76	7.60	12.01	0.97	0.85	0.04
Scenario 5 - No ventilation	-6.32	6.32	7.04	-10.69	11.90	18.81	0.97	0.62	0.06

Table E.158: Validation metrics for the living room relative humidity for 03:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-8.26	8.26	10.43	-13.88	17.51	28.09	0.94	0.15	0.08
Reference Case (HAMT)	-5.43	5.43	6.31	-9.12	10.59	16.99	0.96	0.69	0.05
Scenario 1 - Low leakage	-15.24	15.24	16.16	-25.59	27.13	43.52	0.91	-1.04	0.12
Scenario 2 - 75 mm floor	-8.09	8.09	8.79	-13.58	14.76	23.67	0.95	0.40	0.07
Scenario 3 - No cooker	-4.76	4.76	5.72	-7.99	9.61	15.42	0.96	0.74	0.05
Scenario 4 - No moisture	-4.25	4.30	5.30	-7.14	8.90	14.28	0.96	0.78	0.04
Scenario 5 - No ventilation	-7.20	7.20	7.93	-12.10	13.32	21.37	0.96	0.51	0.06

Table E.159: Validation metrics for the living room relative humidity for 04:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-11.93	11.93	16.44	-20.62	28.42	47.01	0.69	-1.28	0.13
Reference Case (HAMT)	-8.29	8.29	11.51	-14.33	19.89	32.90	0.73	-0.12	0.09
Scenario 1 - Low leakage	-18.00	18.00	19.65	-31.10	33.97	56.18	0.69	-2.26	0.15
Scenario 2 - 75 mm floor	-11.07	11.07	13.82	-19.13	23.90	39.52	0.72	-0.61	0.11
Scenario 3 - No cooker	-7.62	7.62	11.00	-13.17	19.02	31.46	0.73	-0.02	0.09
Scenario 4 - No moisture	-7.08	7.08	10.61	-12.24	18.33	30.32	0.73	0.05	0.09
Scenario 5 - No ventilation	-10.06	10.06	13.01	-17.38	22.49	37.19	0.73	-0.43	0.10

Table E.160: Validation metrics for the living room relative humidity for 05:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-13.14	13.57	18.40	-23.54	32.96	46.95	0.60	-0.75	0.14
Reference Case (HAMT)	-9.44	9.44	14.00	-16.91	25.09	35.73	0.67	-0.01	0.11
Scenario 1 - Low leakage	-19.42	19.42	22.01	-34.79	39.43	56.16	0.68	-1.50	0.17
Scenario 2 - 75 mm floor	-12.14	12.14	15.94	-21.74	28.57	40.68	0.68	-0.31	0.13
Scenario 3 - No cooker	-8.82	8.82	13.61	-15.80	24.39	34.73	0.67	0.04	0.11
Scenario 4 - No moisture	-8.29	8.29	13.30	-14.85	23.82	33.93	0.67	0.09	0.11
Scenario 5 - No ventilation	-11.09	11.09	15.20	-19.87	27.23	38.77	0.67	-0.19	0.12

Table E.161: Validation metrics for the living room relative humidity for 06:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-6.85	8.82	10.91	-12.02	19.14	29.42	0.96	0.33	0.09
Reference Case (HAMT)	-4.86	4.86	6.06	-8.53	10.64	16.36	0.98	0.79	0.05
Scenario 1 - Low leakage	-16.12	16.12	16.77	-28.30	29.44	45.24	0.94	-0.58	0.13
Scenario 2 - 75 mm floor	-7.59	7.59	8.70	-13.32	15.26	23.46	0.97	0.57	0.07
Scenario 3 - No cooker	-4.28	4.31	5.53	-7.51	9.71	14.92	0.98	0.83	0.05
Scenario 4 - No moisture	-3.76	3.82	5.04	-6.60	8.85	13.60	0.98	0.86	0.04
Scenario 5 - No ventilation	-6.39	6.39	7.56	-11.22	13.28	20.41	0.97	0.68	0.06

Table E.162: Validation metrics for the living room relative humidity for 07:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-5.47	9.65	11.13	-9.31	18.95	33.17	0.96	0.16	0.09
Reference Case (HAMT)	-4.21	4.68	5.57	-7.17	9.49	16.61	0.98	0.79	0.04
Scenario 1 - Low leakage	-15.34	15.34	15.94	-26.13	27.14	47.52	0.94	-0.72	0.12
Scenario 2 - 75 mm floor	-7.20	7.20	8.28	-12.27	14.10	24.69	0.97	0.54	0.06
Scenario 3 - No cooker	-3.63	4.18	5.07	-6.18	8.63	15.12	0.98	0.83	0.04
Scenario 4 - No moisture	-3.08	3.70	4.60	-5.25	7.82	13.70	0.98	0.86	0.04
Scenario 5 - No ventilation	-5.81	5.97	7.05	-9.89	12.00	21.01	0.97	0.66	0.06

Table E.163: Validation metrics for the living room relative humidity for 08:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.42	5.12	5.68	-4.15	9.76	14.51	0.98	0.85	0.05
Reference Case (HAMT)	-1.67	3.21	3.56	-2.86	6.12	9.10	0.99	0.94	0.03
Scenario 1 - Low leakage	-11.40	11.40	13.28	-19.57	22.80	33.90	0.95	0.19	0.10
Scenario 2 - 75 mm floor	-4.53	4.64	5.47	-7.77	9.39	13.97	0.99	0.86	0.04
Scenario 3 - No cooker	-1.11	3.16	3.38	-1.91	5.81	8.64	0.99	0.95	0.03
Scenario 4 - No moisture	-0.59	3.11	3.27	-1.01	5.62	8.35	0.99	0.95	0.03
Scenario 5 - No ventilation	-3.18	3.88	4.43	-5.47	7.60	11.30	0.99	0.91	0.04

Table E.164: Validation metrics for the living room relative humidity for 09:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.55	7.29	10.44	2.73	18.40	25.35	0.79	0.40	0.09
Reference Case (HAMT)	1.61	6.47	7.79	2.84	13.72	18.90	0.83	0.67	0.07
Scenario 1 - Low leakage	-6.60	8.31	10.61	-11.62	18.70	25.75	0.82	0.38	0.09
Scenario 2 - 75 mm floor	-0.93	6.46	7.62	-1.64	13.43	18.49	0.83	0.68	0.06
Scenario 3 - No cooker	2.09	6.58	7.93	3.69	13.98	19.26	0.82	0.65	0.07
Scenario 4 - No moisture	2.57	6.69	8.12	4.53	14.31	19.71	0.82	0.64	0.07
Scenario 5 - No ventilation	0.30	6.34	7.66	0.53	13.51	18.60	0.82	0.68	0.07

Table E.165: Validation metrics for the living room relative humidity for 10:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.23	3.65	4.33	-0.47	9.01	9.39	0.96	0.92	0.04
Reference Case (HAMT)	-1.17	4.24	4.66	-2.44	9.69	10.09	0.98	0.91	0.05
Scenario 1 - Low leakage	-8.17	8.74	11.19	-16.99	23.26	24.22	0.98	0.46	0.10
Scenario 2 - 75 mm floor	-3.41	4.68	5.45	-7.08	11.34	11.81	0.98	0.87	0.05
Scenario 3 - No cooker	-0.76	4.20	4.61	-1.58	9.58	9.98	0.98	0.91	0.05
Scenario 4 - No moisture	-0.31	4.15	4.59	-0.64	9.54	9.93	0.98	0.91	0.05
Scenario 5 - No ventilation	-2.30	4.37	4.98	-4.79	10.36	10.79	0.98	0.89	0.05

Table E.166: Validation metrics for the living room relative humidity for 11:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.43	1.98	2.72	-1.00	6.30	7.07	0.98	0.96	0.03
Reference Case (HAMT)	-2.37	4.53	4.75	-5.47	11.00	12.35	0.97	0.88	0.05
Scenario 1 - Low leakage	-9.25	10.25	11.57	-21.38	26.76	30.05	0.98	0.28	0.12
Scenario 2 - 75 mm floor	-4.49	5.58	5.94	-10.40	13.73	15.42	0.97	0.81	0.06
Scenario 3 - No cooker	-1.99	4.40	4.60	-4.61	10.65	11.96	0.97	0.89	0.05
Scenario 4 - No moisture	-1.53	4.26	4.48	-3.53	10.35	11.63	0.97	0.89	0.05
Scenario 5 - No ventilation	-3.41	4.84	5.26	-7.89	12.17	13.67	0.97	0.85	0.06

Table E.167: Validation metrics for the living room relative humidity for 12:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.53	4.35	5.32	1.31	13.14	14.14	0.92	0.85	0.06
Reference Case (HAMT)	-2.41	6.22	6.85	-5.95	16.92	18.22	0.91	0.76	0.08
Scenario 1 - Low leakage	-9.36	11.20	12.38	-23.11	30.58	32.92	0.95	0.21	0.13
Scenario 2 - 75 mm floor	-4.31	6.69	7.53	-10.65	18.59	20.01	0.91	0.71	0.08
Scenario 3 - No cooker	-2.06	6.11	6.76	-5.08	16.70	17.97	0.91	0.76	0.08
Scenario 4 - No moisture	-1.60	5.99	6.68	-3.96	16.50	17.76	0.91	0.77	0.08
Scenario 5 - No ventilation	-3.40	6.47	7.15	-8.39	17.65	19.00	0.91	0.74	0.08

Table E.168: Validation metrics for the living room relative humidity for 13:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.62	4.03	4.81	-1.77	13.74	12.85	0.91	0.81	0.07
Reference Case (HAMT)	-4.81	7.45	7.78	-13.74	22.23	20.80	0.85	0.51	0.10
Scenario 1 - Low leakage	-12.01	14.21	14.78	-34.32	42.25	39.53	0.73	-0.76	0.18
Scenario 2 - 75 mm floor	-6.44	8.60	8.91	-18.40	25.46	23.82	0.84	0.36	0.11
Scenario 3 - No cooker	-4.50	7.23	7.58	-12.86	21.66	20.27	0.85	0.54	0.10
Scenario 4 - No moisture	-4.07	6.93	7.33	-11.64	20.94	19.59	0.86	0.57	0.10
Scenario 5 - No ventilation	-5.69	8.07	8.36	-16.26	23.88	22.35	0.85	0.44	0.11

Table E.169: Validation metrics for the living room relative humidity for 14:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.99	3.09	3.67	-8.84	10.83	10.16	0.98	0.88	0.05
Reference Case (HAMT)	-6.09	6.09	6.68	-17.97	19.71	18.49	0.97	0.62	0.09
Scenario 1 - Low leakage	-10.44	10.44	10.94	-30.82	32.30	30.30	0.97	-0.03	0.14
Scenario 2 - 75 mm floor	-7.01	7.01	7.58	-20.71	22.38	21.00	0.96	0.50	0.10
Scenario 3 - No cooker	-5.92	5.92	6.51	-17.47	19.21	18.03	0.97	0.63	0.08
Scenario 4 - No moisture	-5.65	5.65	6.25	-16.69	18.46	17.32	0.97	0.66	0.08
Scenario 5 - No ventilation	-7.08	8.22	9.12	-20.89	26.93	25.26	0.85	0.28	0.12

Table E.170: Validation metrics for the living room relative humidity for 15:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.99	4.32	4.72	-5.91	13.96	13.87	0.95	0.81	0.06
Reference Case (HAMT)	-2.89	4.72	5.13	-8.57	15.20	15.09	0.95	0.77	0.07
Scenario 1 - Low leakage	-3.36	4.91	5.40	-9.94	15.99	15.89	0.96	0.75	0.07
Scenario 2 - 75 mm floor	-3.10	4.84	5.28	-9.17	15.62	15.52	0.96	0.76	0.07
Scenario 3 - No cooker	-2.87	4.71	5.12	-8.49	15.15	15.05	0.95	0.78	0.07
Scenario 4 - No moisture	-2.80	4.67	5.07	-8.29	15.01	14.91	0.95	0.78	0.07
Scenario 5 - No ventilation	-6.49	7.56	8.62	-19.22	25.53	25.35	0.85	0.36	0.11

Table E.171: Validation metrics for the living room relative humidity for 16:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.13	3.55	4.49	0.37	13.15	15.18	0.96	0.82	0.06
Reference Case (HAMT)	-0.77	3.76	4.58	-2.24	13.39	15.45	0.97	0.81	0.06
Scenario 1 - Low leakage	-1.17	3.89	4.68	-3.43	13.71	15.82	0.97	0.80	0.06
Scenario 2 - 75 mm floor	-0.96	3.85	4.66	-2.80	13.64	15.74	0.97	0.81	0.06
Scenario 3 - No cooker	-0.74	3.75	4.57	-2.18	13.36	15.42	0.97	0.81	0.06
Scenario 4 - No moisture	-0.68	3.72	4.54	-1.99	13.28	15.32	0.97	0.82	0.06
Scenario 5 - No ventilation	-6.63	6.63	8.49	-19.40	24.84	28.67	0.87	0.36	0.11

Table E.172: Validation metrics for the living room relative humidity for 17:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	6.60	6.60	7.19	17.40	18.94	17.76	0.98	0.75	0.10
Reference Case (HAMT)	3.98	4.10	4.83	10.48	12.71	11.93	0.99	0.89	0.06
Scenario 1 - Low leakage	2.49	3.46	3.88	6.56	10.21	9.58	0.99	0.93	0.05
Scenario 2 - 75 mm floor	3.44	3.68	4.35	9.07	11.47	10.76	0.99	0.91	0.06
Scenario 3 - No cooker	4.05	4.16	4.89	10.67	12.88	12.09	0.99	0.88	0.06
Scenario 4 - No moisture	4.22	4.29	5.04	11.11	13.28	12.46	0.99	0.88	0.07
Scenario 5 - No ventilation	-3.79	7.21	8.53	-9.99	22.46	21.07	0.87	0.65	0.10

Table E.173: Validation metrics for the living room relative humidity for 18:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	6.98	8.17	9.44	15.95	21.58	24.61	0.88	0.50	0.11
Reference Case (HAMT)	2.37	5.79	6.61	5.41	15.11	17.23	0.92	0.76	0.08
Scenario 1 - Low leakage	-5.26	6.65	9.29	-12.02	21.23	24.20	0.92	0.52	0.10
Scenario 2 - 75 mm floor	1.27	5.31	6.22	2.89	14.22	16.22	0.92	0.78	0.07
Scenario 3 - No cooker	4.28	6.47	6.95	9.79	15.89	18.11	0.93	0.73	0.08
Scenario 4 - No moisture	3.01	6.08	6.92	6.88	15.82	18.04	0.92	0.73	0.08
Scenario 5 - No ventilation	-0.66	4.67	6.40	-1.52	14.64	16.69	0.91	0.77	0.07

Table E.174: Validation metrics for the living room relative humidity for 19:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.53	5.89	7.71	7.20	15.74	21.24	0.87	0.67	0.08
Reference Case (HAMT)	-0.94	4.34	6.34	-1.91	12.93	17.46	0.89	0.77	0.06
Scenario 1 - Low leakage	-13.13	13.13	15.27	-26.80	31.17	42.06	0.87	-0.31	0.13
Scenario 2 - 75 mm floor	-2.09	4.88	6.56	-4.27	13.40	18.08	0.89	0.76	0.06
Scenario 3 - No cooker	3.89	5.50	7.30	7.95	14.91	20.12	0.89	0.70	0.08
Scenario 4 - No moisture	-0.06	4.30	6.31	-0.13	12.88	17.38	0.89	0.78	0.06
Scenario 5 - No ventilation	-3.04	5.39	7.03	-6.21	14.36	19.38	0.88	0.72	0.07

Table E.175: Validation metrics for the living room relative humidity for 20:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	6.76	6.76	9.31	12.96	17.86	24.37	0.87	0.45	0.09
Reference Case (HAMT)	2.10	4.73	6.12	4.02	11.73	16.01	0.89	0.76	0.06
Scenario 1 - Low leakage	-9.90	9.90	12.10	-18.99	23.20	31.67	0.88	0.06	0.10
Scenario 2 - 75 mm floor	0.81	4.46	5.69	1.55	10.91	14.90	0.90	0.79	0.05
Scenario 3 - No cooker	3.80	5.65	7.06	7.28	13.54	18.48	0.88	0.68	0.07
Scenario 4 - No moisture	3.02	5.24	6.57	5.80	12.59	17.19	0.89	0.72	0.06
Scenario 5 - No ventilation	0.23	4.66	5.83	0.44	11.17	15.25	0.89	0.78	0.05

Table E.176: Validation metrics for the living room relative humidity for 21:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	5.22	5.47	6.85	9.87	12.95	16.85	0.95	0.73	0.07
Reference Case (HAMT)	1.15	3.42	4.27	2.18	8.07	10.50	0.96	0.89	0.04
Scenario 1 - Low leakage	-10.55	10.55	12.33	-19.95	23.32	30.34	0.94	0.11	0.10
Scenario 2 - 75 mm floor	-0.31	3.37	4.00	-0.59	7.56	9.83	0.96	0.91	0.04
Scenario 3 - No cooker	2.16	3.98	4.73	4.08	8.95	11.64	0.96	0.87	0.04
Scenario 4 - No moisture	2.11	3.97	4.72	3.99	8.92	11.61	0.96	0.87	0.04
Scenario 5 - No ventilation	-0.56	3.53	4.18	-1.06	7.91	10.29	0.96	0.90	0.04

Table E.177: Validation metrics for the living room relative humidity for 22:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.37	5.72	6.15	6.12	11.17	15.05	0.95	0.77	0.06
Reference Case (HAMT)	0.22	1.48	2.22	0.40	4.03	5.43	0.99	0.97	0.02
Scenario 1 - Low leakage	-11.39	11.39	12.14	-20.70	22.06	29.71	0.99	0.09	0.10
Scenario 2 - 75 mm floor	-1.48	2.32	2.52	-2.69	4.57	6.16	0.99	0.96	0.02
Scenario 3 - No cooker	1.01	1.93	2.54	1.84	4.61	6.21	0.98	0.96	0.02
Scenario 4 - No moisture	1.21	2.00	2.64	2.19	4.79	6.46	0.98	0.96	0.02
Scenario 5 - No ventilation	-1.43	2.28	2.44	-2.60	4.43	5.97	0.99	0.96	0.02

Table E.178: Validation metrics for the living room relative humidity for 23:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.47	5.26	5.81	-0.85	10.59	14.90	0.95	0.78	0.05
Reference Case (HAMT)	-1.73	3.21	4.66	-3.16	8.48	11.94	0.94	0.86	0.04
Scenario 1 - Low leakage	-12.58	12.58	13.52	-22.91	24.63	34.65	0.93	-0.21	0.11
Scenario 2 - 75 mm floor	-3.52	3.90	5.65	-6.41	10.30	14.49	0.94	0.79	0.05
Scenario 3 - No cooker	-1.08	2.97	4.40	-1.96	8.02	11.28	0.94	0.87	0.04
Scenario 4 - No moisture	-0.78	2.89	4.33	-1.41	7.88	11.09	0.94	0.88	0.04
Scenario 5 - No ventilation	-3.28	3.69	5.66	-5.97	10.30	14.50	0.94	0.79	0.05

E.6.3 Bedroom Air Temperature

E.6.3.1 Overall Validation Metrics

Table E.179 contains the validation metrics for the bedroom air temperature for the summer and winter weeks combined.

Table E.179: Validation metrics for the bedroom air temperature for the summer and winter week combined

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.06	2.63	3.20	4.52	13.59	9.54	0.90	0.78	0.07
Reference Case (HAMT)	1.13	2.46	3.08	4.81	13.09	9.19	0.92	0.80	0.06
Scenario 1 - Low leakage	0.96	2.50	3.09	4.10	13.11	9.20	0.91	0.80	0.06
Scenario 2 - 75 mm floor	1.27	2.46	3.11	5.39	13.21	9.27	0.92	0.79	0.07
Scenario 3 - No cooker	1.15	2.45	3.07	4.88	13.06	9.17	0.92	0.80	0.06
Scenario 4 - No moisture	1.10	2.47	3.06	4.66	13.00	9.12	0.92	0.80	0.06
Scenario 5 - No ventilation	0.48	1.93	2.32	2.05	9.87	6.93	0.94	0.88	0.05

E.6.3.2 Weekly Validation Metrics

The validation metrics for the bedroom air temperature for the summer and winter weeks are presented in Tables E.180 and E.181.

Table E.180: Validation metrics for the bedroom air temperature for the summer week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.20	3.47	4.01	11.29	14.13	16.29	0.89	0.43	0.07
Reference Case (HAMT)	3.21	3.35	3.97	11.31	13.98	16.12	0.90	0.44	0.07
Scenario 1 - Low leakage	3.07	3.27	3.91	10.80	13.77	15.87	0.89	0.46	0.07
Scenario 2 - 75 mm floor	3.36	3.46	4.06	11.84	14.29	16.47	0.90	0.42	0.07
Scenario 3 - No cooker	3.22	3.36	3.97	11.33	13.99	16.13	0.90	0.44	0.07
Scenario 4 - No moisture	3.16	3.34	3.93	11.12	13.83	15.95	0.90	0.45	0.07
Scenario 5 - No ventilation	2.00	2.21	2.70	7.05	9.49	10.94	0.95	0.74	0.05

Table E.181: Validation metrics for the bedroom air temperature for the winter week

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.08	1.79	2.09	-5.77	11.18	10.82	0.94	0.77	0.05
Reference Case (HAMT)	-0.95	1.57	1.80	-5.06	9.61	9.29	0.94	0.83	0.05
Scenario 1 - Low leakage	-1.14	1.73	1.95	-6.09	10.42	10.07	0.94	0.80	0.05
Scenario 2 - 75 mm floor	-0.83	1.46	1.69	-4.42	9.06	8.76	0.94	0.85	0.04
Scenario 3 - No cooker	-0.92	1.54	1.77	-4.91	9.45	9.14	0.94	0.83	0.04
Scenario 4 - No moisture	-0.96	1.59	1.82	-5.16	9.73	9.41	0.94	0.82	0.05
Scenario 5 - No ventilation	-1.04	1.65	1.88	-5.55	10.07	9.74	0.94	0.81	0.05

E.6.3.3 Daily Validation Metrics

The validation metrics for the bedroom air temperature for the summer days are presented in Tables E.182 to E.188.

Table E.182: Validation metrics for the bedroom air temperature for 23 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.21	3.74	4.33	11.90	16.04	41.62	0.52	-0.80	0.08
Reference Case (HAMT)	3.24	3.58	4.30	12.02	15.93	41.34	0.51	-0.78	0.08
Scenario 1 - Low leakage	3.04	3.51	4.22	11.27	15.65	40.62	0.47	-0.72	0.08
Scenario 2 - 75 mm floor	3.38	3.64	4.36	12.54	16.15	41.91	0.54	-0.82	0.09
Scenario 3 - No cooker	3.26	3.59	4.31	12.06	15.95	41.40	0.51	-0.78	0.08
Scenario 4 - No moisture	3.21	3.61	4.28	11.91	15.87	41.19	0.52	-0.76	0.08
Scenario 5 - No ventilation	0.80	1.42	1.77	2.98	6.57	17.05	0.94	0.70	0.03

Table E.183: Validation metrics for the bedroom air temperature for 24 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.13	2.56	3.27	7.72	11.85	16.45	0.93	0.75	0.06
Reference Case (HAMT)	2.32	2.52	3.41	8.39	12.36	17.15	0.93	0.73	0.06
Scenario 1 - Low leakage	2.07	2.41	3.34	7.50	12.10	16.80	0.92	0.74	0.06
Scenario 2 - 75 mm floor	2.46	2.58	3.48	8.92	12.60	17.49	0.93	0.72	0.06
Scenario 3 - No cooker	2.32	2.52	3.41	8.40	12.36	17.16	0.93	0.73	0.06
Scenario 4 - No moisture	2.22	2.50	3.32	8.04	12.04	16.71	0.93	0.74	0.06
Scenario 5 - No ventilation	1.15	1.27	1.85	4.15	6.69	9.29	0.98	0.92	0.03

Table E.184: Validation metrics for the bedroom air temperature for 25 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.94	3.17	3.99	10.52	14.29	28.27	0.84	0.33	0.07
Reference Case (HAMT)	2.96	3.04	3.97	10.58	14.22	28.13	0.84	0.34	0.07
Scenario 1 - Low leakage	2.78	2.95	3.90	9.96	13.97	27.64	0.83	0.36	0.07
Scenario 2 - 75 mm floor	3.10	3.15	4.03	11.10	14.44	28.57	0.85	0.32	0.08
Scenario 3 - No cooker	2.96	3.04	3.97	10.60	14.22	28.13	0.84	0.34	0.07
Scenario 4 - No moisture	2.90	3.04	3.93	10.40	14.07	27.85	0.84	0.35	0.07
Scenario 5 - No ventilation	1.52	1.58	2.14	5.46	7.65	15.13	0.96	0.81	0.04

Table E.185: Validation metrics for the bedroom air temperature for 26 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.69	3.77	4.37	12.52	14.80	30.04	0.89	0.26	0.08
Reference Case (HAMT)	3.68	3.70	4.35	12.48	14.75	29.92	0.89	0.26	0.08
Scenario 1 - Low leakage	3.54	3.59	4.29	12.02	14.55	29.52	0.88	0.28	0.08
Scenario 2 - 75 mm floor	3.83	3.83	4.45	12.99	15.07	30.59	0.90	0.23	0.08
Scenario 3 - No cooker	3.68	3.70	4.35	12.49	14.75	29.93	0.89	0.26	0.08
Scenario 4 - No moisture	3.63	3.67	4.30	12.32	14.57	29.56	0.89	0.28	0.08
Scenario 5 - No ventilation	2.16	2.22	2.58	7.30	8.74	17.73	0.97	0.74	0.04

Table E.186: Validation metrics for the bedroom air temperature for 27 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	3.38	3.38	3.76	11.33	12.63	26.65	0.93	0.27	0.07
Reference Case (HAMT)	3.34	3.34	3.70	11.20	12.42	26.22	0.93	0.30	0.07
Scenario 1 - Low leakage	3.25	3.25	3.63	10.91	12.20	25.74	0.93	0.32	0.06
Scenario 2 - 75 mm floor	3.49	3.49	3.81	11.72	12.80	27.02	0.94	0.25	0.07
Scenario 3 - No cooker	3.34	3.34	3.70	11.22	12.43	26.23	0.93	0.30	0.07
Scenario 4 - No moisture	3.30	3.30	3.67	11.08	12.32	25.99	0.93	0.31	0.06
Scenario 5 - No ventilation	1.94	2.12	2.40	6.51	8.04	16.97	0.98	0.71	0.04

Table E.187: Validation metrics for the bedroom air temperature for 28 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	2.68	3.28	3.70	8.21	11.35	21.97	0.90	0.58	0.06
Reference Case (HAMT)	2.95	3.33	3.87	9.05	11.85	22.95	0.90	0.54	0.06
Scenario 1 - Low leakage	2.89	3.30	3.85	8.86	11.80	22.84	0.90	0.55	0.06
Scenario 2 - 75 mm floor	3.21	3.48	4.03	9.85	12.35	23.91	0.91	0.50	0.06
Scenario 3 - No cooker	2.96	3.33	3.87	9.07	11.85	22.95	0.90	0.54	0.06
Scenario 4 - No moisture	2.81	3.27	3.76	8.62	11.53	22.32	0.90	0.57	0.06
Scenario 5 - No ventilation	2.59	3.01	3.44	7.95	10.56	20.44	0.92	0.64	0.05

Table E.188: Validation metrics for the bedroom air temperature for 29 February 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	4.40	4.40	4.51	18.13	18.58	135.86	0.64	-22.75	0.10
Reference Case (HAMT)	3.98	3.98	4.10	16.39	16.91	123.64	0.61	-18.67	0.09
Scenario 1 - Low leakage	3.88	3.88	4.03	16.00	16.59	121.34	0.60	-17.95	0.09
Scenario 2 - 75 mm floor	4.05	4.05	4.16	16.67	17.14	125.38	0.61	-19.23	0.09
Scenario 3 - No cooker	3.99	3.99	4.11	16.42	16.93	123.83	0.61	-18.73	0.09
Scenario 4 - No moisture	4.01	4.01	4.13	16.51	17.01	124.39	0.61	-18.91	0.09
Scenario 5 - No ventilation	3.84	3.84	3.93	15.83	16.21	118.51	0.71	-17.07	0.09

The validation metrics for the bedroom air temperature for the winter days are presented in Tables E.189 to E.195.

Table E.189: Validation metrics for the bedroom air temperature for 25 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	-0.70	1.54	1.83	-3.59	9.39	16.82	0.89	0.69	0.05
Reference Case (HAMT)	-0.54	1.39	1.59	-2.77	8.18	14.66	0.90	0.76	0.04
Scenario 1 - Low leakage	-0.63	1.59	1.78	-3.24	9.15	16.39	0.88	0.71	0.04
Scenario 2 - 75 mm floor	-0.41	1.30	1.52	-2.10	7.80	13.97	0.90	0.79	0.04
Scenario 3 - No cooker	-0.51	1.36	1.56	-2.62	8.02	14.37	0.90	0.77	0.04
Scenario 4 - No moisture	-0.55	1.39	1.60	-2.82	8.23	14.75	0.90	0.76	0.04
Scenario 5 - No ventilation	-0.72	1.56	1.77	-3.69	9.08	16.26	0.89	0.71	0.04

Table E.190: Validation metrics for the bedroom air temperature for 26 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R²	IC
Reference Case (CTF)	-1.19	1.52	1.76	-6.64	9.86	16.98	0.96	0.74	0.05
Reference Case (HAMT)	-0.99	1.30	1.44	-5.52	8.09	13.93	0.96	0.82	0.04
Scenario 1 - Low leakage	-1.28	1.55	1.67	-7.15	9.36	16.12	0.96	0.76	0.04
Scenario 2 - 75 mm floor	-0.88	1.20	1.33	-4.93	7.43	12.80	0.96	0.85	0.04
Scenario 3 - No cooker	-0.96	1.27	1.39	-5.35	7.81	13.45	0.96	0.84	0.04
Scenario 4 - No moisture	-1.01	1.32	1.47	-5.63	8.22	14.17	0.96	0.82	0.04
Scenario 5 - No ventilation	-1.14	1.46	1.62	-6.39	9.04	15.57	0.96	0.78	0.04

Table E.191: Validation metrics for the bedroom air temperature for 27 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.63	1.96	2.24	-9.85	13.48	15.98	0.98	0.76	0.06
Reference Case (HAMT)	-1.54	1.77	1.91	-9.29	11.53	13.67	0.98	0.82	0.05
Scenario 1 - Low leakage	-1.85	2.02	2.18	-11.16	13.11	15.54	0.98	0.77	0.06
Scenario 2 - 75 mm floor	-1.46	1.67	1.79	-8.79	10.80	12.81	0.98	0.85	0.05
Scenario 3 - No cooker	-1.51	1.75	1.88	-9.12	11.32	13.41	0.98	0.83	0.05
Scenario 4 - No moisture	-1.56	1.80	1.95	-9.41	11.73	13.90	0.98	0.82	0.05
Scenario 5 - No ventilation	-1.65	1.87	2.04	-9.92	12.28	14.55	0.98	0.80	0.06

Table E.192: Validation metrics for the bedroom air temperature for 28 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.65	1.98	2.16	-9.43	12.39	12.90	0.97	0.87	0.06
Reference Case (HAMT)	-1.50	1.87	2.05	-8.61	11.77	12.26	0.97	0.89	0.05
Scenario 1 - Low leakage	-1.62	1.98	2.20	-9.30	12.61	13.13	0.97	0.87	0.06
Scenario 2 - 75 mm floor	-1.42	1.81	2.00	-8.16	11.48	11.96	0.98	0.89	0.05
Scenario 3 - No cooker	-1.47	1.84	2.03	-8.43	11.65	12.13	0.97	0.89	0.05
Scenario 4 - No moisture	-1.53	1.88	2.07	-8.76	11.84	12.33	0.97	0.89	0.05
Scenario 5 - No ventilation	-1.52	1.88	2.07	-8.69	11.88	12.37	0.97	0.88	0.05

Table E.193: Validation metrics for the bedroom air temperature for 29 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.37	1.81	2.14	-7.04	10.99	22.71	0.93	0.46	0.05
Reference Case (HAMT)	-1.26	1.62	1.83	-6.48	9.39	19.40	0.94	0.60	0.04
Scenario 1 - Low leakage	-1.48	1.81	2.01	-7.62	10.36	21.40	0.94	0.52	0.05
Scenario 2 - 75 mm floor	-1.10	1.47	1.68	-5.64	8.62	17.80	0.94	0.67	0.04
Scenario 3 - No cooker	-1.23	1.59	1.80	-6.34	9.27	19.14	0.94	0.61	0.04
Scenario 4 - No moisture	-1.27	1.63	1.85	-6.55	9.53	19.69	0.94	0.59	0.05
Scenario 5 - No ventilation	-1.31	1.67	1.90	-6.74	9.76	20.17	0.94	0.57	0.05

Table E.194: Validation metrics for the bedroom air temperature for 30 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.36	1.63	1.97	1.87	10.36	23.06	0.93	0.52	0.05
Reference Case (HAMT)	0.32	1.28	1.61	1.69	8.48	18.88	0.93	0.68	0.04
Scenario 1 - Low leakage	0.17	1.28	1.60	0.91	8.42	18.76	0.93	0.68	0.04
Scenario 2 - 75 mm floor	0.41	1.23	1.57	2.16	8.25	18.37	0.94	0.70	0.04
Scenario 3 - No cooker	0.35	1.26	1.60	1.84	8.40	18.70	0.94	0.68	0.04
Scenario 4 - No moisture	0.31	1.31	1.64	1.62	8.61	19.17	0.93	0.67	0.04
Scenario 5 - No ventilation	0.24	1.33	1.65	1.24	8.67	19.31	0.93	0.66	0.04

Table E.195: Validation metrics for the bedroom air temperature for 31 August 2012

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.37	2.06	2.45	-6.52	11.70	16.97	0.94	0.70	0.06
Reference Case (HAMT)	-1.11	1.75	2.03	-5.31	9.67	14.03	0.94	0.80	0.05
Scenario 1 - Low leakage	-1.28	1.85	2.09	-6.08	9.95	14.44	0.94	0.78	0.05
Scenario 2 - 75 mm floor	-0.93	1.58	1.87	-4.43	8.90	12.91	0.94	0.83	0.04
Scenario 3 - No cooker	-1.09	1.73	2.00	-5.19	9.52	13.82	0.94	0.80	0.05
Scenario 4 - No moisture	-1.14	1.78	2.05	-5.44	9.80	14.22	0.94	0.79	0.05
Scenario 5 - No ventilation	-1.17	1.80	2.07	-5.56	9.86	14.31	0.94	0.79	0.05

E.6.3.4 Overall Hourly Validation Metrics

The first hourly-based validation analysis considered results from the summer and winter week. The validation metrics for the bedroom air temperature are presented in Tables E.196 to E.219.

Table E.196: Validation metrics for the bedroom air temperature for 00:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.17	1.59	1.85	0.80	8.92	11.55	0.98	0.88	0.04
Reference Case (HAMT)	0.03	1.58	1.80	0.15	8.67	11.23	0.99	0.88	0.04
Scenario 1 - Low leakage	-0.21	1.57	1.81	-1.02	8.73	11.31	0.99	0.88	0.04
Scenario 2 - 75 mm floor	0.21	1.63	1.86	1.02	8.97	11.62	0.99	0.88	0.04
Scenario 3 - No cooker	0.04	1.57	1.79	0.21	8.63	11.18	0.99	0.89	0.04
Scenario 4 - No moisture	0.05	1.59	1.81	0.27	8.74	11.32	0.98	0.88	0.04
Scenario 5 - No ventilation	-0.01	1.59	1.82	-0.05	8.78	11.37	0.99	0.88	0.04

Table E.197: Validation metrics for the bedroom air temperature for 01:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.39	1.67	1.86	1.92	9.21	11.25	0.98	0.88	0.05
Reference Case (HAMT)	0.16	1.59	1.77	0.78	8.77	10.71	0.98	0.89	0.04
Scenario 1 - Low leakage	-0.05	1.56	1.79	-0.27	8.86	10.82	0.98	0.89	0.04
Scenario 2 - 75 mm floor	0.32	1.65	1.84	1.56	9.09	11.11	0.98	0.88	0.04
Scenario 3 - No cooker	0.17	1.58	1.77	0.84	8.74	10.67	0.98	0.89	0.04
Scenario 4 - No moisture	0.19	1.61	1.80	0.96	8.88	10.85	0.98	0.89	0.04
Scenario 5 - No ventilation	0.09	1.56	1.76	0.45	8.71	10.64	0.98	0.89	0.04

Table E.198: Validation metrics for the bedroom air temperature for 02:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.72	1.80	2.05	3.63	10.31	11.75	0.98	0.86	0.05
Reference Case (HAMT)	0.41	1.71	1.91	2.08	9.60	10.95	0.98	0.88	0.05
Scenario 1 - Low leakage	0.20	1.69	1.91	1.01	9.60	10.95	0.98	0.88	0.05
Scenario 2 - 75 mm floor	0.55	1.77	1.99	2.78	10.00	11.41	0.98	0.86	0.05
Scenario 3 - No cooker	0.42	1.71	1.91	2.13	9.58	10.93	0.98	0.88	0.05
Scenario 4 - No moisture	0.46	1.74	1.94	2.29	9.75	11.12	0.98	0.87	0.05
Scenario 5 - No ventilation	0.32	1.66	1.86	1.63	9.35	10.66	0.98	0.88	0.05

Table E.199: Validation metrics for the bedroom air temperature for 03:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.93	1.96	2.23	4.79	11.42	12.81	0.98	0.83	0.06
Reference Case (HAMT)	0.55	1.85	2.03	2.83	10.44	11.71	0.98	0.86	0.05
Scenario 1 - Low leakage	0.35	1.83	2.03	1.78	10.42	11.69	0.98	0.86	0.05
Scenario 2 - 75 mm floor	0.67	1.90	2.12	3.44	10.85	12.17	0.98	0.85	0.05
Scenario 3 - No cooker	0.56	1.84	2.03	2.88	10.42	11.69	0.98	0.86	0.05
Scenario 4 - No moisture	0.60	1.88	2.07	3.08	10.63	11.92	0.98	0.86	0.05
Scenario 5 - No ventilation	0.46	1.79	1.97	2.36	10.11	11.33	0.98	0.87	0.05

Table E.200: Validation metrics for the bedroom air temperature for 04:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.44	2.26	2.58	7.42	13.27	14.25	0.95	0.77	0.07
Reference Case (HAMT)	1.00	2.07	2.30	5.12	11.80	12.68	0.96	0.81	0.06
Scenario 1 - Low leakage	0.80	2.05	2.28	4.13	11.72	12.59	0.96	0.82	0.06
Scenario 2 - 75 mm floor	1.10	2.13	2.38	5.64	12.21	13.12	0.96	0.80	0.06
Scenario 3 - No cooker	1.00	2.06	2.30	5.16	11.80	12.68	0.96	0.81	0.06
Scenario 4 - No moisture	1.05	2.11	2.34	5.40	12.03	12.92	0.96	0.81	0.06
Scenario 5 - No ventilation	0.90	1.99	2.22	4.63	11.41	12.25	0.96	0.83	0.06

Table E.201: Validation metrics for the bedroom air temperature for 05:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.50	2.26	2.62	7.82	13.68	14.49	0.96	0.76	0.07
Reference Case (HAMT)	1.01	2.05	2.31	5.28	12.05	12.75	0.97	0.81	0.06
Scenario 1 - Low leakage	0.85	2.06	2.32	4.41	12.11	12.82	0.96	0.81	0.06
Scenario 2 - 75 mm floor	1.09	2.11	2.38	5.70	12.43	13.16	0.97	0.80	0.06
Scenario 3 - No cooker	1.02	2.05	2.31	5.31	12.05	12.75	0.97	0.81	0.06
Scenario 4 - No moisture	1.07	2.10	2.36	5.59	12.32	13.05	0.97	0.81	0.06
Scenario 5 - No ventilation	0.91	1.97	2.22	4.73	11.59	12.27	0.97	0.83	0.06

Table E.202: Validation metrics for the bedroom air temperature for 06:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.35	2.05	2.50	7.17	13.26	14.12	0.96	0.77	0.07
Reference Case (HAMT)	0.85	1.88	2.18	4.50	11.54	12.28	0.97	0.83	0.06
Scenario 1 - Low leakage	0.75	1.85	2.16	3.98	11.42	12.15	0.97	0.83	0.06
Scenario 2 - 75 mm floor	0.91	1.93	2.25	4.84	11.91	12.68	0.97	0.82	0.06
Scenario 3 - No cooker	0.86	1.88	2.18	4.53	11.54	12.28	0.97	0.83	0.06
Scenario 4 - No moisture	0.91	1.93	2.24	4.84	11.86	12.62	0.96	0.82	0.06
Scenario 5 - No ventilation	0.73	1.79	2.07	3.89	10.96	11.67	0.97	0.85	0.05

Table E.203: Validation metrics for the bedroom air temperature for 07:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.61	2.61	3.02	8.57	16.05	16.99	0.94	0.71	0.08
Reference Case (HAMT)	1.10	2.44	2.68	5.85	14.22	15.05	0.95	0.77	0.07
Scenario 1 - Low leakage	0.95	2.40	2.62	5.04	13.93	14.75	0.96	0.78	0.07
Scenario 2 - 75 mm floor	1.15	2.48	2.74	6.12	14.55	15.41	0.95	0.76	0.07
Scenario 3 - No cooker	1.11	2.44	2.67	5.88	14.21	15.05	0.95	0.77	0.07
Scenario 4 - No moisture	1.16	2.48	2.74	6.18	14.55	15.41	0.95	0.76	0.07
Scenario 5 - No ventilation	0.97	2.33	2.54	5.15	13.48	14.28	0.96	0.79	0.07

Table E.204: Validation metrics for the bedroom air temperature for 08:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.31	3.34	3.93	16.19	19.24	20.89	0.97	0.51	0.10
Reference Case (HAMT)	2.83	2.93	3.49	13.83	17.08	18.54	0.98	0.61	0.09
Scenario 1 - Low leakage	2.67	2.82	3.35	13.06	16.41	17.82	0.98	0.64	0.09
Scenario 2 - 75 mm floor	2.87	2.99	3.55	14.04	17.40	18.89	0.98	0.60	0.09
Scenario 3 - No cooker	2.83	2.94	3.49	13.85	17.09	18.56	0.98	0.61	0.09
Scenario 4 - No moisture	2.88	2.98	3.55	14.10	17.38	18.88	0.98	0.60	0.09
Scenario 5 - No ventilation	2.88	2.99	3.57	14.08	17.47	18.97	0.98	0.59	0.09

Table E.205: Validation metrics for the bedroom air temperature for 09:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	4.18	4.20	4.83	18.55	21.43	22.54	0.95	0.32	0.11
Reference Case (HAMT)	3.97	4.06	4.69	17.59	20.79	21.87	0.96	0.36	0.11
Scenario 1 - Low leakage	3.88	4.01	4.63	17.21	20.55	21.62	0.96	0.37	0.11
Scenario 2 - 75 mm floor	3.99	4.09	4.72	17.67	20.93	22.01	0.96	0.35	0.11
Scenario 3 - No cooker	3.97	4.06	4.69	17.61	20.80	21.88	0.96	0.36	0.11
Scenario 4 - No moisture	3.96	4.05	4.68	17.57	20.74	21.81	0.96	0.36	0.11
Scenario 5 - No ventilation	3.08	3.17	3.56	13.64	15.77	16.59	0.98	0.63	0.08

Table E.206: Validation metrics for the bedroom air temperature for 10:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.71	4.00	4.86	15.10	19.76	20.43	0.92	0.44	0.10
Reference Case (HAMT)	3.66	3.95	4.85	14.88	19.70	20.37	0.93	0.44	0.10
Scenario 1 - Low leakage	3.57	3.90	4.81	14.51	19.54	20.21	0.92	0.45	0.10
Scenario 2 - 75 mm floor	3.69	3.99	4.88	14.98	19.84	20.52	0.93	0.44	0.10
Scenario 3 - No cooker	3.66	3.95	4.85	14.88	19.70	20.38	0.93	0.44	0.10
Scenario 4 - No moisture	3.62	3.91	4.80	14.72	19.51	20.18	0.93	0.46	0.10
Scenario 5 - No ventilation	2.15	2.45	2.96	8.76	12.05	12.47	0.97	0.79	0.06

Table E.207: Validation metrics for the bedroom air temperature for 11:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.77	3.40	4.12	10.65	15.81	16.48	0.92	0.62	0.08
Reference Case (HAMT)	2.89	3.42	4.20	11.11	16.13	16.81	0.92	0.60	0.08
Scenario 1 - Low leakage	2.80	3.46	4.18	10.77	16.05	16.73	0.92	0.60	0.08
Scenario 2 - 75 mm floor	2.94	3.46	4.25	11.29	16.31	17.00	0.92	0.59	0.08
Scenario 3 - No cooker	2.89	3.42	4.20	11.11	16.13	16.81	0.92	0.60	0.08
Scenario 4 - No moisture	2.82	3.37	4.12	10.82	15.82	16.49	0.93	0.62	0.08
Scenario 5 - No ventilation	1.02	1.75	2.20	3.93	8.46	8.82	0.96	0.89	0.04

Table E.208: Validation metrics for the bedroom air temperature for 12:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.90	4.15	4.90	10.29	17.36	22.92	0.82	0.48	0.09
Reference Case (HAMT)	3.20	4.17	5.00	11.35	17.73	23.41	0.84	0.46	0.09
Scenario 1 - Low leakage	3.08	4.18	4.98	10.93	17.65	23.30	0.84	0.46	0.09
Scenario 2 - 75 mm floor	3.28	4.19	5.05	11.63	17.90	23.63	0.85	0.45	0.09
Scenario 3 - No cooker	3.20	4.17	5.00	11.36	17.74	23.42	0.84	0.46	0.09
Scenario 4 - No moisture	3.10	4.10	4.91	10.98	17.39	22.96	0.84	0.48	0.09
Scenario 5 - No ventilation	1.22	2.24	2.73	4.33	9.67	12.77	0.94	0.84	0.05

Table E.209: Validation metrics for the bedroom air temperature for 13:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.63	3.63	4.05	5.61	13.90	22.51	0.81	0.58	0.07
Reference Case (HAMT)	2.11	3.53	4.12	7.25	14.15	22.93	0.84	0.56	0.07
Scenario 1 - Low leakage	1.95	3.62	4.13	6.70	14.18	22.98	0.83	0.56	0.07
Scenario 2 - 75 mm floor	2.23	3.53	4.17	7.64	14.32	23.19	0.84	0.55	0.07
Scenario 3 - No cooker	2.11	3.53	4.12	7.25	14.15	22.93	0.84	0.56	0.07
Scenario 4 - No moisture	1.99	3.47	4.02	6.82	13.81	22.37	0.84	0.58	0.07
Scenario 5 - No ventilation	0.23	1.72	2.00	0.80	6.87	11.13	0.95	0.90	0.03

Table E.210: Validation metrics for the bedroom air temperature for 14:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.27	3.59	3.93	4.24	13.13	20.35	0.86	0.66	0.07
Reference Case (HAMT)	1.88	3.43	4.02	6.30	13.45	20.84	0.89	0.65	0.07
Scenario 1 - Low leakage	1.69	3.55	4.05	5.64	13.54	20.99	0.87	0.64	0.07
Scenario 2 - 75 mm floor	2.03	3.41	4.08	6.79	13.64	21.14	0.89	0.64	0.07
Scenario 3 - No cooker	1.88	3.43	4.02	6.29	13.45	20.84	0.89	0.65	0.07
Scenario 4 - No moisture	1.74	3.37	3.91	5.81	13.06	20.24	0.89	0.67	0.07
Scenario 5 - No ventilation	0.05	1.78	2.15	0.17	7.19	11.14	0.96	0.90	0.04

Table E.211: Validation metrics for the bedroom air temperature for 15:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.15	3.71	3.95	3.81	13.10	19.31	0.86	0.67	0.07
Reference Case (HAMT)	1.79	3.50	3.99	5.93	13.24	19.52	0.89	0.66	0.07
Scenario 1 - Low leakage	1.56	3.68	4.05	5.17	13.43	19.79	0.88	0.66	0.07
Scenario 2 - 75 mm floor	1.95	3.47	4.05	6.47	13.42	19.77	0.90	0.66	0.07
Scenario 3 - No cooker	1.79	3.50	4.00	5.92	13.25	19.52	0.89	0.66	0.07
Scenario 4 - No moisture	1.66	3.46	3.90	5.50	12.93	19.05	0.89	0.68	0.07
Scenario 5 - No ventilation	-0.08	2.37	2.66	-0.28	8.81	12.98	0.93	0.85	0.04

Table E.212: Validation metrics for the bedroom air temperature for 16:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.51	3.26	3.49	1.72	11.81	17.65	0.85	0.70	0.06
Reference Case (HAMT)	1.18	3.04	3.43	3.99	11.59	17.32	0.88	0.71	0.06
Scenario 1 - Low leakage	1.00	3.20	3.50	3.37	11.85	17.71	0.86	0.70	0.06
Scenario 2 - 75 mm floor	1.37	2.99	3.44	4.62	11.65	17.41	0.88	0.71	0.06
Scenario 3 - No cooker	1.18	3.04	3.43	3.99	11.59	17.32	0.88	0.71	0.06
Scenario 4 - No moisture	1.06	3.00	3.35	3.57	11.33	16.93	0.88	0.72	0.06
Scenario 5 - No ventilation	-0.48	2.02	2.43	-1.62	8.22	12.28	0.93	0.86	0.04

Table E.213: Validation metrics for the bedroom air temperature for 17:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.25	2.99	3.16	-0.88	11.21	21.61	0.82	0.66	0.05
Reference Case (HAMT)	0.40	2.61	2.88	1.41	10.20	19.65	0.85	0.72	0.05
Scenario 1 - Low leakage	0.28	2.72	2.96	0.99	10.49	20.23	0.84	0.71	0.05
Scenario 2 - 75 mm floor	0.61	2.48	2.82	2.17	9.99	19.25	0.86	0.73	0.05
Scenario 3 - No cooker	0.39	2.61	2.88	1.40	10.20	19.67	0.85	0.72	0.05
Scenario 4 - No moisture	0.28	2.63	2.87	1.00	10.19	19.64	0.85	0.72	0.05
Scenario 5 - No ventilation	-0.90	1.87	2.34	-3.18	8.31	16.01	0.92	0.82	0.04

Table E.214: Validation metrics for the bedroom air temperature for 18:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.61	3.04	3.34	-2.32	12.68	23.40	0.81	0.63	0.06
Reference Case (HAMT)	-0.08	2.71	3.02	-0.31	11.46	21.16	0.85	0.70	0.06
Scenario 1 - Low leakage	-0.13	2.74	3.06	-0.48	11.62	21.46	0.84	0.69	0.06
Scenario 2 - 75 mm floor	0.11	2.62	2.93	0.42	11.10	20.48	0.86	0.72	0.05
Scenario 3 - No cooker	0.10	2.57	2.90	0.40	11.01	20.32	0.86	0.72	0.05
Scenario 4 - No moisture	-0.17	2.72	3.02	-0.64	11.47	21.17	0.84	0.70	0.06
Scenario 5 - No ventilation	-1.01	2.08	2.56	-3.82	9.73	17.96	0.91	0.78	0.05

Table E.215: Validation metrics for the bedroom air temperature for 19:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.62	2.22	2.41	-6.70	9.96	16.68	0.92	0.72	0.05
Reference Case (HAMT)	-1.03	1.69	1.90	-4.24	7.86	13.16	0.94	0.83	0.04
Scenario 1 - Low leakage	-1.17	1.82	2.00	-4.85	8.25	13.82	0.93	0.81	0.04
Scenario 2 - 75 mm floor	-0.77	1.49	1.73	-3.16	7.15	11.98	0.94	0.86	0.03
Scenario 3 - No cooker	-0.96	1.64	1.86	-3.96	7.70	12.89	0.94	0.83	0.04
Scenario 4 - No moisture	-1.18	1.80	1.98	-4.88	8.20	13.73	0.94	0.81	0.04
Scenario 5 - No ventilation	-0.96	1.75	2.01	-3.96	8.31	13.91	0.92	0.80	0.04

Table E.216: Validation metrics for the bedroom air temperature for 20:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.87	1.42	1.72	-3.73	7.37	13.19	0.94	0.85	0.04
Reference Case (HAMT)	-0.42	1.15	1.42	-1.81	6.09	10.90	0.95	0.90	0.03
Scenario 1 - Low leakage	-0.63	1.27	1.53	-2.71	6.56	11.74	0.95	0.88	0.03
Scenario 2 - 75 mm floor	-0.18	1.07	1.34	-0.76	5.73	10.26	0.96	0.91	0.03
Scenario 3 - No cooker	-0.40	1.14	1.41	-1.70	6.02	10.78	0.95	0.90	0.03
Scenario 4 - No moisture	-0.54	1.18	1.44	-2.30	6.16	11.02	0.95	0.90	0.03
Scenario 5 - No ventilation	-0.14	1.30	1.65	-0.58	7.05	12.62	0.93	0.86	0.03

Table E.217: Validation metrics for the bedroom air temperature for 21:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.32	1.15	1.43	-1.43	6.33	9.83	0.96	0.90	0.03
Reference Case (HAMT)	-0.04	0.99	1.32	-0.20	5.86	9.11	0.97	0.92	0.03
Scenario 1 - Low leakage	-0.28	1.13	1.42	-1.23	6.28	9.76	0.96	0.90	0.03
Scenario 2 - 75 mm floor	0.18	1.00	1.33	0.81	5.88	9.13	0.97	0.92	0.03
Scenario 3 - No cooker	-0.02	0.98	1.31	-0.10	5.82	9.04	0.97	0.92	0.03
Scenario 4 - No moisture	-0.11	1.00	1.30	-0.50	5.76	8.95	0.97	0.92	0.03
Scenario 5 - No ventilation	0.29	1.28	1.66	1.26	7.34	11.40	0.95	0.87	0.04

Table E.218: Validation metrics for the bedroom air temperature for 22:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.40	1.35	1.58	-1.86	7.25	10.77	0.96	0.88	0.04
Reference Case (HAMT)	-0.29	1.26	1.50	-1.34	6.91	10.26	0.97	0.89	0.03
Scenario 1 - Low leakage	-0.53	1.37	1.60	-2.43	7.35	10.92	0.96	0.88	0.04
Scenario 2 - 75 mm floor	-0.08	1.25	1.49	-0.39	6.83	10.14	0.97	0.89	0.03
Scenario 3 - No cooker	-0.27	1.25	1.49	-1.26	6.85	10.17	0.97	0.89	0.03
Scenario 4 - No moisture	-0.32	1.26	1.49	-1.47	6.85	10.17	0.97	0.89	0.03
Scenario 5 - No ventilation	-0.19	1.38	1.63	-0.88	7.47	11.09	0.96	0.87	0.04

Table E.219: Validation metrics for the bedroom air temperature for 23:00 (February and August combined)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.04	1.49	1.77	0.18	8.32	11.45	0.95	0.86	0.04
Reference Case (HAMT)	0.01	1.46	1.70	0.06	8.01	11.03	0.96	0.87	0.04
Scenario 1 - Low leakage	-0.23	1.50	1.75	-1.10	8.22	11.32	0.96	0.86	0.04
Scenario 2 - 75 mm floor	0.20	1.49	1.73	0.94	8.16	11.23	0.97	0.86	0.04
Scenario 3 - No cooker	0.03	1.45	1.69	0.13	7.97	10.97	0.96	0.87	0.04
Scenario 4 - No moisture	0.01	1.45	1.70	0.07	8.00	11.01	0.96	0.87	0.04
Scenario 5 - No ventilation	0.02	1.52	1.76	0.09	8.26	11.37	0.96	0.86	0.04

E.6.3.5 Summer Hourly Validation Metrics

The second hourly-based validation analysis considered only results from the summer week. The validation metrics for the bedroom air temperature are presented in Tables E.220 to E.243.

Table E.220: Validation metrics for the bedroom air temperature for 00:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.76	1.76	2.05	6.89	8.03	26.87	0.93	0.14	0.04
Reference Case (HAMT)	1.61	1.61	1.89	6.29	7.39	24.71	0.95	0.27	0.04
Scenario 1 - Low leakage	1.34	1.37	1.72	5.26	6.73	22.51	0.95	0.39	0.03
Scenario 2 - 75 mm floor	1.84	1.84	2.10	7.20	8.22	27.48	0.96	0.10	0.04
Scenario 3 - No cooker	1.61	1.61	1.89	6.30	7.40	24.75	0.95	0.27	0.04
Scenario 4 - No moisture	1.64	1.64	1.92	6.44	7.53	25.19	0.95	0.24	0.04
Scenario 5 - No ventilation	1.58	1.58	1.88	6.19	7.38	24.67	0.95	0.27	0.04

Table E.221: Validation metrics for the bedroom air temperature for 01:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.97	1.97	2.16	7.87	8.63	27.51	0.94	0.09	0.04
Reference Case (HAMT)	1.71	1.71	1.90	6.83	7.58	24.17	0.95	0.30	0.04
Scenario 1 - Low leakage	1.50	1.50	1.77	5.99	7.04	22.45	0.95	0.39	0.04
Scenario 2 - 75 mm floor	1.92	1.92	2.10	7.66	8.36	26.66	0.95	0.14	0.04
Scenario 3 - No cooker	1.72	1.72	1.91	6.85	7.59	24.21	0.95	0.29	0.04
Scenario 4 - No moisture	1.77	1.77	1.95	7.05	7.79	24.84	0.95	0.26	0.04
Scenario 5 - No ventilation	1.63	1.63	1.84	6.49	7.34	23.40	0.95	0.34	0.04

Table E.222: Validation metrics for the bedroom air temperature for 02:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.40	2.40	2.53	9.68	10.21	29.39	0.96	-0.12	0.05
Reference Case (HAMT)	2.06	2.06	2.19	8.29	8.84	25.46	0.98	0.16	0.05
Scenario 1 - Low leakage	1.85	1.85	2.05	7.47	8.25	23.76	0.97	0.27	0.04
Scenario 2 - 75 mm floor	2.24	2.24	2.38	9.04	9.58	27.59	0.98	0.01	0.05
Scenario 3 - No cooker	2.06	2.06	2.19	8.30	8.85	25.49	0.98	0.16	0.05
Scenario 4 - No moisture	2.12	2.12	2.25	8.56	9.08	26.14	0.98	0.12	0.05
Scenario 5 - No ventilation	1.92	1.92	2.08	7.74	8.38	24.14	0.97	0.25	0.04

Table E.223: Validation metrics for the bedroom air temperature for 03:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.73	2.73	2.86	11.14	11.67	33.68	0.94	-0.49	0.06
Reference Case (HAMT)	2.30	2.30	2.43	9.40	9.91	28.61	0.96	-0.07	0.05
Scenario 1 - Low leakage	2.11	2.11	2.28	8.63	9.32	26.91	0.95	0.05	0.05
Scenario 2 - 75 mm floor	2.47	2.47	2.59	10.08	10.59	30.56	0.96	-0.22	0.06
Scenario 3 - No cooker	2.30	2.30	2.43	9.41	9.92	28.64	0.96	-0.07	0.05
Scenario 4 - No moisture	2.37	2.37	2.50	9.70	10.20	29.45	0.96	-0.14	0.05
Scenario 5 - No ventilation	2.15	2.15	2.30	8.79	9.38	27.08	0.96	0.04	0.05

Table E.224: Validation metrics for the bedroom air temperature for 04:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.94	2.94	3.08	12.20	12.75	33.28	0.94	-0.48	0.07
Reference Case (HAMT)	2.44	2.44	2.58	10.11	10.70	27.93	0.96	-0.04	0.06
Scenario 1 - Low leakage	2.26	2.26	2.46	9.39	10.18	26.57	0.96	0.06	0.05
Scenario 2 - 75 mm floor	2.59	2.59	2.73	10.74	11.32	29.56	0.96	-0.16	0.06
Scenario 3 - No cooker	2.44	2.44	2.58	10.12	10.71	27.96	0.96	-0.04	0.06
Scenario 4 - No moisture	2.52	2.52	2.66	10.46	11.03	28.79	0.96	-0.10	0.06
Scenario 5 - No ventilation	2.28	2.28	2.44	9.45	10.12	26.42	0.96	0.07	0.05

Table E.225: Validation metrics for the bedroom air temperature for 05:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.07	3.07	3.26	12.93	13.70	35.52	0.90	-0.67	0.07
Reference Case (HAMT)	2.52	2.52	2.71	10.62	11.39	29.51	0.93	-0.16	0.06
Scenario 1 - Low leakage	2.35	2.35	2.58	9.91	10.87	28.18	0.92	-0.05	0.06
Scenario 2 - 75 mm floor	2.65	2.65	2.83	11.17	11.93	30.90	0.93	-0.27	0.06
Scenario 3 - No cooker	2.53	2.53	2.71	10.63	11.40	29.53	0.93	-0.16	0.06
Scenario 4 - No moisture	2.62	2.62	2.80	11.02	11.78	30.53	0.93	-0.24	0.06
Scenario 5 - No ventilation	2.34	2.34	2.55	9.85	10.73	27.82	0.93	-0.03	0.06

Table E.226: Validation metrics for the bedroom air temperature for 06:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.16	3.16	3.34	13.52	14.29	36.33	0.91	-0.75	0.08
Reference Case (HAMT)	2.58	2.58	2.76	11.01	11.79	29.98	0.93	-0.19	0.06
Scenario 1 - Low leakage	2.41	2.41	2.64	10.31	11.28	28.69	0.92	-0.09	0.06
Scenario 2 - 75 mm floor	2.69	2.69	2.87	11.49	12.27	31.19	0.93	-0.29	0.06
Scenario 3 - No cooker	2.58	2.58	2.76	11.02	11.80	30.00	0.93	-0.19	0.06
Scenario 4 - No moisture	2.68	2.68	2.86	11.45	12.22	31.08	0.93	-0.28	0.06
Scenario 5 - No ventilation	2.37	2.37	2.57	10.12	11.01	27.99	0.93	-0.04	0.06

Table E.227: Validation metrics for the bedroom air temperature for 07:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.95	3.95	4.01	16.58	16.84	59.89	0.93	-3.61	0.09
Reference Case (HAMT)	3.34	3.34	3.39	14.00	14.22	50.56	0.95	-2.29	0.08
Scenario 1 - Low leakage	3.16	3.16	3.24	13.28	13.58	48.30	0.93	-2.00	0.07
Scenario 2 - 75 mm floor	3.43	3.43	3.48	14.41	14.62	52.00	0.95	-2.48	0.08
Scenario 3 - No cooker	3.34	3.34	3.39	14.01	14.22	50.58	0.95	-2.29	0.08
Scenario 4 - No moisture	3.44	3.44	3.49	14.44	14.66	52.13	0.95	-2.50	0.08
Scenario 5 - No ventilation	3.10	3.10	3.16	12.99	13.26	47.15	0.94	-1.86	0.07

Table E.228: Validation metrics for the bedroom air temperature for 08:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	5.24	5.24	5.26	20.57	20.66	77.50	0.99	-5.35	0.11
Reference Case (HAMT)	4.67	4.67	4.71	18.33	18.49	69.37	0.99	-4.09	0.10
Scenario 1 - Low leakage	4.48	4.48	4.53	17.58	17.79	66.74	0.99	-3.71	0.10
Scenario 2 - 75 mm floor	4.76	4.76	4.80	18.68	18.86	70.76	0.99	-4.30	0.10
Scenario 3 - No cooker	4.67	4.67	4.71	18.33	18.50	69.39	0.99	-4.09	0.10
Scenario 4 - No moisture	4.76	4.76	4.80	18.69	18.84	70.66	0.99	-4.28	0.10
Scenario 5 - No ventilation	4.79	4.79	4.83	18.80	18.97	71.15	0.98	-4.36	0.10

Table E.229: Validation metrics for the bedroom air temperature for 09:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	6.32	6.32	6.38	22.84	23.07	63.98	0.95	-4.30	0.13
Reference Case (HAMT)	6.18	6.18	6.26	22.32	22.63	62.76	0.93	-4.10	0.13
Scenario 1 - Low leakage	6.14	6.14	6.22	22.17	22.48	62.35	0.93	-4.03	0.13
Scenario 2 - 75 mm floor	6.22	6.22	6.31	22.48	22.79	63.19	0.93	-4.17	0.13
Scenario 3 - No cooker	6.18	6.18	6.26	22.32	22.63	62.77	0.93	-4.10	0.13
Scenario 4 - No moisture	6.16	6.16	6.24	22.24	22.55	62.54	0.93	-4.06	0.13
Scenario 5 - No ventilation	4.41	4.41	4.54	15.93	16.40	45.47	0.93	-1.68	0.09

Table E.230: Validation metrics for the bedroom air temperature for 10:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	6.35	6.35	6.49	21.17	21.65	48.61	0.94	-1.60	0.12
Reference Case (HAMT)	6.34	6.34	6.51	21.15	21.70	48.74	0.94	-1.61	0.12
Scenario 1 - Low leakage	6.30	6.30	6.47	21.01	21.56	48.43	0.94	-1.58	0.12
Scenario 2 - 75 mm floor	6.39	6.39	6.55	21.31	21.86	49.09	0.94	-1.65	0.12
Scenario 3 - No cooker	6.34	6.34	6.51	21.15	21.70	48.74	0.94	-1.61	0.12
Scenario 4 - No moisture	6.27	6.27	6.44	20.92	21.47	48.22	0.94	-1.56	0.12
Scenario 5 - No ventilation	3.34	3.34	3.60	11.13	12.02	26.99	0.95	0.20	0.06

Table E.231: Validation metrics for the bedroom air temperature for 11:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	5.60	5.60	5.67	17.76	17.96	38.34	0.98	-0.76	0.10
Reference Case (HAMT)	5.73	5.73	5.79	18.17	18.37	39.20	0.98	-0.84	0.10
Scenario 1 - Low leakage	5.68	5.68	5.74	18.01	18.21	38.87	0.98	-0.81	0.10
Scenario 2 - 75 mm floor	5.79	5.79	5.86	18.37	18.57	39.62	0.98	-0.88	0.10
Scenario 3 - No cooker	5.73	5.73	5.79	18.17	18.37	39.20	0.98	-0.84	0.10
Scenario 4 - No moisture	5.61	5.61	5.68	17.80	18.00	38.41	0.98	-0.77	0.10
Scenario 5 - No ventilation	1.99	2.40	2.83	6.31	8.97	19.15	0.90	0.56	0.05

Table E.232: Validation metrics for the bedroom air temperature for 12:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	6.41	6.41	6.60	18.91	19.47	39.80	0.95	-0.77	0.11
Reference Case (HAMT)	6.66	6.66	6.84	19.64	20.17	41.23	0.95	-0.90	0.11
Scenario 1 - Low leakage	6.60	6.60	6.78	19.45	19.99	40.87	0.95	-0.87	0.11
Scenario 2 - 75 mm floor	6.75	6.75	6.92	19.89	20.41	41.71	0.95	-0.95	0.11
Scenario 3 - No cooker	6.66	6.66	6.84	19.64	20.17	41.24	0.95	-0.90	0.11
Scenario 4 - No moisture	6.50	6.50	6.69	19.18	19.73	40.33	0.95	-0.82	0.11
Scenario 5 - No ventilation	2.69	2.81	3.41	7.92	10.06	20.56	0.91	0.53	0.05

Table E.233: Validation metrics for the bedroom air temperature for 13:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	5.11	5.11	5.29	14.90	15.41	33.24	0.97	-0.23	0.08
Reference Case (HAMT)	5.45	5.45	5.59	15.90	16.31	35.18	0.97	-0.38	0.09
Scenario 1 - Low leakage	5.39	5.39	5.53	15.71	16.13	34.79	0.97	-0.35	0.09
Scenario 2 - 75 mm floor	5.56	5.56	5.69	16.22	16.61	35.81	0.97	-0.43	0.09
Scenario 3 - No cooker	5.45	5.45	5.59	15.90	16.31	35.18	0.97	-0.38	0.09
Scenario 4 - No moisture	5.27	5.27	5.43	15.38	15.83	34.14	0.97	-0.30	0.08
Scenario 5 - No ventilation	1.68	1.84	2.31	4.89	6.73	14.52	0.96	0.77	0.03

Table E.234: Validation metrics for the bedroom air temperature for 14:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	4.85	4.85	5.01	13.72	14.16	27.03	0.97	0.13	0.08
Reference Case (HAMT)	5.31	5.31	5.44	15.01	15.37	29.33	0.98	-0.03	0.08
Scenario 1 - Low leakage	5.24	5.24	5.37	14.82	15.19	28.99	0.98	0.00	0.08
Scenario 2 - 75 mm floor	5.44	5.44	5.57	15.38	15.73	30.02	0.98	-0.08	0.08
Scenario 3 - No cooker	5.31	5.31	5.44	15.01	15.37	29.33	0.98	-0.03	0.08
Scenario 4 - No moisture	5.10	5.10	5.24	14.43	14.82	28.28	0.97	0.04	0.08
Scenario 5 - No ventilation	1.80	1.85	2.44	5.10	6.91	13.19	0.96	0.79	0.03

Table E.235: Validation metrics for the bedroom air temperature for 15:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	4.86	4.86	4.88	13.59	13.64	26.35	1.00	0.19	0.07
Reference Case (HAMT)	5.29	5.29	5.31	14.80	14.85	28.69	1.00	0.04	0.08
Scenario 1 - Low leakage	5.24	5.24	5.26	14.65	14.70	28.39	1.00	0.06	0.08
Scenario 2 - 75 mm floor	5.42	5.42	5.45	15.17	15.23	29.42	1.00	-0.01	0.08
Scenario 3 - No cooker	5.29	5.29	5.31	14.80	14.85	28.69	1.00	0.04	0.08
Scenario 4 - No moisture	5.12	5.12	5.14	14.31	14.37	27.75	1.00	0.10	0.08
Scenario 5 - No ventilation	2.01	2.57	2.95	5.61	8.25	15.93	0.93	0.70	0.04

Table E.236: Validation metrics for the bedroom air temperature for 16:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	3.77	3.77	3.97	10.84	11.42	22.73	0.98	0.35	0.06
Reference Case (HAMT)	4.22	4.22	4.38	12.13	12.60	25.08	0.98	0.20	0.07
Scenario 1 - Low leakage	4.19	4.19	4.36	12.06	12.52	24.93	0.98	0.21	0.07
Scenario 2 - 75 mm floor	4.36	4.36	4.51	12.52	12.97	25.82	0.98	0.16	0.07
Scenario 3 - No cooker	4.22	4.22	4.38	12.13	12.60	25.08	0.98	0.20	0.07
Scenario 4 - No moisture	4.06	4.06	4.23	11.66	12.15	24.18	0.98	0.26	0.06
Scenario 5 - No ventilation	1.37	1.72	2.40	3.93	6.89	13.71	0.94	0.76	0.03

Table E.237: Validation metrics for the bedroom air temperature for 17:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.32	3.17	3.36	7.04	10.23	32.04	0.95	0.03	0.05
Reference Case (HAMT)	2.72	3.29	3.48	8.27	10.57	33.11	0.95	-0.04	0.05
Scenario 1 - Low leakage	2.71	3.28	3.47	8.24	10.55	33.06	0.95	-0.03	0.05
Scenario 2 - 75 mm floor	2.88	3.31	3.53	8.74	10.72	33.58	0.96	-0.07	0.06
Scenario 3 - No cooker	2.72	3.29	3.48	8.26	10.57	33.11	0.95	-0.04	0.05
Scenario 4 - No moisture	2.57	3.25	3.43	7.80	10.42	32.65	0.95	-0.01	0.05
Scenario 5 - No ventilation	0.46	1.48	2.28	1.40	6.93	21.71	0.96	0.55	0.03

Table E.238: Validation metrics for the bedroom air temperature for 18:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.35	2.50	3.01	7.49	9.60	38.04	0.96	-0.35	0.05
Reference Case (HAMT)	2.63	2.63	3.16	8.38	10.07	39.90	0.96	-0.48	0.05
Scenario 1 - Low leakage	2.62	2.62	3.14	8.36	10.04	39.76	0.96	-0.47	0.05
Scenario 2 - 75 mm floor	2.73	2.73	3.21	8.72	10.25	40.62	0.97	-0.54	0.05
Scenario 3 - No cooker	2.68	2.68	3.19	8.54	10.19	40.37	0.97	-0.52	0.05
Scenario 4 - No moisture	2.52	2.58	3.10	8.05	9.89	39.19	0.96	-0.43	0.05
Scenario 5 - No ventilation	0.90	1.26	2.03	2.86	6.46	25.60	0.96	0.39	0.03

Table E.239: Validation metrics for the bedroom air temperature for 19:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.95	2.14	2.34	-3.36	8.31	27.63	0.82	0.14	0.04
Reference Case (HAMT)	-0.30	1.63	1.85	-1.06	6.58	21.89	0.84	0.46	0.03
Scenario 1 - Low leakage	-0.50	1.79	1.95	-1.77	6.93	23.06	0.83	0.40	0.03
Scenario 2 - 75 mm floor	-0.02	1.48	1.74	-0.06	6.18	20.55	0.84	0.53	0.03
Scenario 3 - No cooker	-0.27	1.63	1.86	-0.94	6.62	22.01	0.84	0.46	0.03
Scenario 4 - No moisture	-0.56	1.79	1.98	-1.98	7.02	23.37	0.83	0.39	0.03
Scenario 5 - No ventilation	-0.07	1.66	1.99	-0.24	7.05	23.47	0.82	0.38	0.04

Table E.240: Validation metrics for the bedroom air temperature for 20:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.14	1.24	1.66	-0.53	6.06	24.59	0.88	0.37	0.03
Reference Case (HAMT)	0.37	1.02	1.43	1.36	5.24	21.24	0.90	0.53	0.03
Scenario 1 - Low leakage	0.11	1.12	1.48	0.41	5.42	22.01	0.89	0.49	0.03
Scenario 2 - 75 mm floor	0.64	1.02	1.45	2.36	5.29	21.48	0.90	0.52	0.03
Scenario 3 - No cooker	0.38	1.02	1.44	1.40	5.25	21.29	0.90	0.53	0.03
Scenario 4 - No moisture	0.17	1.07	1.44	0.61	5.27	21.38	0.89	0.52	0.03
Scenario 5 - No ventilation	1.03	1.27	1.79	3.76	6.56	26.61	0.89	0.26	0.03

Table E.241: Validation metrics for the bedroom air temperature for 21:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.49	1.16	1.52	1.86	5.72	21.40	0.84	0.52	0.03
Reference Case (HAMT)	0.81	1.05	1.48	3.07	5.58	20.89	0.87	0.54	0.03
Scenario 1 - Low leakage	0.51	1.11	1.49	1.90	5.60	20.97	0.84	0.54	0.03
Scenario 2 - 75 mm floor	1.07	1.17	1.60	4.03	6.01	22.48	0.87	0.47	0.03
Scenario 3 - No cooker	0.82	1.05	1.49	3.09	5.60	20.96	0.87	0.54	0.03
Scenario 4 - No moisture	0.69	1.06	1.44	2.59	5.42	20.28	0.87	0.57	0.03
Scenario 5 - No ventilation	1.55	1.55	2.01	5.83	7.54	28.24	0.87	0.17	0.04

Table E.242: Validation metrics for the bedroom air temperature for 22:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	0.81	1.08	1.40	3.13	5.42	20.89	0.86	0.56	0.03
Reference Case (HAMT)	0.92	1.01	1.37	3.58	5.32	20.50	0.88	0.58	0.03
Scenario 1 - Low leakage	0.66	1.02	1.31	2.57	5.09	19.62	0.86	0.61	0.03
Scenario 2 - 75 mm floor	1.16	1.16	1.52	4.50	5.88	22.67	0.89	0.49	0.03
Scenario 3 - No cooker	0.93	1.02	1.38	3.61	5.33	20.57	0.88	0.58	0.03
Scenario 4 - No moisture	0.87	1.00	1.34	3.37	5.20	20.06	0.88	0.60	0.03
Scenario 5 - No ventilation	1.19	1.19	1.56	4.62	6.05	23.35	0.88	0.45	0.03

Table E.243: Validation metrics for the bedroom air temperature for 23:00 (February)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.52	1.52	1.91	5.98	7.52	27.08	0.85	0.27	0.04
Reference Case (HAMT)	1.47	1.47	1.82	5.78	7.16	25.77	0.88	0.33	0.04
Scenario 1 - Low leakage	1.22	1.31	1.70	4.82	6.70	24.11	0.85	0.42	0.03
Scenario 2 - 75 mm floor	1.69	1.69	1.99	6.64	7.83	28.20	0.88	0.20	0.04
Scenario 3 - No cooker	1.47	1.47	1.82	5.80	7.17	25.83	0.88	0.33	0.04
Scenario 4 - No moisture	1.47	1.47	1.82	5.76	7.15	25.75	0.88	0.34	0.04
Scenario 5 - No ventilation	1.54	1.54	1.87	6.05	7.37	26.55	0.88	0.29	0.04

E.6.3.6 Winter Hourly Validation Metrics

The final hourly-based validation analysis considered only results from the winter week. The validation metrics for the bedroom air temperature are presented in Tables E.244 to E.267.

Table E.244: Validation metrics for the bedroom air temperature for 00:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.43	1.43	1.62	-9.01	10.19	27.16	0.93	0.35	0.05
Reference Case (HAMT)	-1.55	1.55	1.70	-9.74	10.70	28.54	0.94	0.28	0.05
Scenario 1 - Low leakage	-1.77	1.77	1.89	-11.13	11.93	31.81	0.94	0.11	0.06
Scenario 2 - 75 mm floor	-1.42	1.42	1.58	-8.95	9.96	26.55	0.94	0.38	0.05
Scenario 3 - No cooker	-1.52	1.52	1.68	-9.60	10.57	28.18	0.94	0.30	0.05
Scenario 4 - No moisture	-1.53	1.53	1.69	-9.67	10.64	28.38	0.94	0.29	0.05
Scenario 5 - No ventilation	-1.60	1.60	1.75	-10.09	11.03	29.40	0.94	0.24	0.05

Table E.245: Validation metrics for the bedroom air temperature for 01:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.20	1.36	1.50	-7.79	9.77	24.84	0.90	0.46	0.05
Reference Case (HAMT)	-1.40	1.46	1.64	-9.09	10.64	27.05	0.91	0.36	0.05
Scenario 1 - Low leakage	-1.61	1.61	1.82	-10.49	11.81	30.03	0.91	0.21	0.06
Scenario 2 - 75 mm floor	-1.29	1.37	1.54	-8.38	10.01	25.45	0.91	0.43	0.05
Scenario 3 - No cooker	-1.38	1.44	1.62	-8.97	10.53	26.77	0.91	0.37	0.05
Scenario 4 - No moisture	-1.38	1.45	1.63	-8.99	10.57	26.86	0.91	0.37	0.05
Scenario 5 - No ventilation	-1.45	1.49	1.68	-9.41	10.92	27.75	0.91	0.33	0.05

Table E.246: Validation metrics for the bedroom air temperature for 02:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.96	1.20	1.41	-6.37	9.43	23.93	0.88	0.57	0.05
Reference Case (HAMT)	-1.23	1.36	1.58	-8.19	10.53	26.70	0.89	0.47	0.05
Scenario 1 - Low leakage	-1.45	1.52	1.76	-9.68	11.77	29.84	0.89	0.33	0.06
Scenario 2 - 75 mm floor	-1.14	1.30	1.51	-7.58	10.06	25.50	0.89	0.51	0.05
Scenario 3 - No cooker	-1.21	1.35	1.56	-8.08	10.44	26.47	0.89	0.48	0.05
Scenario 4 - No moisture	-1.21	1.35	1.57	-8.07	10.44	26.48	0.89	0.48	0.05
Scenario 5 - No ventilation	-1.27	1.40	1.61	-8.47	10.75	27.25	0.89	0.44	0.05

Table E.247: Validation metrics for the bedroom air temperature for 03:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.86	1.18	1.33	-5.93	9.13	22.38	0.89	0.63	0.04
Reference Case (HAMT)	-1.20	1.39	1.55	-8.24	10.66	26.13	0.90	0.50	0.05
Scenario 1 - Low leakage	-1.42	1.56	1.74	-9.77	12.03	29.47	0.89	0.36	0.06
Scenario 2 - 75 mm floor	-1.12	1.34	1.50	-7.75	10.30	25.25	0.90	0.53	0.05
Scenario 3 - No cooker	-1.18	1.38	1.54	-8.14	10.58	25.93	0.90	0.50	0.05
Scenario 4 - No moisture	-1.17	1.38	1.53	-8.09	10.55	25.86	0.90	0.51	0.05
Scenario 5 - No ventilation	-1.23	1.42	1.58	-8.50	10.87	26.64	0.90	0.48	0.05

Table E.248: Validation metrics for the bedroom air temperature for 04:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.06	1.59	1.97	-0.38	13.30	25.37	0.66	0.44	0.07
Reference Case (HAMT)	-0.44	1.69	1.97	-3.01	13.32	25.41	0.68	0.44	0.06
Scenario 1 - Low leakage	-0.66	1.84	2.09	-4.45	14.13	26.97	0.65	0.36	0.07
Scenario 2 - 75 mm floor	-0.39	1.67	1.96	-2.66	13.24	25.27	0.68	0.44	0.06
Scenario 3 - No cooker	-0.43	1.69	1.97	-2.92	13.30	25.38	0.68	0.44	0.06
Scenario 4 - No moisture	-0.42	1.69	1.97	-2.85	13.31	25.40	0.68	0.44	0.06
Scenario 5 - No ventilation	-0.48	1.70	1.97	-3.23	13.33	25.45	0.68	0.43	0.06

Table E.249: Validation metrics for the bedroom air temperature for 05:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.08	1.44	1.78	-0.52	12.18	19.19	0.84	0.65	0.06
Reference Case (HAMT)	-0.50	1.58	1.83	-3.42	12.54	19.75	0.85	0.63	0.06
Scenario 1 - Low leakage	-0.66	1.77	2.03	-4.54	13.90	21.89	0.81	0.54	0.07
Scenario 2 - 75 mm floor	-0.47	1.57	1.83	-3.20	12.53	19.73	0.85	0.63	0.06
Scenario 3 - No cooker	-0.49	1.58	1.83	-3.34	12.52	19.72	0.85	0.63	0.06
Scenario 4 - No moisture	-0.47	1.58	1.82	-3.25	12.51	19.71	0.85	0.63	0.06
Scenario 5 - No ventilation	-0.53	1.59	1.83	-3.62	12.58	19.81	0.85	0.63	0.06

Table E.250: Validation metrics for the bedroom air temperature for 06:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.46	0.93	1.17	-3.17	8.14	12.59	0.93	0.84	0.04
Reference Case (HAMT)	-0.87	1.19	1.38	-6.09	9.58	14.81	0.93	0.78	0.05
Scenario 1 - Low leakage	-0.91	1.30	1.53	-6.33	10.62	16.42	0.92	0.72	0.05
Scenario 2 - 75 mm floor	-0.86	1.18	1.37	-5.98	9.54	14.75	0.93	0.78	0.05
Scenario 3 - No cooker	-0.87	1.18	1.37	-6.02	9.53	14.74	0.93	0.78	0.05
Scenario 4 - No moisture	-0.85	1.18	1.36	-5.93	9.47	14.65	0.93	0.78	0.05
Scenario 5 - No ventilation	-0.90	1.21	1.39	-6.27	9.69	14.98	0.93	0.77	0.05

Table E.251: Validation metrics for the bedroom air temperature for 07:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.73	1.27	1.46	-5.25	10.58	16.33	0.90	0.75	0.05
Reference Case (HAMT)	-1.13	1.54	1.69	-8.21	12.20	18.83	0.90	0.67	0.06
Scenario 1 - Low leakage	-1.27	1.63	1.81	-9.16	13.08	20.18	0.90	0.62	0.06
Scenario 2 - 75 mm floor	-1.13	1.53	1.69	-8.19	12.23	18.87	0.90	0.67	0.06
Scenario 3 - No cooker	-1.13	1.53	1.68	-8.16	12.16	18.76	0.90	0.67	0.06
Scenario 4 - No moisture	-1.11	1.53	1.67	-8.07	12.11	18.69	0.90	0.67	0.06
Scenario 5 - No ventilation	-1.16	1.55	1.70	-8.37	12.32	19.02	0.90	0.66	0.06

Table E.252: Validation metrics for the bedroom air temperature for 08:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.38	1.44	1.79	8.95	11.63	22.04	0.91	0.56	0.06
Reference Case (HAMT)	0.98	1.20	1.47	6.39	9.53	18.06	0.92	0.71	0.05
Scenario 1 - Low leakage	0.86	1.16	1.39	5.58	9.06	17.16	0.92	0.74	0.05
Scenario 2 - 75 mm floor	0.98	1.21	1.48	6.35	9.60	18.18	0.91	0.70	0.05
Scenario 3 - No cooker	0.99	1.20	1.47	6.44	9.56	18.12	0.92	0.71	0.05
Scenario 4 - No moisture	1.00	1.21	1.48	6.51	9.63	18.24	0.92	0.70	0.05
Scenario 5 - No ventilation	0.96	1.19	1.46	6.26	9.47	17.94	0.92	0.71	0.05

Table E.253: Validation metrics for the bedroom air temperature for 09:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	2.04	2.09	2.44	11.74	13.99	27.82	0.89	0.27	0.07
Reference Case (HAMT)	1.76	1.94	2.18	10.08	12.50	24.86	0.90	0.42	0.07
Scenario 1 - Low leakage	1.63	1.89	2.06	9.33	11.82	23.51	0.91	0.48	0.06
Scenario 2 - 75 mm floor	1.75	1.95	2.19	10.04	12.54	24.94	0.90	0.42	0.07
Scenario 3 - No cooker	1.76	1.94	2.18	10.11	12.53	24.92	0.90	0.42	0.07
Scenario 4 - No moisture	1.77	1.94	2.19	10.15	12.56	24.98	0.90	0.41	0.07
Scenario 5 - No ventilation	1.74	1.93	2.17	10.00	12.44	24.74	0.90	0.43	0.06

Table E.254: Validation metrics for the bedroom air temperature for 10:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	1.08	1.65	2.26	5.63	11.76	20.49	0.79	0.51	0.06
Reference Case (HAMT)	0.98	1.56	2.15	5.08	11.18	19.47	0.80	0.55	0.06
Scenario 1 - Low leakage	0.84	1.51	2.10	4.38	10.92	19.02	0.80	0.57	0.06
Scenario 2 - 75 mm floor	0.98	1.59	2.16	5.11	11.26	19.61	0.80	0.55	0.06
Scenario 3 - No cooker	0.98	1.57	2.15	5.10	11.19	19.49	0.80	0.55	0.06
Scenario 4 - No moisture	0.97	1.55	2.15	5.04	11.18	19.47	0.80	0.55	0.06
Scenario 5 - No ventilation	0.97	1.56	2.14	5.04	11.16	19.43	0.80	0.56	0.06

Table E.255: Validation metrics for the bedroom air temperature for 11:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.06	1.19	1.34	-0.28	6.52	13.14	0.90	0.81	0.03
Reference Case (HAMT)	0.05	1.11	1.31	0.27	6.36	12.81	0.91	0.82	0.03
Scenario 1 - Low leakage	-0.07	1.24	1.39	-0.35	6.79	13.67	0.89	0.80	0.03
Scenario 2 - 75 mm floor	0.09	1.13	1.33	0.42	6.47	13.04	0.90	0.82	0.03
Scenario 3 - No cooker	0.06	1.11	1.31	0.28	6.36	12.81	0.91	0.82	0.03
Scenario 4 - No moisture	0.02	1.13	1.31	0.11	6.38	12.85	0.91	0.82	0.03
Scenario 5 - No ventilation	0.06	1.10	1.30	0.27	6.35	12.79	0.91	0.82	0.03

Table E.256: Validation metrics for the bedroom air temperature for 12:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-0.60	1.89	2.09	-2.69	9.30	42.73	0.85	-0.59	0.05
Reference Case (HAMT)	-0.25	1.67	1.81	-1.13	8.04	36.93	0.86	-0.18	0.04
Scenario 1 - Low leakage	-0.43	1.77	1.90	-1.91	8.45	38.83	0.84	-0.31	0.04
Scenario 2 - 75 mm floor	-0.18	1.63	1.76	-0.81	7.82	35.94	0.85	-0.12	0.04
Scenario 3 - No cooker	-0.25	1.67	1.81	-1.12	8.04	36.93	0.86	-0.18	0.04
Scenario 4 - No moisture	-0.31	1.69	1.84	-1.36	8.16	37.48	0.85	-0.22	0.04
Scenario 5 - No ventilation	-0.25	1.66	1.80	-1.09	8.00	36.76	0.86	-0.17	0.04

Table E.257: Validation metrics for the bedroom air temperature for 13:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.84	2.14	2.21	-7.67	9.19	47.74	0.73	-1.49	0.04
Reference Case (HAMT)	-1.23	1.61	1.66	-5.11	6.90	35.82	0.74	-0.40	0.03
Scenario 1 - Low leakage	-1.49	1.84	1.89	-6.19	7.89	40.96	0.71	-0.84	0.04
Scenario 2 - 75 mm floor	-1.11	1.49	1.54	-4.62	6.44	33.43	0.74	-0.22	0.03
Scenario 3 - No cooker	-1.23	1.62	1.66	-5.12	6.90	35.85	0.74	-0.41	0.03
Scenario 4 - No moisture	-1.30	1.67	1.71	-5.42	7.15	37.11	0.74	-0.51	0.03
Scenario 5 - No ventilation	-1.21	1.60	1.64	-5.05	6.83	35.50	0.74	-0.38	0.03

Table E.258: Validation metrics for the bedroom air temperature for 14:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.32	2.32	2.39	-9.48	9.80	43.44	0.94	-0.77	0.05
Reference Case (HAMT)	-1.54	1.54	1.67	-6.32	6.82	30.25	0.94	0.14	0.03
Scenario 1 - Low leakage	-1.87	1.87	1.98	-7.64	8.11	35.95	0.94	-0.21	0.04
Scenario 2 - 75 mm floor	-1.38	1.38	1.53	-5.66	6.25	27.72	0.94	0.28	0.03
Scenario 3 - No cooker	-1.55	1.55	1.67	-6.33	6.83	30.29	0.94	0.14	0.03
Scenario 4 - No moisture	-1.63	1.63	1.75	-6.67	7.15	31.69	0.94	0.06	0.03
Scenario 5 - No ventilation	-1.70	1.70	1.81	-6.96	7.40	32.81	0.95	-0.01	0.04

Table E.259: Validation metrics for the bedroom air temperature for 15:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.56	2.56	2.73	-10.43	11.11	43.68	0.88	-1.15	0.05
Reference Case (HAMT)	-1.71	1.71	1.93	-6.98	7.85	30.86	0.89	-0.07	0.04
Scenario 1 - Low leakage	-2.12	2.12	2.28	-8.62	9.29	36.52	0.89	-0.50	0.04
Scenario 2 - 75 mm floor	-1.52	1.52	1.76	-6.18	7.17	28.20	0.88	0.11	0.03
Scenario 3 - No cooker	-1.72	1.72	1.93	-6.99	7.86	30.91	0.89	-0.07	0.04
Scenario 4 - No moisture	-1.80	1.80	2.01	-7.33	8.18	32.16	0.88	-0.16	0.04
Scenario 5 - No ventilation	-2.17	2.17	2.33	-8.84	9.48	37.26	0.89	-0.56	0.05

Table E.260: Validation metrics for the bedroom air temperature for 16:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.76	2.76	2.93	-11.33	12.05	69.45	0.90	-2.40	0.06
Reference Case (HAMT)	-1.86	1.86	2.06	-7.64	8.47	48.81	0.90	-0.68	0.04
Scenario 1 - Low leakage	-2.20	2.20	2.36	-9.04	9.68	55.81	0.88	-1.20	0.05
Scenario 2 - 75 mm floor	-1.62	1.62	1.83	-6.68	7.51	43.32	0.90	-0.32	0.04
Scenario 3 - No cooker	-1.86	1.86	2.06	-7.66	8.48	48.90	0.90	-0.69	0.04
Scenario 4 - No moisture	-1.94	1.94	2.14	-7.99	8.79	50.66	0.90	-0.81	0.04
Scenario 5 - No ventilation	-2.33	2.33	2.46	-9.56	10.12	58.34	0.88	-1.40	0.05

Table E.261: Validation metrics for the bedroom air temperature for 17:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.81	2.81	2.94	-11.96	12.52	52.20	0.91	-1.33	0.06
Reference Case (HAMT)	-1.92	1.92	2.11	-8.18	8.97	37.39	0.90	-0.20	0.04
Scenario 1 - Low leakage	-2.15	2.15	2.34	-9.15	9.94	41.44	0.88	-0.47	0.05
Scenario 2 - 75 mm floor	-1.65	1.65	1.85	-7.04	7.88	32.86	0.90	0.08	0.04
Scenario 3 - No cooker	-1.93	1.93	2.11	-8.21	8.99	37.46	0.90	-0.20	0.04
Scenario 4 - No moisture	-2.00	2.00	2.18	-8.52	9.27	38.66	0.90	-0.28	0.04
Scenario 5 - No ventilation	-2.25	2.25	2.40	-9.58	10.23	42.62	0.90	-0.56	0.05

Table E.262: Validation metrics for the bedroom air temperature for 18:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-3.57	3.57	3.64	-16.69	17.04	69.01	0.94	-2.21	0.08
Reference Case (HAMT)	-2.79	2.79	2.88	-13.04	13.48	54.59	0.93	-1.01	0.06
Scenario 1 - Low leakage	-2.87	2.87	2.98	-13.42	13.94	56.45	0.92	-1.15	0.07
Scenario 2 - 75 mm floor	-2.51	2.51	2.61	-11.73	12.18	49.35	0.94	-0.64	0.06
Scenario 3 - No cooker	-2.47	2.47	2.58	-11.53	12.05	48.82	0.93	-0.61	0.06
Scenario 4 - No moisture	-2.86	2.86	2.94	-13.35	13.77	55.76	0.94	-1.10	0.06
Scenario 5 - No ventilation	-2.91	2.91	3.01	-13.60	14.07	56.98	0.93	-1.19	0.07

Table E.263: Validation metrics for the bedroom air temperature for 19:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-2.29	2.29	2.47	-11.36	12.26	46.70	0.90	-1.02	0.06
Reference Case (HAMT)	-1.75	1.75	1.95	-8.69	9.64	36.73	0.90	-0.25	0.05
Scenario 1 - Low leakage	-1.85	1.85	2.04	-9.14	10.10	38.46	0.89	-0.37	0.05
Scenario 2 - 75 mm floor	-1.51	1.51	1.72	-7.49	8.51	32.42	0.90	0.03	0.04
Scenario 3 - No cooker	-1.65	1.65	1.86	-8.18	9.20	35.06	0.90	-0.14	0.04
Scenario 4 - No moisture	-1.80	1.80	1.99	-8.91	9.84	37.48	0.90	-0.30	0.05
Scenario 5 - No ventilation	-1.85	1.85	2.03	-9.14	10.05	38.29	0.90	-0.36	0.05

Table E.264: Validation metrics for the bedroom air temperature for 20:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.60	1.60	1.78	-8.25	9.20	33.92	0.91	0.05	0.04
Reference Case (HAMT)	-1.22	1.28	1.41	-6.29	7.29	26.89	0.92	0.40	0.04
Scenario 1 - Low leakage	-1.38	1.42	1.58	-7.11	8.15	30.04	0.91	0.26	0.04
Scenario 2 - 75 mm floor	-1.00	1.12	1.22	-5.15	6.29	23.18	0.93	0.56	0.03
Scenario 3 - No cooker	-1.17	1.25	1.38	-6.07	7.11	26.21	0.92	0.43	0.03
Scenario 4 - No moisture	-1.24	1.30	1.43	-6.43	7.41	27.30	0.92	0.39	0.04
Scenario 5 - No ventilation	-1.30	1.33	1.48	-6.71	7.66	28.25	0.92	0.34	0.04

Table E.265: Validation metrics for the bedroom air temperature for 21:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.14	1.14	1.33	-6.13	7.17	19.22	0.95	0.62	0.03
Reference Case (HAMT)	-0.90	0.94	1.14	-4.88	6.14	16.45	0.95	0.72	0.03
Scenario 1 - Low leakage	-1.06	1.14	1.34	-5.73	7.24	19.40	0.93	0.61	0.03
Scenario 2 - 75 mm floor	-0.71	0.82	0.99	-3.81	5.31	14.23	0.96	0.79	0.03
Scenario 3 - No cooker	-0.87	0.92	1.11	-4.68	5.99	16.05	0.95	0.73	0.03
Scenario 4 - No moisture	-0.92	0.94	1.14	-4.94	6.17	16.53	0.95	0.72	0.03
Scenario 5 - No ventilation	-0.98	1.02	1.21	-5.28	6.52	17.47	0.95	0.69	0.03

Table E.266: Validation metrics for the bedroom air temperature for 22:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.62	1.62	1.74	-9.12	9.82	25.23	0.95	0.31	0.05
Reference Case (HAMT)	-1.51	1.51	1.63	-8.50	9.17	23.57	0.96	0.40	0.04
Scenario 1 - Low leakage	-1.72	1.72	1.84	-9.70	10.40	26.74	0.95	0.23	0.05
Scenario 2 - 75 mm floor	-1.33	1.33	1.46	-7.50	8.21	21.11	0.96	0.52	0.04
Scenario 3 - No cooker	-1.48	1.48	1.60	-8.33	9.01	23.17	0.96	0.42	0.04
Scenario 4 - No moisture	-1.51	1.51	1.63	-8.51	9.17	23.57	0.96	0.40	0.04
Scenario 5 - No ventilation	-1.57	1.57	1.69	-8.86	9.52	24.47	0.96	0.35	0.05

Table E.267: Validation metrics for the bedroom air temperature for 23:00 (August)

	MBE	MAE	RMSE	NMBE	CVRMSE	NRMSE	r	R^2	IC
Reference Case (CTF)	-1.44	1.45	1.61	-8.45	9.42	24.48	0.95	0.40	0.04
Reference Case (HAMT)	-1.44	1.44	1.58	-8.45	9.23	23.97	0.95	0.42	0.04
Scenario 1 - Low leakage	-1.69	1.69	1.79	-9.90	10.49	27.25	0.96	0.25	0.05
Scenario 2 - 75 mm floor	-1.29	1.29	1.43	-7.53	8.37	21.74	0.95	0.52	0.04
Scenario 3 - No cooker	-1.42	1.42	1.55	-8.30	9.09	23.61	0.95	0.44	0.04
Scenario 4 - No moisture	-1.44	1.44	1.57	-8.41	9.21	23.91	0.95	0.42	0.04
Scenario 5 - No ventilation	-1.50	1.50	1.63	-8.77	9.53	24.77	0.95	0.38	0.05