University of Oxford

Department of Engineering Science

Fourth Year Research Project

Hybrid Heating Systems for Buildings

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Abstract

Decarbonising the energy sector plays an important and significant role towards both reducing greenhouse gas emissions and tackling climate change. This is brought about through the global transition away from carbon intensive energy sources, and towards renewable and sustainable energy generation.

Building heating contributes a large amount towards total UK emissions, and its decarbonisation still presents one of the most complex and challenging tasks in the transition towards net-zero carbon emissions. Dynamic thermal modelling of buildings provides a way of understanding, and subsequently reducing, building heating demands. It ultimately supports and facilitates the decarbonisation of building heating, particularly in the domestic and commercial sectors which are the largest contributors to building heating emissions.

This study develops an external weather model, comprising a solar radiation model and building exterior convective heat transfer coefficient modelling, specifically for investigating building heating and thermal balance. The solar radiation model considers the amount of solar radiation incident on a building's exterior and solves the complex interaction of building shadowing in dense urban environments. To compliment this, the modelling of building exterior convective heat transfer coefficients considers the interaction of wind with building exterior surfaces and evaluates building exterior $CHTC$ values. Both of these influences are important considerations towards investigating a buildings thermal performance and must be accounted for when generating accurate building thermal models.

The overall model is built specifically for integration with an existing thermal network model, this being the Oxford Thermal Network Model Software (TNMS). Together, both models enable the development of an accurate, fast, and predictive tool to support dynamic thermal modelling of buildings within complex urban environments. Building thermal network models are able to be built, and subsequently solved using the important building specific, and weather influenced, boundary conditions output from the external weather model.

Through the understanding of building thermal performances and heating demands gained from such models, measures can be put in place to reduce these heating demands, and ultimately their associated emissions. Such models could be used to coach changes to behaviour, or improvements to the building itself which can be through integration of renewable heating and energy systems.

Acknowledgements

I would first like to give thanks to my supervisor Professor Budimir Rosic for his guidance throughout this research project. His vision, encouragement, and attention to detail all provided me with the additional motivation to really push and give my all to this project. I would also like to give a huge thanks to Mark Baker at the Osney Thermo-Fluids Laboratory, who provided invaluable support throughout the entirety of the project. Mark was an extraordinary help, and through his guidance too also encouraged me to give my all to this project. It has been a pleasure to work with both Budimir and Mark this academic year.

Contents

Nomenclature

Acronyms and Names

CO_2 Carbon dioxide

CAD Computer-aided design

CFD Computational fluid dynamics

FRT Focused ray tracing

POV Point of view

PV Photovoltaic

RT Forward ray tracing

ST Solar thermal

TNM Thermal Network Model

TNMS Oxford Thermal Network Model Software

Variables

α_S Solar altitude angle

β Surface tilt angle

δ_S Sun declination angle

ϕ Solar zenith angle

ρ_G Ground albedo coefficient

θ Angle between the Sun's rays and surface normal

θ_w Angle between wind direction and surface normal

A_S Solar azimuth angle

$CHTC$ Convective heat transfer coefficient

G_{beam} Direct solar irradiance or beam radiation on a tilted surface

$G_{diffuse}$ Diffuse solar irradiance or diffuse radiation on a tilted surface

G_{ground} Ground reflected irradiance or radiation on a tilted surface

G_t Total irradiance or total radiation incident on a tilted surface

h Hour angle

L Local latitude angle

q_c Convective heat flux

T_{air} Ambient air temperature

T_{sur} Building surface temperature

U_{10} Wind speed at reference height of 10 m

USF_B Beam Unshaded Factor

1 Introduction

Without immediate intervention, the planet Earth will continue to suffer as a result of human-caused global warming. The effects resulting from changes to the climate are already being experienced through rising sea levels, extreme weathers, and increased temperatures [1]. To ensure these effects do not continue to pose a threat to future generations, the emission of greenhouse gases must be reduced. This is ultimately through urgent reformation and decarbonisation of the energy sector, where the path to net-zero emissions is brought about by the transition towards more sustainable energy generation. This is through the utilisation of renewable sources of energy, namely both solar and wind energies which are relevant and prominent examples.

Despite the fall in UK greenhouse gas emissions through 2022, carbon dioxide (CO_2) still contributed to 79% of the UK's total greenhouse gas emissions. This is estimated at 417.1 million tonnes carbon dioxide equivalent $(MtCO_2e)$. The decline in CO_2 is primarily believed to be as a result of a "reduction in [gas] and fuel use to heat buildings" [2]. This demonstrates the significant effect building heating has towards reducing overall emissions, however there is still significant potential to exploit this area for further improvement. This is because the building sector is a large contributor of CO_2 worldwide, and its 15% share of total emissions from end-use sectors "doubles if indirect emissions from electricity and heat production are included" [3]. This alone warrants investigation towards renewable forms of heat generation, especially within the UK where natural gas for heating is the primary form of emissions in both the residential and public sectors.

Within the domestic sector, decreases in emissions in recent years are attested to "less energy being used to heat homes." Decreases in emissions are also seen within the commercial and public sectors too, and similarly these are attested to "less heating used in buildings" [2]. The decarbonisation of heating buildings is an important and necessary measure to reduce total emissions coming from the residential, public, and business sectors. The transition away from traditional heating however is not an easy one, and presents one of the most challenging tasks as we strive for net-zero carbon emissions. Reducing the contribution towards total emissions, and decarbonising heating within buildings, consists of both

- Understanding and reducing building heating demand
- Replacing carbon intensive heating sources with renewable forms of heat generation

This project aims to develop a building dynamic thermal model upon an existing thermal network model to incorporate features specific for a building's heating. From this investigation, optimised heating systems comprising renewable technologies, such as heat pumps, can be considered.

2 Building Heating Systems

2.1 Overview of Heating within UK Buildings

The use of natural gas for heating is the primary form of emissions in both the residential and public sectors. Combined, the building and the heating sectors "account for almost one third of the UK's annual carbon footprint" [4]. Figure 1 shows the UK emissions in 2019 by sector. It highlights the contribution of the building sector (30%) and the significant impact of heating (23%), particularly in domestic homes which accounts for 17% of total UK emissions.

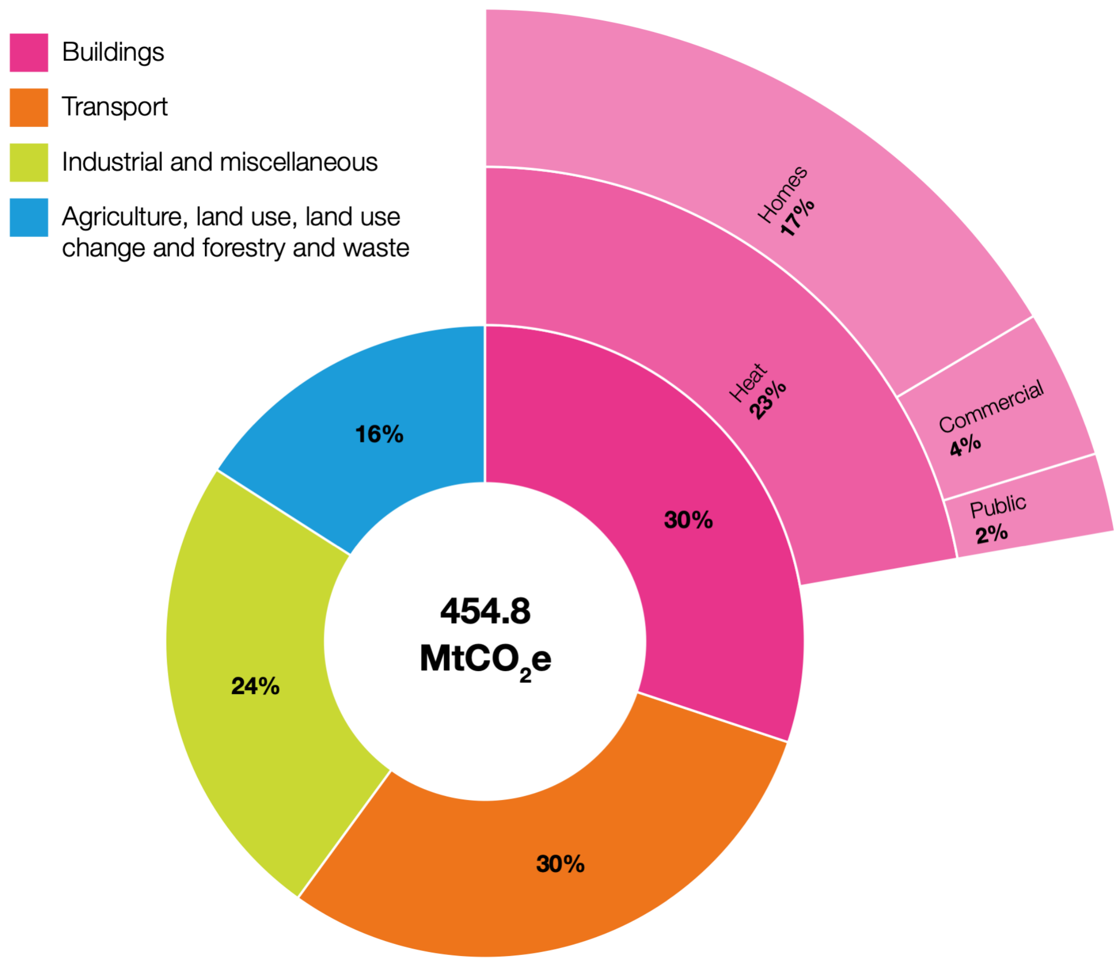


Figure 1: Proportion of emissions in 2019 from buildings, with the largest proportion of this stemming from heating in homes [5]

Demonstrated in Figure 1, the heating of homes, followed by commercial heating, contributes a great amount towards total emissions from buildings. The decarbonisation of both domestic and commercial heating tackles this directly, and ultimately reduces overall emissions.

Model (TNM), is introduced and later explored in Section 4.2. It is quite "common in engineering applications to use simplified Thermal Network Models instead of a more complex full conjugate heat transfer analysis" [20]. The development of my external weather model, comprising the solar radiation and building exterior $CHTC$ models, will be such to compliment and interface with building thermal network models, used to "replicate [the] dynamics of heat transfer in [investigated] buildings" [19]. Differently to the study by A. Boodi et al, the thermal network model incorporated within my study is based on a recently developed and "novel automated TNM construction software." Although built primarily for applications in power generation, the Oxford Thermal Network Model Software (TNMS) can "rapidly [build complex thermal network models] from CAD geometry," and has both been "validated against analytic solutions" and "used to construct a full machine model of the Mitsubishi Heavy Industries turbine" [20].

Figure 2 highlights the software requirements when using the TNMS, and the adapted workflow when integrated with my `python` external weather model.

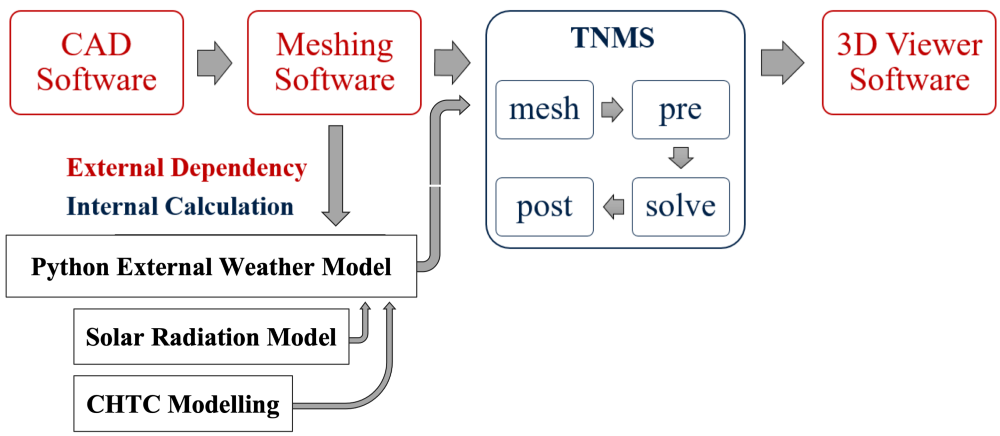
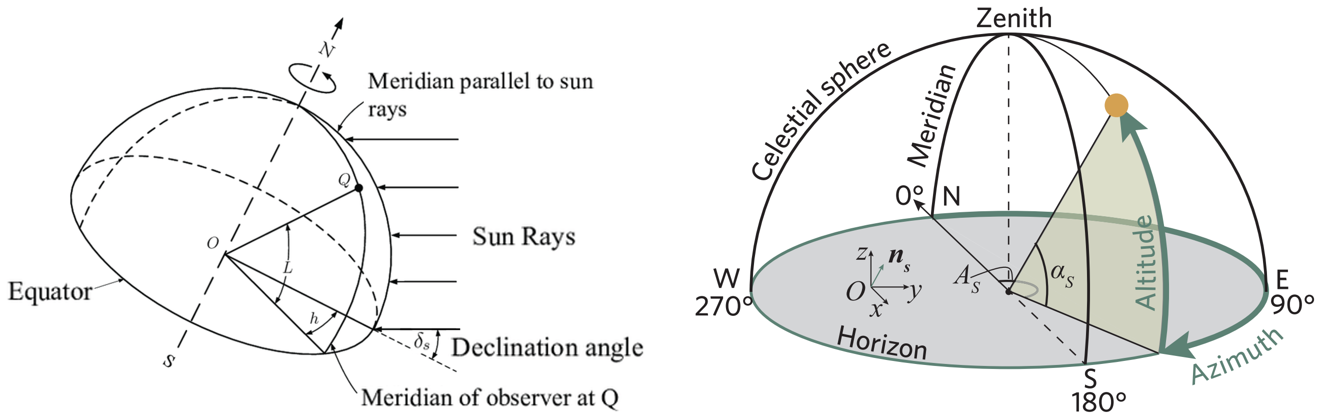


Figure 2: The structure and external dependencies of the TNMS, showing the adapted workflow upon integration with the external weather model [20]

An adaptation of a figure from Mark Baker's PhD thesis [20], which at the current time of writing is not yet available online, Figure 2 highlights the structure and constituent sections forming the TNMS code. It also illustrates how my `python` external weather model works alongside the TNMS. This is to provide boundary condition information to the TNMS

To summarise, the past studies investigated have highlighted the importance of both solar radiation and convective heat effects on building heating. These effects however have traditionally been isolated, which highlights the opportunity to combine these two mechanisms together towards analysis of building heating. This study will consider a unique approach, which has not been addressed through past investigations, where real-time and predictive information can be utilised to enable fast and accurate dynamic thermal modelling of buildings within complex urban environments, through thermal network modelling.



(a) Fundamental Sun angles [28]

(b) Horizontal coordinate system [29]

Figure 5: Solar Tracking Angles

Determining the solar azimuth and solar altitude angles for a particular location, at a given point in time, comes down to the exact location on Earth's surface the Sun is being observed from. As such, both the latitudinal and longitudinal coordinates are necessary too. Subsequently from these values, the solar position can be denoted by a unit vector $S = \boldsymbol{n_S}(x_S, y_S, z_S)$ in corresponding Cartesian coordinate system, dependent on the exact orientation of the Cartesian coordinate system in relation to the four cardinal directions [29]. An example orientation can be seen above in Figure 5b.

4.3.3 Solar Radiation on Surfaces

Solar radiation incident on a surface, whether it be on building faces, PV panels or ST collectors, comprises three components: direct-beam radiation G_{beam} which describes the light incident directly from the Sun itself, diffuse radiation $G_{diffuse}$ which is light from the rest of the sky, and ground reflected radiation G_{ground} for any non-horizontal surface where light is reflected from the ground.

$$G_t = G_{beam} + G_{diffuse} + G_{ground}, \tag{1}$$

where G_t $[W/m^2]$ is the sum of the three components, and hence the total radiation incident on a tilted surface [30]. The ground reflected component is often found to be neglected and ignored but all contributions are important to obtain accurate estimations, and hence G_t can be represented one way as

$$G_t = G_{normal} cos\theta + 2G_R \frac{(1 + cos\beta)}{2} + \rho_G (G_{beam} + G_{diffuse}) \frac{(1 - cos\beta)}{2}, \tag{2}$$

where G_{normal} is the beam radiation on a horizontal surface (when the Sun is directly overhead/normal),

5 Development of the Solar Radiation Model

The solar radiation model, as part of the overall external weather model, is built using `Python`. It primarily calculates and quantifies the amount of solar radiation incident on the external surfaces of buildings within an urban environment. The output of the solar radiation model is heat flux boundary condition information, which allows for the dynamic thermal modelling of investigated buildings to be performed.

5.1 Building of the Python Model

The model utilises useful `python` modules, libraries, and library collections: these namely being `NumPy`, `Pysolar`, `datetime`, and `GeoPy`. The `json` built in package reads weather information, presented in the form of a `json` file, directly from the online open-source weather API *Open-Meteo* [46] which collaborates with national weather services. This is done through the specification of the desired weather variables, of which there are many to choose from, and the building location. The building's location is requested by the code, and can be inputted in the form of either its geographic position (longitude/latitude) or its place name or address. The `json` package subsequently stores the data, which is able to encompasses historical (dating back to 1940), live/current, and forecast (up to sixteen days in advance) weather information, dependent upon what is desired by the user, as a dictionary data structure, `dict`.

The three fundamental components considered during solar radiation modelling, and thus contributing to the functionality of this particular model, have previously been explored in Section 4.3. To reiterate more concisely here, they are:

- astrological information,
- surface information, and
- climate and weather data,

where astrological information primarily describes the position of the Sun in the sky. Surface information considers the possible shadow-casting objects within the area of interest, and the subsequent effects of their shading. Finally, climate and weather data, obtained through *Open-Meteo*, is utilised for the quantification of both the incident solar radiation values and building external $CHTC$ values, as later seen in Section 6.

Figure 9 illustrates how these components fit together to form the developed solar radiation model.

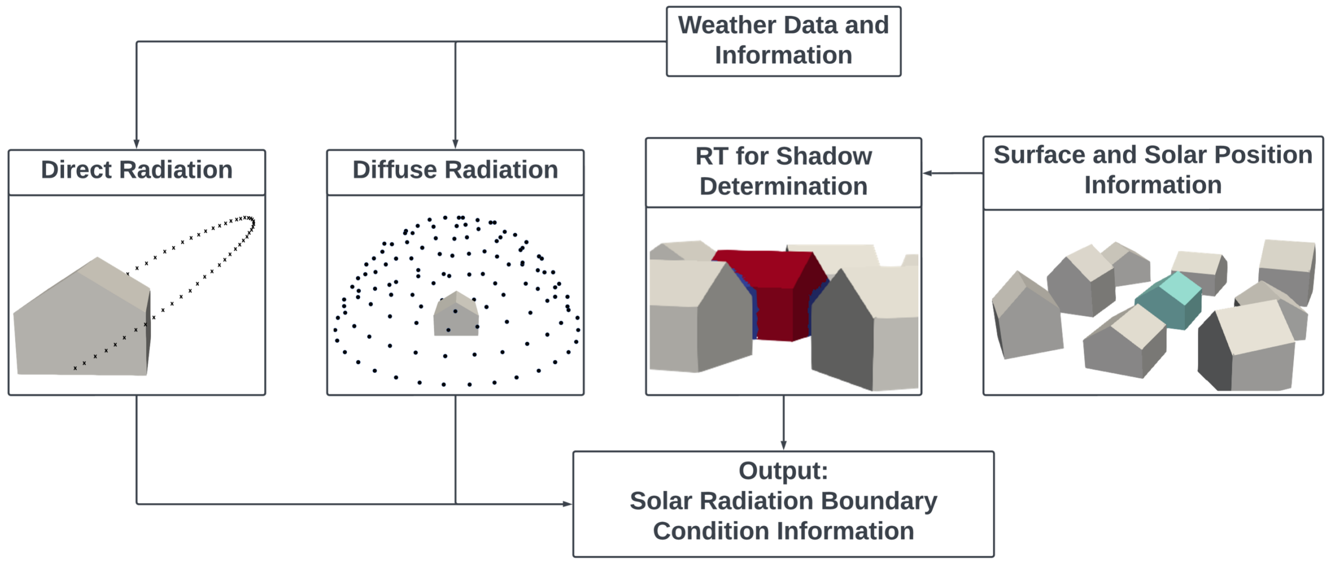


Figure 9: Block diagram showcasing the solar radiation model and its constituent components

5.1.1 Sun Tracking

The determination and tracking of the Sun's position, as it appears from a point on the Earth's surface, is an essential component to the solar radiation model. The pseudocode for this within the solar radiation model is shown in Algorithm 1:

Algorithm 1 Sun Tracking

Input: Building Location, Dates/Times of Investigation
Output: Sun Position Vector(s)

1: Specify building location from entry of its geographic position, place name, or address
2: Specify the date and time of interest, or if a larger time frame is considered, specify the range of times/dates (datetimes)
3: **for** all datetimes considered **do**
4:     Find solar altitude and solar azimuth angles, as functions of datetime and building location
5:     Find and store Sun Position Vector
6: **end for**

Note: The term *datetime* represents an instant in time, typically expressed as a date and time of day [47]

Here, `GeoPy` is used to first and foremost identify the specified target building location. This is via search of its unique longitude and latitude coordinates, from entry of either its place name (town/city/country) or its specific address. The code allows also for the direct entry of the target building's longitude and latitude coordinates, specifying its particular geographic position, should they be known instead. This is all encompassed in `line 1` of Algorithm 1 above.

Upon specification of the target building location, the particular dates and times of building investigation, commonly amalgamated together and referred to as datetimes, can also be specified. Coincidentally, The pseudocode for the incorporation of weather data from *Open-Meteo* is shown next in Algorithm 2.

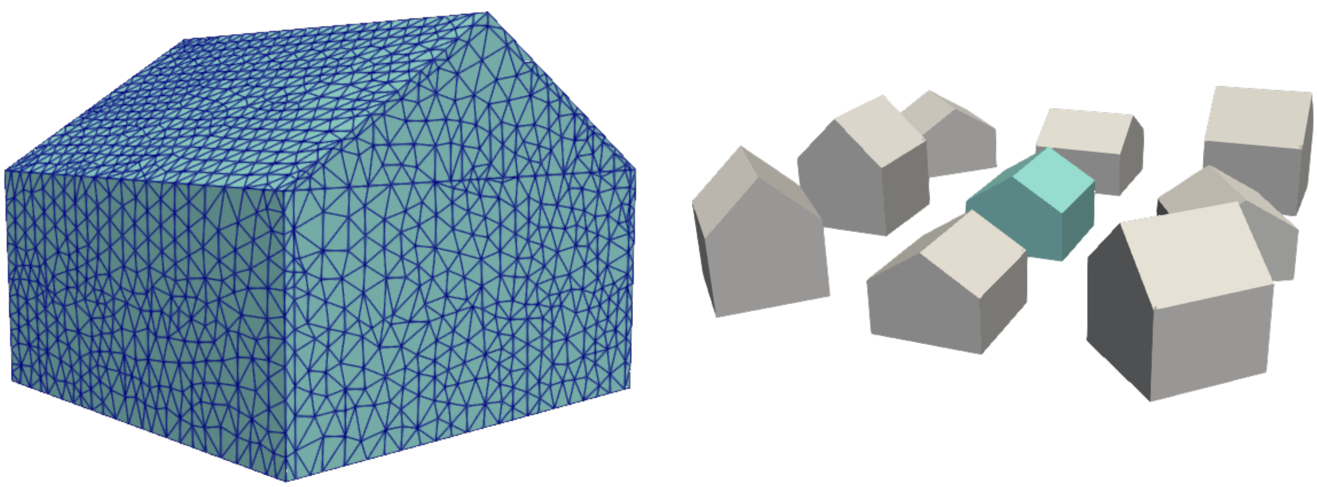
Algorithm 2 Importing Weather Information and Data

Input: Building Location, Time Frame of Investigation [Past, Current/Live, Forecast]
Output: Weather Variables

```
Consider building location and the dates/times (datetimes) of interest - both previously specified
for all datetimes considered do
    Import json file from Open-Meteo containing weather data for the target building location and the
    investigated time frame
    Read json file and store weather data within python dictionary data structure
end for
```

5.1.3 Building of Urban Environments

Ensuring smooth integration of the solar radiation model with the TNMS remained a key design requirement throughout its development. This has been of influence towards both the generation of urban environments within the model, in which an example is seen in Figure 12, and the manner in which the boundary condition information is output by the model for subsequent use in the TNMS.



(a) Expected resolution of target building mesh for later generation of TNM

(b) Generic urban environment example, specifying target building in blue

Figure 12: Representation of target and surrounding buildings within urban environment

As previously mentioned in Section 4.2, and similar to the TNMS, mesh data in the form of ANSYS Fluent mesh files are read into the solar radiation model by the `python` library *meshio* [25]. The representative 3D urban environments, comprising the target investigated buildings, and those surrounding, are then able to quickly be constructed using my code. This automates the generation of the urban environment, and allows for CAD models of buildings and their environments, even if complex, to be investigated.

The pseudocode for the generation of the urban environment shown in Figure 12, as well as the generation of other urban environment follows, is shown in Algorithm 3.

Algorithm 3 Building of Urban Environment

Input: Building CAD Models, Building Locations/Orientations in Reference Coordinate System
Output: Urban Environment
Intermediate: Meshing of Building CAD for ANSYS Fluent Mesh Files using Meshing Software

```
Read geometry information from building mesh files using python library meshio and store within code as python dictionary data structures
Identify target building of interest
Group remaining building information for neighbouring/surrounding buildings
for all buildings considered, including target and neighbouring/surrounding do
    Recall building positional parameters (location/orientation)
    Identify cells on external surfaces of building mesh using zone and cell information
    for all cells on external surface do
        Identify connecting nodes and corresponding node coordinates
        Transform node coordinates if necessary according to building position parameters
        Store cell information (zone, coordinates)
        Generate and uniquely name a python dictionary data structure containing building surface and position information, representative of building itself
    end for
    Group all buildings, represented by their respective dictionary data structures, together to generate unique urban environment, comprising the target building and those surrounding
end for
```

Though only buildings are mentioned and have been considered this far, Section 4.3.5 did highlight trees and poles as other potentially shadow-casting objects. The use of *building* here is hence quite generic, and the CAD models, which are imported as mesh files, can indeed be CAD models of trees, poles, or other arbitrary geometries. This was considered when determining the manner in which the CAD geometries of the surrounding buildings were to be imported into the model.

As observed, the geometry built and primarily considered is an accurate depiction and model of a common UK domestic house. Highlighted early on in Section 2, homes are the largest contributor to building associated greenhouse emissions. This, for all intents and purposes, lent this model geometry to be a relevant focus and building/object for the developed solar radiation model.

When imported, there is the functionality to rotate building or object orientations, as well as translate building/object coordinates; there is also the ability to scale should this be necessary. The example urban environment previously shown in Figure 12, despite being an arbitrary representation of a possible neighbourhood, showcases these added functionalities, as well as the automated ability to quickly add to the urban environment itself within my `python` code.

Importing the CAD geometries of the neighbouring and surrounding buildings also through the use of

The study by A. Arias-Rosales and P.R. LeDuc [10] presented the general main steps for the RT technique, however its application within my study has been adapted and is ultimately different to theirs. Its particular implementation towards targeted building within my investigation is seen illustrated through a flowchart in Figure 13. The flowchart includes the main steps which I have adapted for my particular investigation and is supported by illustrations from own application.

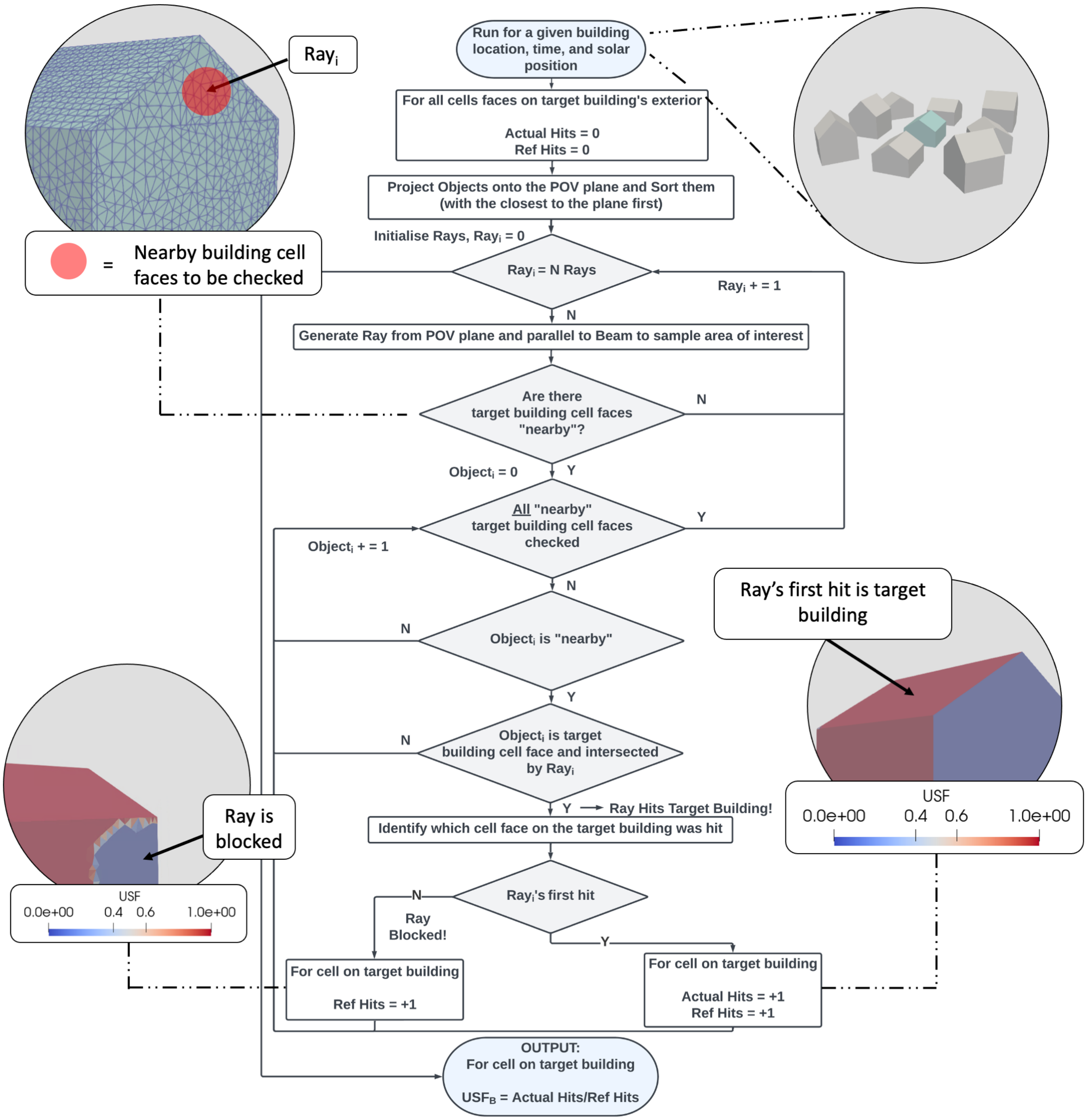


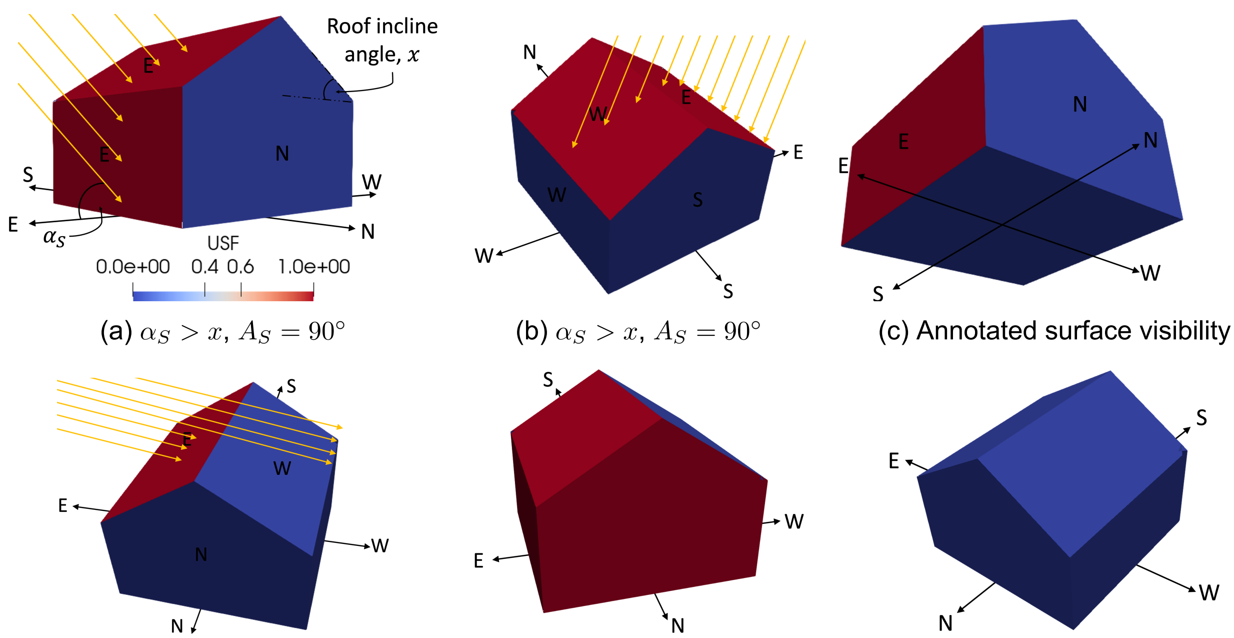
Figure 13: Flowchart showing main steps for Forward Ray Tracing technique for shadow determination of a target building within a complex urban environment [10]

5.2 Model Validation

This section demonstrates correct implementation of the forward ray tracing technique within the `python` solar radiation model. It showcases its ability to work with the varying urban environments which may be built to present and output the correct USF_B values for the investigated target building. Different solar positions are investigated to visualise and subsequently validate the calculated USF_B values for a combination of different environment scenarios, with different solar/Sun positions. This imitates how the Sun's position, as seen from a particular location on the earth, varies throughout the day, and therefore so do the regions on the target building that are unobstructed and exposed to direct radiation.

5.2.1 Target Building Visibility and Exposure to Sun

The exposure, and visibility by the Sun, of different surfaces on the target building is explored by considering an isolated building, exposed to the Sun at different solar positions. This is visualised in Figure 14 through a number of different scenarios. The USF_B figure legend is attached in Figure 14a, where $USF_B = 1$, depicted by red colouring, indicates seen by the Sun, and $USF_B = 0$, depicted by blue colouring, indicates not seen by the Sun.



(a) $\alpha_S > x$, $A_S = 90°$ (b) $\alpha_S > x$, $A_S = 90°$ (c) Annotated surface visibility

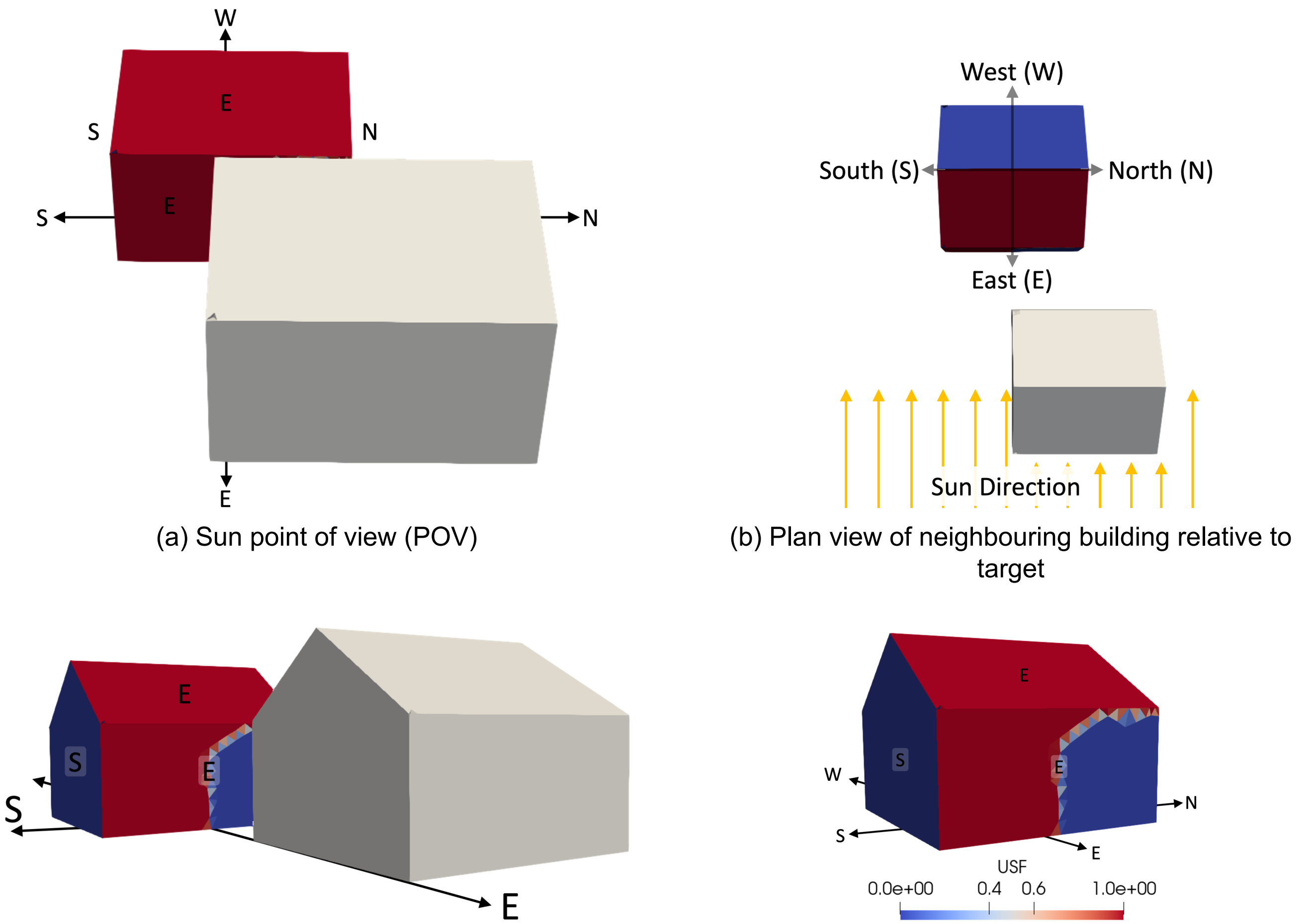
(d) $\alpha_S < x$, $A_S = 90°$ (e) 06:00, 1st May 2023 (f) 22:00, 1st May 2023

Figure 14: Building USF_B values for varying solar altitude α_S and solar azimuth A_S angles

The target building in each of the figures is orientated to best visualise the different USF_B values on the different building faces. It is worth clarifying that this is not as they would have been seen by the Sun at the particular Sun positions. This is because only the surfaces which are visible by the Sun would be

5.2.2 Effect of Shading from Surrounding Buildings

As illustrated in Figure 12b, neighbouring and surrounding buildings can rapidly be built within the solar radiation model to generate the explored urban environment. Through use of the forward ray tracing algorithm, outlined in Figure 13, these shadowing buildings can be investigated for shading of the target building. Validating the effects of shading from these surrounding buildings is explored here, for a target building also exposed to the Sun at different solar positions. For simplicity of visualisation, as well as clarity, a single other shadowing building is first considered; this is seen below in Figure 15.



(a) Sun point of view (POV)

(b) Plan view of neighbouring building relative to target

(c) Position of neighbouring building relative to target

(d) Visible and expected shaded region on target building

Figure 15: Demonstration of shading from a single neighbouring building by observation of USF_B on target building

In the scenario seen above, the Sun is positioned at an azimuth angle $A_S = 90°$ and an altitude angle $\alpha_S < x$ where x, as previously defined in Figure 14a, is the roof incline angle. This Sun position is similar to that of the second scenario explored and previously seen in Figure 14. Different to that case however, a neighbouring building has been situated to partially block the target building from the Sun. The position of this building can be seen in Figures 15a, 15b and 15c, and the Sun direction is also illustrated in

Figure 15c too. The visible, as well as expected, region of shade is observed in Figure 15d; this is the identifiable blue region of the target building's side face where cell faces, unlike the rest on that surface, do not occupy values of $USF_B = 1$. Referring back to the flowchart in Figure 13, this is because the rays generated from the Sun's POV and directed towards that particular area on the target building interact with the shadowing building prior to interacting with the target building. In other words, those particular incoming rays are blocked by the neighbouring building, revealing the region of shading from sunlight.

The effect of shading in a second more complex urban environment is considered next; this in Figure 16.

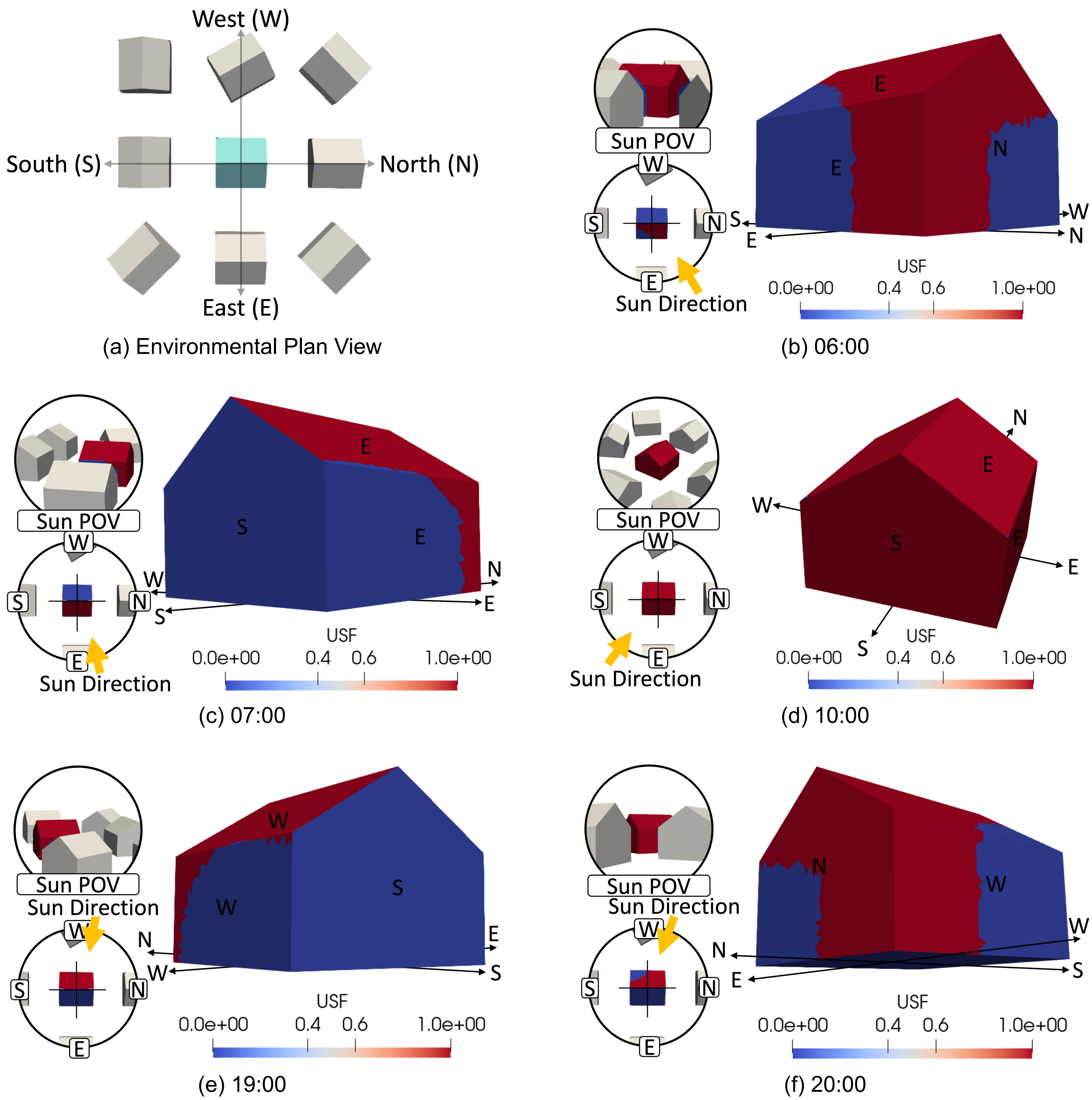
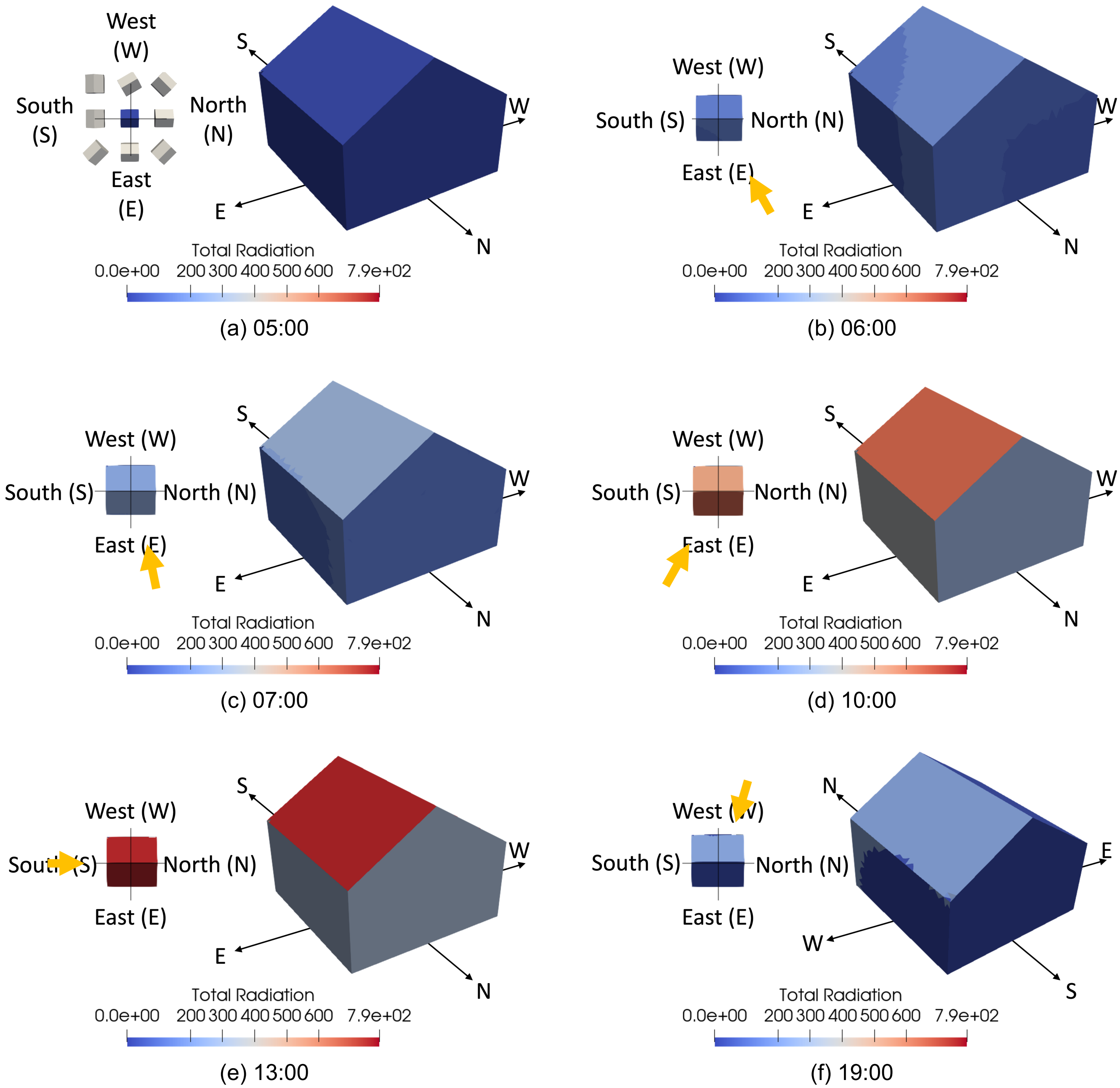


Figure 16: Shading of target building within complex urban environment through 01/05/2023

5.3 Modelling of Incident Solar Radiation

Recalling from Section 4.3.3, the total amount of solar radiation incident on an exterior surface of the target building, G_t, comprises of three contributing components. Quantifying the contribution of each of these components towards G_t for a particular surface is shown in Equations 1, 2, and 3. Equation 3 is populated within the solar radiation model, and its application, as well as the correct assignment of G_t values to building exterior cell faces is visualised below in Figure 17. A plan view of the building is also included for each timestamp, showing the relative position of the Sun in the sky (yellow arrow).



(a) 05:00 (b) 06:00 (c) 07:00 (d) 10:00 (e) 13:00 (f) 19:00

Figure 17: Variation in target building surface G_t values, recorded in W/m^2, throughout 01/05/2023, and hence also for the varying Sun position and solar angles through the day

6 Modelling of Building Exterior Convective Heat Transfer Coefficients

To compliment the solar radiation model as well as the TNMS too, and different to most other building thermal models, building external surface $CHTC$ values are considered also with the solar radiation within this study. This makes the $CHTC$ values the second of the two main pieces of boundary condition information considered for use in the thermal network modelling of buildings.

The modelling of building exterior $CHTC$ values considers the interaction of the surrounding wind with the building's exterior surfaces, as has previously been discussed in Section 4.4. Similar to the solar radiation model, this forms a second part of the overall `python` model which outputs boundary condition information for use with the TNMS.

Empirical correlations for the $CHTC$ on the windward and leeward faces, derived by H. Montazeri and B. Blacken [17], were presented in Tables 3 and 4, respectively. These are implemented within the `python` code, which can be seen showcased below in Figure 18.

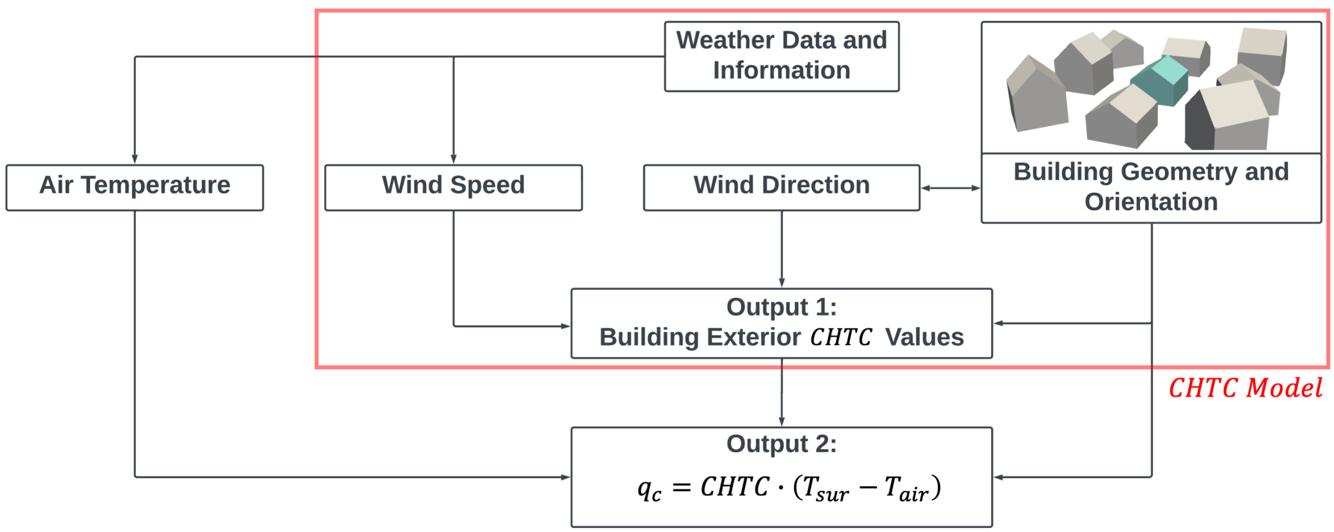


Figure 18: Flowchart showing the modelling of building exterior $CHTC$ values

Quantifying the building exterior $CHTC$ values is encompassed within the red highlighted area above. It facilitates the determination of the convective heat flux q_c which is what is to be used within the TNMS. For the modelling of $CHTC$ values, the additional weather variables are also stored in the `python` model:

- Wind speed $[m/s]$ and wind direction $[°]$, with $0°$ blowing from the north, and $90°$ from the east
- Outdoor air temperature $[°C]$

A plot of their temporal variation through 5 May 2023 is seen in Figure 19. To add to these variables, soil temperature $[°C]$ is also stored as necessary boundary condition for a comprehensive building's TNM.

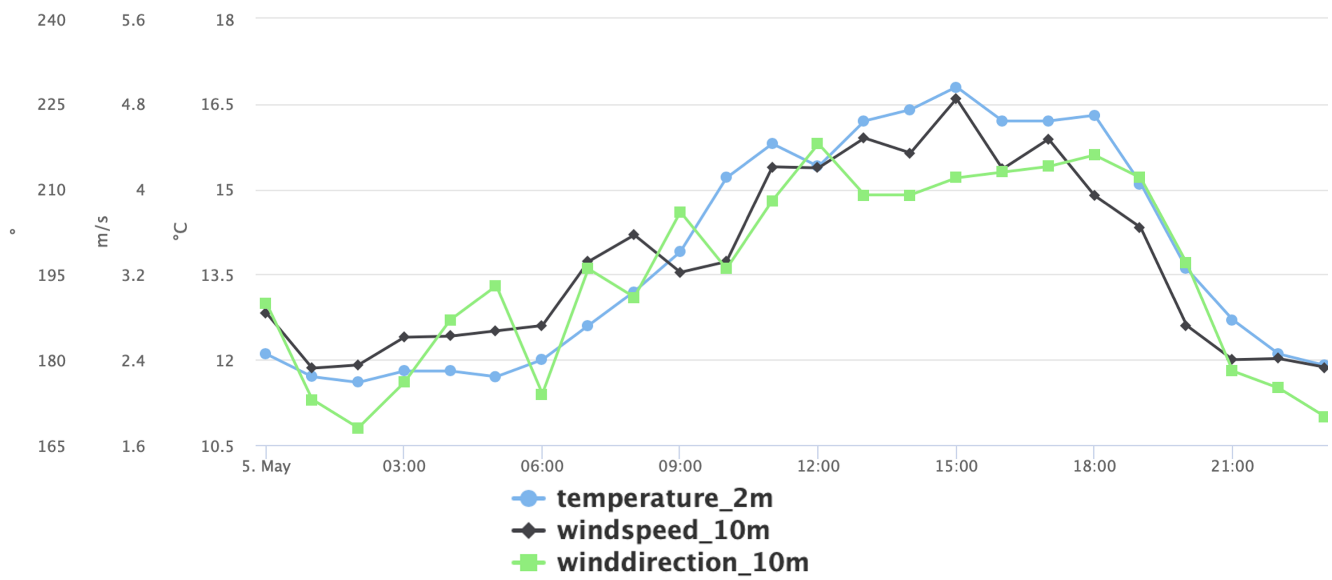


Figure 19: Example temporal plot for both wind (speed, direction) and air temperature variations in Oxford through 5 May 2023 [46]

The correct application of the empirical $CHTC$ and assignment to building exterior cell faces is visualised below in Figure 20. Accompanying each is a plan view, showing wind direction (blue arrow).

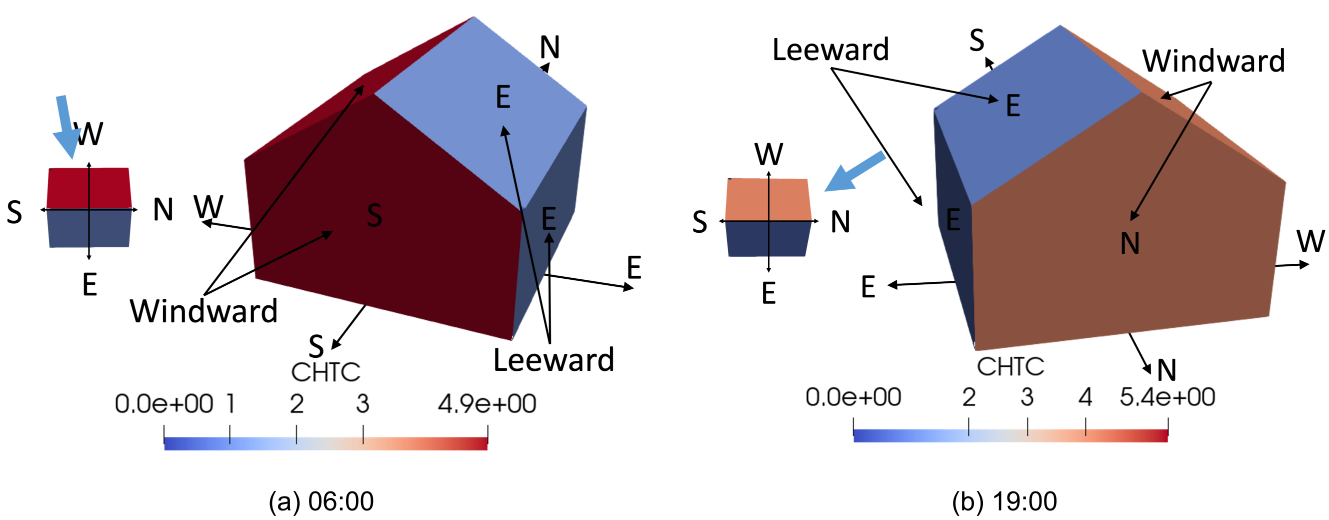


Figure 20: Variation in target building $CHTC$ values, recorded in $W/m^2/°C$, at two time stamps during 01/05/2023

Visually however, it can be seen that these simple $CHTC$ correlations do not truly capture the complexities characterising wind flow around a building. This includes flow impingement, separation, recirculation, and reattachment, which all have an effect on local $CHTC$ values on a building's exterior. This reinforces the need for further development towards $CHTC$ modelling and implementation, which will be discussed further in Section 8.

7 Integration with the TNMS

The purpose of both the developed solar radiation model and the building exterior $CHTC$ model is for integration with the existing Thermal Network Model Software (TNMS). This requirement has influenced the manner in which information is taken into the `python` model, and the manner it is subsequently output.

The overall `python` model outputs the boundary condition information through an EXCEL file. A workbook is output for each modelled simulation and is formed of worksheets containing the boundary conditions for each time instant, or *datetime*, considered within the simulation. There can also be one, or multiple, worksheets within a workbook, and each worksheet is named accordingly for easy identification. The recorded boundary condition information is correctly assigned to each cell face on the target building's exterior within each worksheet, and Figure 21 showcases how the two models are combined to record this information.

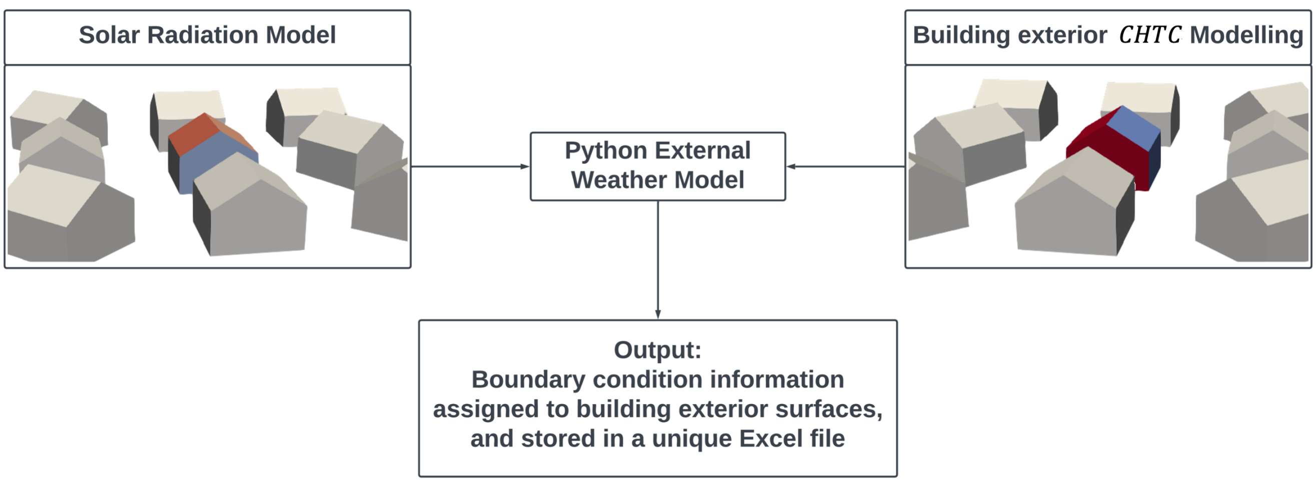


Figure 21: Amalgamation of the solar radiation model and the building exterior $CHTC$ model to form the overall external weather model which records and outputs the boundary condition information

Although a simple depiction of the overall external weather model, the individual and intricate components to both the solar radiation and $CHTC$ models were detailed in Figures 9 and 18 respectively.

The output EXCEL workbook keeps accurate track of the mesh cell face and zone information. It correctly assigns the building exterior cell face USF_B values, as well as the cell solar irradiance G_t and $CHTC$ values to these cell faces. This can then be used to assign these boundary conditions to these faces in thermal network models.

7.1 Thermal Network Modelling of Target Building

In order to gain a full understanding of the thermal network modelling concept, a simplified and representative model of the target house was constructed manually. The overall model considered 24 nodes in total with 52 connections, and was favoured over relying solely on the black box implementation of the TNMS. Figure 22 illustrates the representative thermal network model.

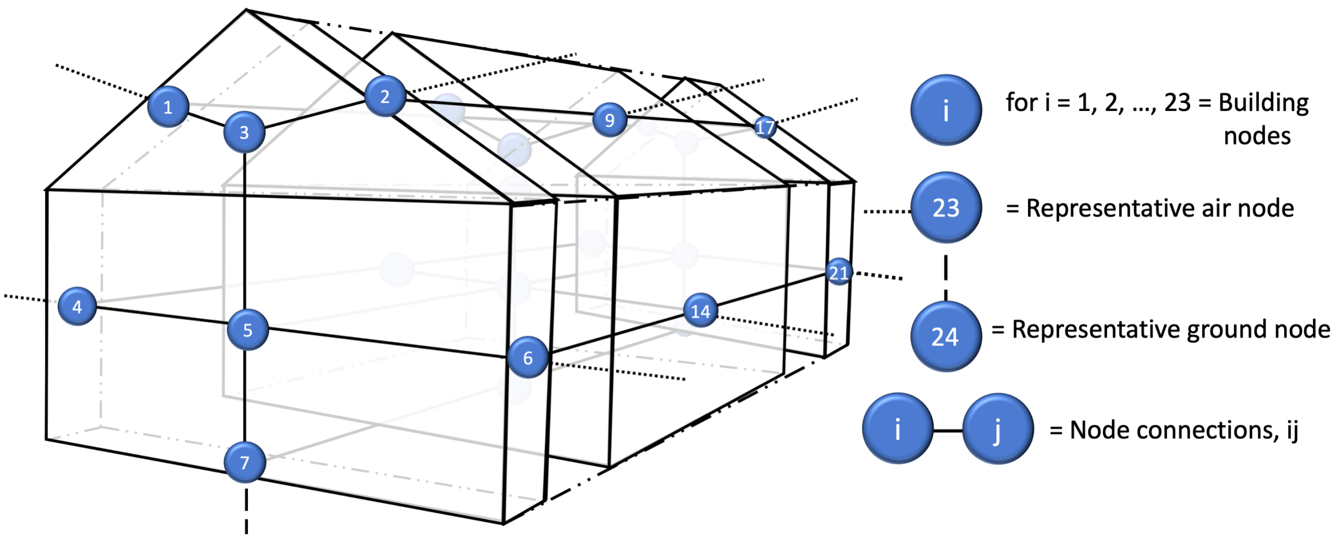


Figure 22: Representative thermal network model of target building

Of the 24 nodes considered, 22 are associated with the target building itself. The remaining two representative nodes are given to the ambient air, node 23, which is connected to the building exterior surface nodes and the ground underneath, node 24, which is connected to the building floor surface nodes.

To form the 3D TNM, the target building is split into three sections; these are a front, middle, and back sections. The sections can be inferred from Figure 22, along with their associated nodes and node connections, and the connections between sections. The front and back sections are identical, and they model the exterior front and back faces of the target building respectively. The middle section models the side and side roof faces of the target building, the building ground floor, and the building's interior. This includes an internal ceiling, and two void spaces representative of the building's interior open spaces.

Figure 23 considers the front section of the building. It illustrates the associated 2D TNM, comprising the individual nodes and the thermal resistances for each connection between nodes. Each individual node has an associated thermal capacitance value which for simplicity is not shown in Figure 23. This is however shown in Figure 24, which highlights node 4 and its nodal connections. This includes its connection to node 8, which is in the middle section of the three. Together, the individual TNMs associated with the three sections, along with the nodal connections between sections, form the overall 3D TNM.

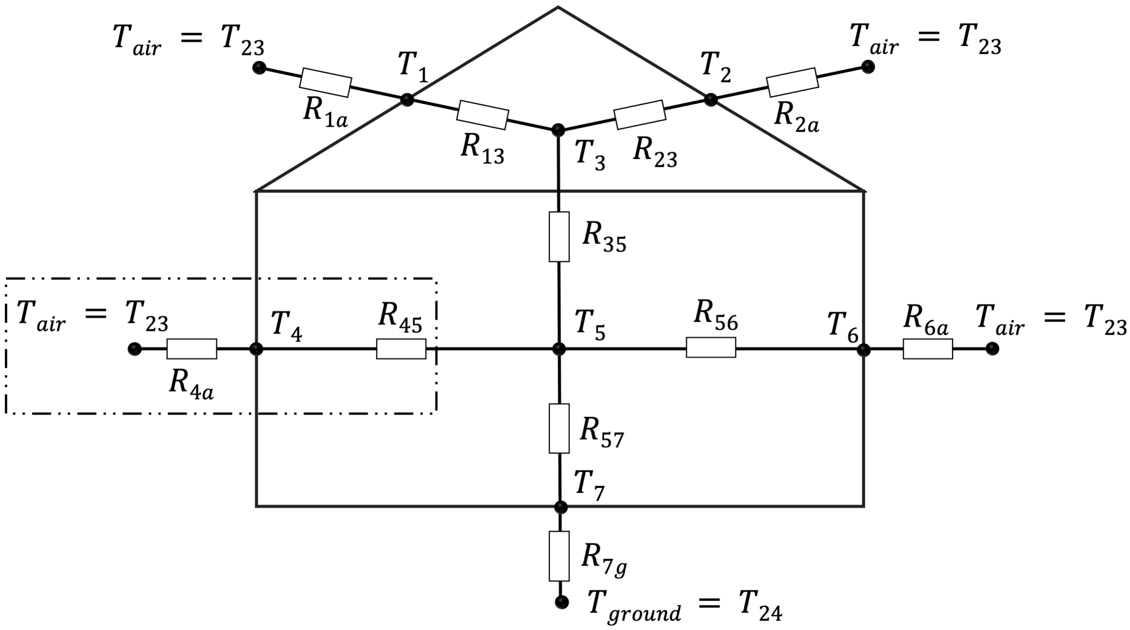


Figure 23: 2D TNM associated with the front section

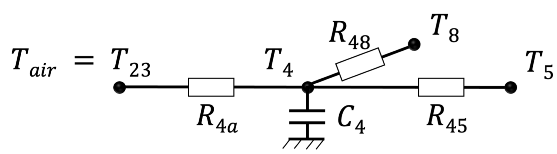


Figure 24: Node 4, along with its nodal connections and associated thermal capacitance

To solve, Kirchoff's current law is considered. This is applied to node 4 next in Equations 7 to 9.

$$\frac{T_{air} - T_4}{R_{4a}} + \frac{T_5 - T_4}{R_{45}} + \frac{T_8 - T_4}{R_{48}} - C_4 \frac{dT_4}{dt} = 0. \tag{7}$$

The forward difference, $dT = T^{k+1} - T^k$, is introduced with time instance k and time step Δt to give

$$\frac{T_{air}^k - T_4^k}{R_{4a}} + \frac{T_5^k - T_4^k}{R_{45}} + \frac{T_8^k - T_4^k}{R_{48}} - C_4 \frac{T_4^{k+1} - T_4^k}{\Delta t} = 0. \tag{8}$$

This is rearranged to solve for T_4 at the next instance of $k+1$, which gives

$$T_4^{k+1} = T_4^k + \frac{\Delta t}{C_4}\left[\frac{T_{air}^k - T_4^k}{R_{4a}} + \frac{T_5^k - T_4^k}{R_{45}} + \frac{T_8^k - T_4^k}{R_{48}}\right]. \tag{9}$$

For a generic node i which has n connections to nodes j, this is shown to give Equation 10.

$$T_i^{k+1} = T_i^k + \frac{\Delta t}{C_i} \Sigma_j^n \left(\frac{T_j^k - T_i^k}{R_{ij}}\right). \tag{10}$$

8 Applications of Project and Future Developments

The primary application of this project is to support and facilitate the decrease in emissions resulting from heating buildings. This is by understanding and reducing building heating demands and replacing carbon intensive heating sources with renewable forms of heat generation.

The `python` external weather model, comprising the solar radiation model and the $CHTC$ model, compliments the existing TNMS. It has been transferred to the research group for full integration to the software, such to enable the dynamic thermal modelling of buildings. Discussed in the previous section, this is through the construction of quick yet accurate building thermal network models, supplemented with building heating specific boundary conditions and other potential sources, and/or sinks, of heat. This enables the understanding of building thermal performances and heating demands, through variations in weather influences and conditions, and enables predictions of future building demands too. From this understanding, measures can be put in place to in turn reduce these heating demands, and can either be from changes to behaviour, or improvements to the building itself. These improvements to the building can come in various shapes and forms and can include the integration of renewable forms of heat generation, such as those introduced in Section 2, as well as other storage devices such as borehole thermal energy storage (BTES). The dynamic thermal modelling of buildings can help selection of these heating systems in buildings through consideration of its thermal requirements and needs. This can also support integration with smart home heating technologies, especially through predictive measures and being prepared for expected times of either higher heating demands or, conversely, cooling demands too. Additionally, understanding of the solar potential too can also support the implementation of other forms of renewable technologies, namely solar PV and ST collectors, which again supports the decarbonisation of heating and energy systems within building.

To further improve accuracy of results, improvements and developments can be made towards certain components of the solar radiation model. This is primarily through further investigation of $CHTC$ correlations, especially for buildings within an urban environment. Its general lack of consideration as an influence in most $CHTC$ correlations was discussed as a limitation in Section 4.4. A second improvement would be with greater accuracy towards building modelling, particularly towards windows which allow for direct radiation penetration into buildings. Simultaneously,“windows [do also] behave like heat sinks due to their high transmittance,” and impact the “total energy absorbed by buildings” [8]. Both of these possible developments will in turn improve the accuracy towards building thermal modelling and as such, they both warrant further investigation.

9 Conclusions

Dynamic thermal modelling within buildings provides a way of both understanding and reducing building heating demands and supporting the decarbonisation of domestic and commercial heating. As has been emphasised through the beginning sections of this report, and again in the previous section, both measures are necessary to reduce total greenhouse gas emissions. This is particularly important within the domestic sector which, referring back to Figure 1, contributes the greatest towards total UK emissions from buildings.

This report has showcased the development of an external weather model, built using `Python` for incorporation and integration with the existing TNMS. The developed model combined with the TNMS allows for the creation of an accurate, fast, and predictive tool to support dynamic thermal modelling within buildings. The model comprises both a solar radiation model and building exterior convective heat transfer coefficient $(CHTC)$ modelling.

The solar radiation model is implemented to investigate the solar potential of a target building. This building can either be a domestic building, as demonstrated in the building model used in this study, or a larger commercial building. The model is shown to solve the complex interaction of building shadowing in dense urban environments. In addition, the building exterior convective heat transfer coefficient model incorporates $CHTC$ calculations to investigate the convective heat transfer processes, driven by the flow of surrounding wind and its interaction with the target building's exterior faces. Both models have been designed in a manner which is not solely applicable to a single target building, but capable of being scaled towards larger design problems.

Previous studies have highlighted the importance of both solar radiation and convective effects on building heating. However, these effects have traditionally been isolated, with many studies neglecting one of these critical aspects. A unique thermal model was developed, incorporating both heat transfer mechanisms in domestic building analysis.

Combined in a novel `python` code, real-time or predictive weather effects can robustly be converted to thermal network boundary conditions. Constructed specifically for integration with the Oxford Thermal Network Model Software (TNMS), this new external weather boundary condition model opens the door to dynamic thermal modelling of complex urban environments.