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Risk Identification in the Early Design Stage Using Thermal Simulations—A Case Study

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Abstract: The likely increasing temperature predicted by UK Climate Impacts Program (UKCIP) underlines the risk of overheating and potential increase in cooling loads in most of UK dwellings. This could also increase the possibility of failure in building performance evaluation methods and add even more uncertainty to the decision-making process in a low-carbon building design process. This paper uses a 55-unit residential unit project in Cardiff, UK as a case study to evaluate the potential of thermal simulations to identify risk in the early design stage. Overheating, increase in energy loads, carbon emissions, and thermal bridges are considered as potential risks in this study. DesignBuilder (DesignBuilder Software Ltd., Stroud, UK) was the dynamic thermal simulation software used in this research. Simulations compare results in the present, 2050, and 2080 time slices and quantifies the overall cooling and heating loads required to keep the operative temperature within the comfort zone. Overall carbon emissions are also calculated and a considerable reduction in the future is predicted. Further analysis was taken by THERM (Lawrence Berkeley National Laboratory, Berkeley, CA, USA) and Psi THERM (Passivate, London, UK) to evaluate the thermal bridge risk in most common junctions of the case study and the results reveal the potential of thermal assessment methods to improve design details before the start of construction stage.

Keywords: heating and cooling loads; carbon emissions; thermal bridge simulations

1. Introduction

The UK government had, until recently, set an ambitious target of new dwellings to meet zero carbon requirements by 2016. The plans included encouraging 'Modern Methods of Construction' (MMC) and developing building standards [1]. The building envelope is, therefore, expected to play a significant role in achieving these high-performance standards. Furthermore, the government has also set an ambitious target of reducing carbon emissions by 50% in the built environment by 2025 [2]. 'Fabric first' is an approach taken in order to achieve the target which is on the basis of increased and improved insulation and reduced thermal losses by removing thermal bridging and increasing air tightness [3,4]. However, the recent usage of MMC with high levels of insulation in the UK has raised an issue regarding potential overheating risk [5]. Apparently, this could become more severe as recent predictions show a considerable shift in temperature by 2080 [6]. Sajjadian [7] revealed the significance of alleviating such risk by modern and traditional passive design features, and also highlighted the fact that thermally-lightweight homes might experience levels of discomfort due to higher room temperatures. This research emphasised that brick and block construction systems with a higher level of thermal mass may result in less energy consumption over their lifetime in comparison with lightweight construction systems, such as timber frame and steel frame. Orme et al. [8] presented a study which also clarified that in a lightweight, well-insulated house an outdoor air temperature of 29 °C may cause overheating to more than 39 °C inside the building. However, Andric et al. [9] evaluated the long-term impact of climate change on the heating demand in the future using a six-storey multi-apartment detached building in four different European cities and demonstrated a considerable reduction in the heating demand in low, medium, and high emission scenarios of climate change. Further techniques to address the overheating issue conducted by Three Regions Climate Change Group [10] in London, East and South East of England and they reported improved air movement, ventilation, solar control, cooler floors, and increased façade reflectivity were efficient in decreasing overheating hours. Gaterell, et al. [11] conducted a similar study in Southeast England on a detached house and found double glazing and loft insulation as effective solutions. In another study by Hulme et al. [12] reducing air leakage, additional insulation, and enhancing solar gain were found to cause an increase in discomfort hours in summer in different locations in the UK, and Department for Communities and Local Government (DCLG) [13] reported that, in any climate change scenario, heating loads remain prominent until 2080.

2. Problem Statement

Residential buildings are contributing to a substantial proportion of the UK's CO_2 emissions as a consequence of consuming energy for electrical appliances, heating, lighting, and cooking [14]. A warmer future climate is expected to change the comfort conditions and the patterns of energy use in existing UK home stock. This is why an emerging policy on climate change adaptation is focused on addressing overheating in existing and new housing. Climate change underlines a reason for long-term thinking in the design process and it is important to address the possible impacts of climate change on the new residential buildings. Figure 1 shows likely changes in the mean annual temperature in the UK by 2080 in different scenarios.

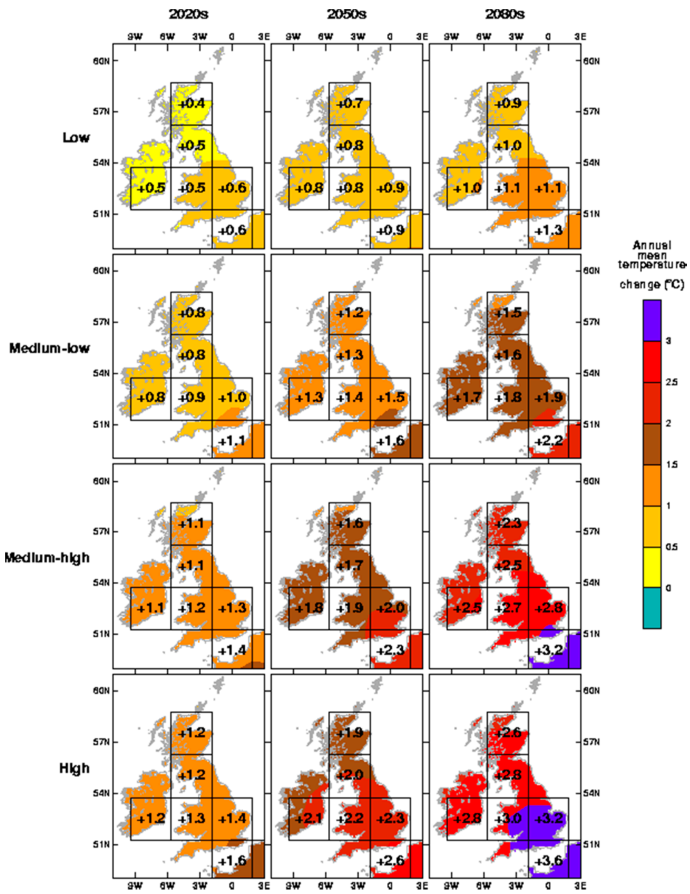


Figure 1. Mean annual temperature increase in 2020, 2050, and 2080; 90% probability level, unlikely to be less than the degrees shown on the maps [15].

Figure 1 demonstrates that expected temperature increase would be considerable for many cities, especially in South Wales in the UK by 2080 even if the low emission scenario takes place. Therefore, a focus on future building performance should be active now. A large number of UK dwellings have no mechanical cooling systems [13]. Consequently, temperature increases will increase occupants' vulnerability to overheating [16]. Furthermore, there is a potential risk of heat loss through poor design detailing, which is widely neglected. This is also considered as a considerable risk affecting building performance during operation that can be rectified by simplified thermal modelling.

3. Methodology

This paper presents a study on a multi-story residential building in South Wales, UK that uses a lightweight steel frame as a structural system. Figure 2 shows the location of the building in the city of Cardiff, UK.

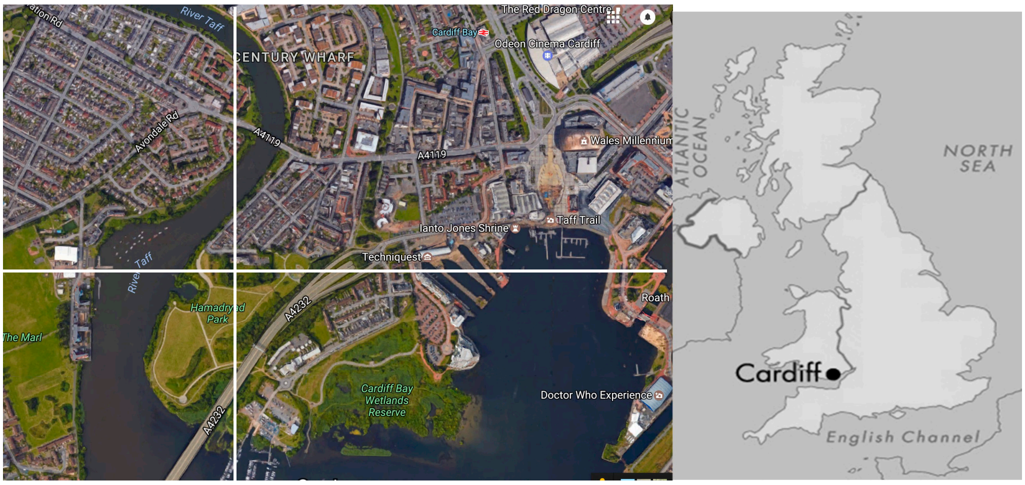


Figure 2. Building location, 51°27′44.8″ N 3°10′27.6″ W. Graphic by author data from [15].

The research questions in this study mainly focus on how current UK building standards and design implications would perform in the future and evaluates the impact of climate change as a potential risk to buildings. Further investigation on risk identification focuses on thermal bridge simulation in order to find any potential failure in design details and to further avoid unwanted heat loss during building operation. This study is not representative of a common practice in the region and the applied research methodology used in this study is focused to predict and improve building performance for new developments with an understanding of potential climate change risk.

In order to meet the requirements, dynamic thermal simulation is used to assess the performance of the building in current and future climates. Assessing the impact of future climates on UK homes is well documented. Cardiff climate data and HadCM3 (Hadley Center Coupled Model, coupled atmosphere-ocean general circulation model) output files were used as the input for the CCWorldWeatherGen tool developed by Sustainable Energy Research Group at the University of Southampton [17]. 'CCWorldWeather Gen' can create future weather files in .EPW (EnergyPlus Weather Data) format required for simulation in DesignBuilder (DB is a dynamic thermal simulation software which employs EnergyPlus as its calculation engine. EnergyPlus is an open source program developed by US Department of Energy). The software is highly validated and widely used by building researchers). These files, which provided hourly weather data, are used for modelling future impacts on the case study [18]. Further investigation on 2D and 3D thermal bridge analysis is also taken by THERM and PSI THERM programs. Figure 3 shows the methodology used in this study.

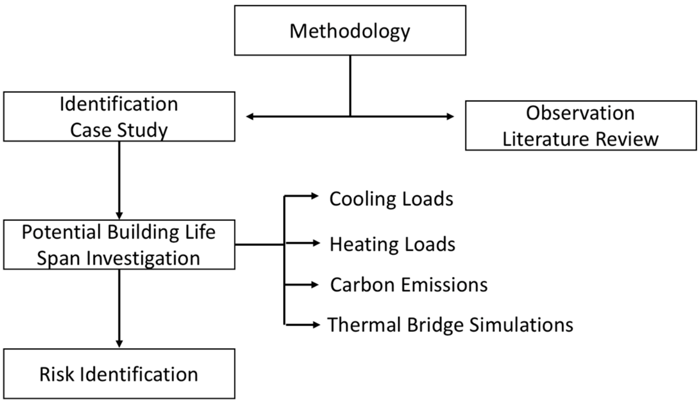


Figure 3. Flowchart of the research methodology.

3.1. Case Study

A case study used for dynamic thermal simulations by DB software is a 55-unit residential building in Cardiff, UK. Figure 4 demonstrates the 3D model and floor plans (a,b) used for the simulations (every room is considered in the simulations). Table 1 also shows the fabric details and heating systems considered for simulations.

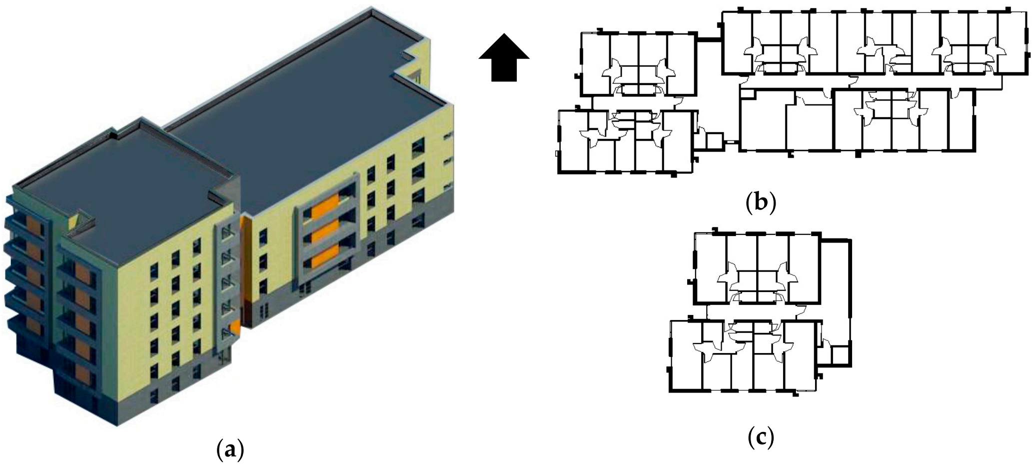


Figure 4. 3D model (**a**); (**b**) ground floor to 3rd floor; and (**c**) 4th and 5th floor, the arrow shows the north side.

Table 1. Fabric details and heating systems.

Fabric	Type	Detail
External Wall 1	Hybrid Steel frame construction	U-Value 0.17
Sheltered Wall 1—to unheated communal areas	Twin steel stud construction	U-Value 0.18
Party wall 1	Fully filled and sealed party wall	
Floor 1—Ground	Solid concrete 150 mm slab	U-Value 0.17
Floor 2—Over Plant room	No flats over this area	U-Value 0.18
Roof	Warm flat roof construction	U-Value 0.11
Windows	Based upon aluminium windows	U-Value 1.5
Doors—to unheated communal areas		U-Value 1.5
	Heating Systems	
Main heating	Community heating based on gas boilers	88.6% efficiency
Heat distribution	Pre-insulated low temperature/variable flow	
Emitters	Radiators	
Secondary heating	None	

Table 1. *Cont.*

PVs	Minimum of 13.6 kWp. south orientation and based upon a maximum collector tilt of 30°	<20% shading assumed
	Other	
Thermal mass	Low	
Lighting	100% low energy lighting	
Ventilation/Mechanical Cooling	Mechanical ventilation is used/no mechanical cooling	

3.2. Comfort Zone

Generally, there are two well-known approaches for thermal comfort definition–the rational or heat-balance approach, and the adaptive approach. The most well-known method in the heat balance approach is "Predicted Mean Vote" (PMV) and the "Predicted Percentage of Dissatisfied" (PPD) model proposed by Fanger has been accepted widely by scholars. However, Fanger's model has failed in the results for naturally-ventilated buildings and increasing dissatisfaction with this approach has driven interest in a variable indoor temperature standards model [19]. Nicol and Roaf [20] suggested the Equation (1) model for occupants of naturally-ventilated buildings. Other adaptive models are suggested by Humphrey's models [21] for neutral temperature, as given by Equations (2) and (3). De Dear et al. also suggested Equations (4) and (5) [22]:

$$Tn, o = 17 + 0.38 \times To \tag{1}$$

$$Tn, i = 2.6 + 0.831 \times Ti \tag{2}$$

$$Tn, o = 11.9 + 0.534 \times To \tag{3}$$

$$Tn, i = 5.41 + 0.731 \times Ti \tag{4}$$

$$Tn, o = 17.6 + 0.31T \times o \tag{5}$$

In the above equations, *To* is the outdoor air temperature, *Ti* is the mean indoor air temperature, *Tn,i* is the neutral temperature on the basis of mean indoor air temperature, and *Tn,o* is the neutral temperature on the basis of the mean outdoor air temperature. Additionally, ASHRAE 55 also developed a standard in 2010, which included the metabolic rate into the consideration, as shown in Figure 5 [23]. For simplification in the simulations, this study considered 22–28 °C on the basis of the ASHRAE 55 standard as highly likely to be within the comfort zone in Cardiff and applied this temperature range for heating and cooling systems.

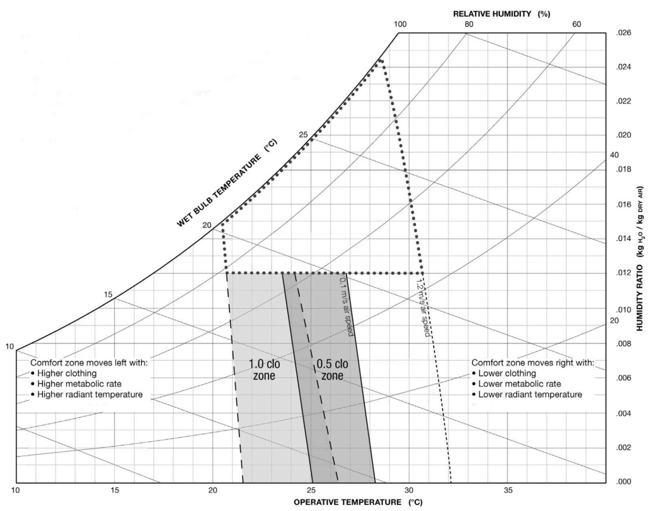
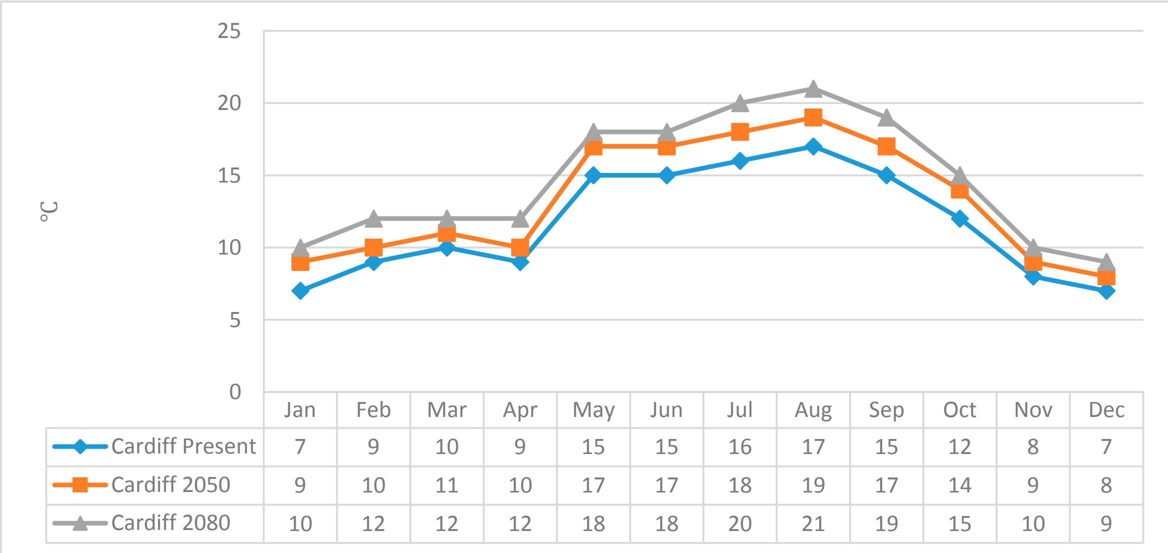


Figure 5. Comfort Zone by ASHRAE.

4. Results and Discussion

Future weather data is created for 2050 and 2080 time slices as explained in the methodology section for Cardiff City where the case study is located. Figure 6 shows the increasing temperature in 2050 and 2080 compared to the current time. Considering the expected durability of buildings, energy assessment and, consequently, design adjustments for the 2080s is useful. In order to evaluate energy consumption and carbon emissions, heating and cooling loads are calculated where the heating setpoint is adjusted at 22 °C and the cooling setpoint is adjusted at 28 °C. Overall carbon emission is also estimated considering the system conditions provided in Table 1.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cardiff Present	7	9	10	9	15	15	16	17	15	12	8	7
Cardiff 2050	9	10	11	10	17	17	18	19	17	14	9	8
Cardiff 2080	10	12	12	12	18	18	20	21	19	15	10	9

Figure 6. Average monthly dry bulb temperature in the current, 2050, and 2080 time slices.

As can be seen from Figure 6, the created weather files show close agreement with Figure 1 predictions and, therefore, are reliable for simulation works in this study. They show a 1 °C to 2 °C average increase per month from each period. Therefore, these results demonstrate the likely decrease in heating loads and potential increase in cooling loads in summertime.

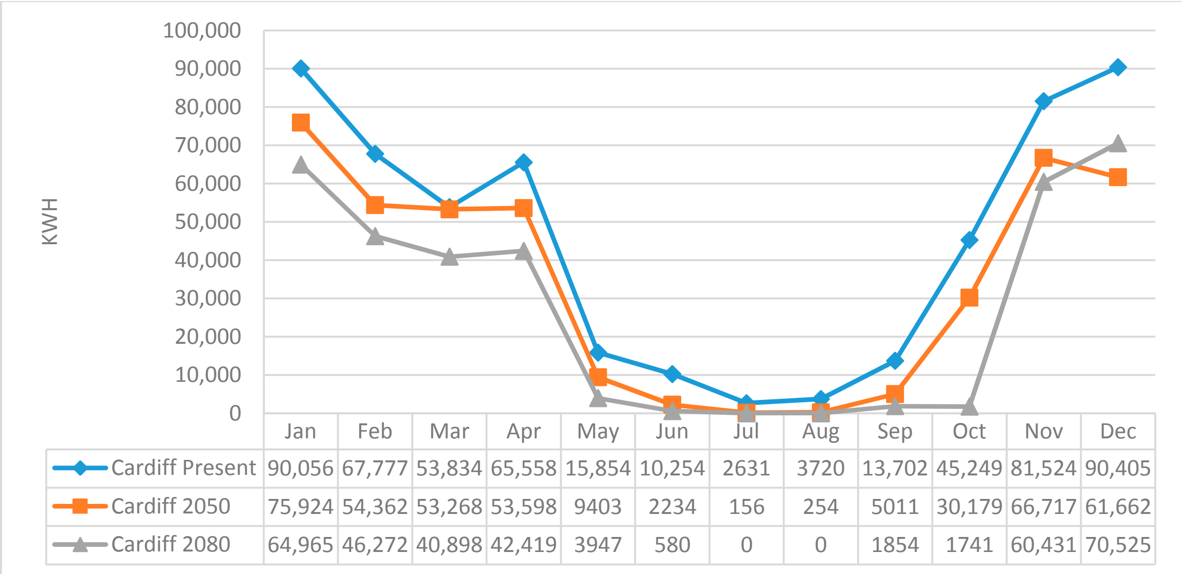
Climate change impact is a double-edged sword and can be both opposable and synergistic to adaptation strategies. Increasing temperature could reduce heating load, while it could also increase cooling loads. Similar to a large number of UK dwellings, active cooling systems are not used for the case study. Therefore, an increasing temperature has the potential to increase occupant vulnerability to overheating in summer months.

Revealing climate change impact could lead to the optimization in the design of a decision-making process and, consequently, improve thermal comfort and reduce energy consumption. This approach causes effective and practical adaptation strategies to reduce overheating, as well as overcooling risks in UK houses. However, it has to be noted that due to the uncertainty of economics, population growth, and politics, different emission scenarios exist, as shown in Figure 1. It is possible that the emissions scenarios will be refined in the future as our understanding of probabilistic change is likely to increase.

4.1. Heating and Cooling Loads

Cardiff has a mild humid temperate climate with warm summers and no dry season. During the year, typical wind speeds differ from 1 m/s to 9 m/s and rarely exceed 14 m/s. Figure 7 demonstrates heating loads in the current, 2050, and 2080 time slices for the entire building. The building consists of 55 units, 12 of which are located on the south side of the building and, therefore, are expected to consume less energy loads compared to other units. The wind is most often towards the west

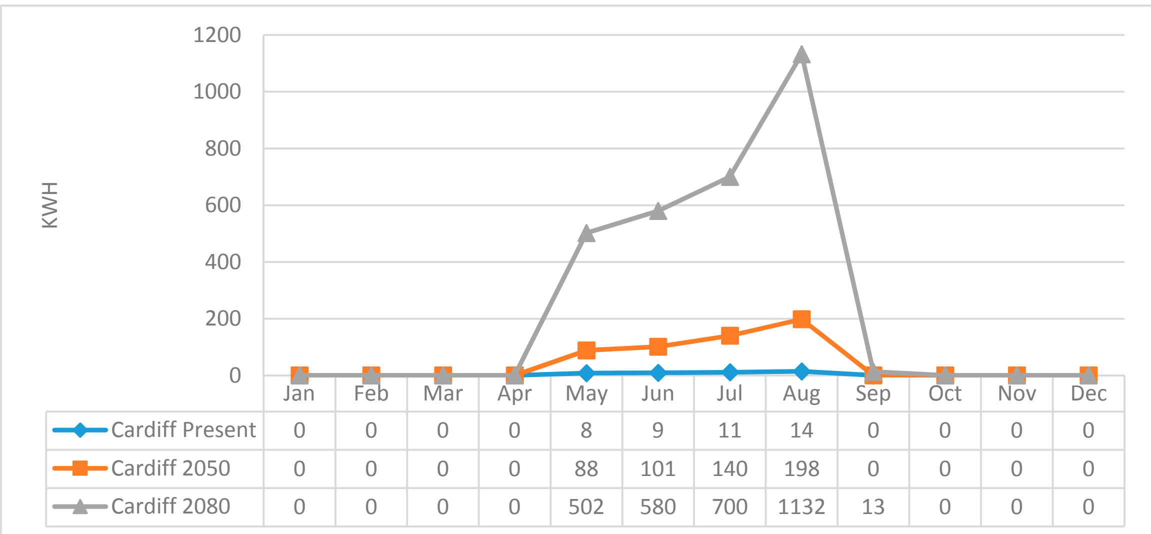
(31% of the time) and less often toward the east (13% of the time) and northeast (13% of the time). Such strong winds are expected to have an impact on overall heating loads for units on these sides.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cardiff Present	90,056	67,777	53,834	65,558	15,854	10,254	2631	3720	13,702	45,249	81,524	90,405
Cardiff 2050	75,924	54,362	53,268	53,598	9403	2234	156	254	5011	30,179	66,717	61,662
Cardiff 2080	64,965	46,272	40,898	42,419	3947	580	0	0	1854	1741	60,431	70,525

Figure 7. Heating loads in the current, 2050, and 2080 time frames.

As can be observed from Figure 7, the temperature increase would cause lower heating loads during the year. This could be up to 25,000 kWh for the entire building in January. It also shows that heating loads are going to be completely removed in June, July, and August months, and cooling loads are required to keep the interior of the building within comfort zone. This result is also comparable to [9] and [13], confirming the reduction of heating loads in future times and that the heating loads remain prominent energy loads until 2080. Figure 8 shows cooling loads requirement for the entire building in the current, 2050, and 2080 time slices.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cardiff Present	0	0	0	0	8	9	11	14	0	0	0	0
Cardiff 2050	0	0	0	0	88	101	140	198	0	0	0	0
Cardiff 2080	0	0	0	0	502	580	700	1132	13	0	0	0

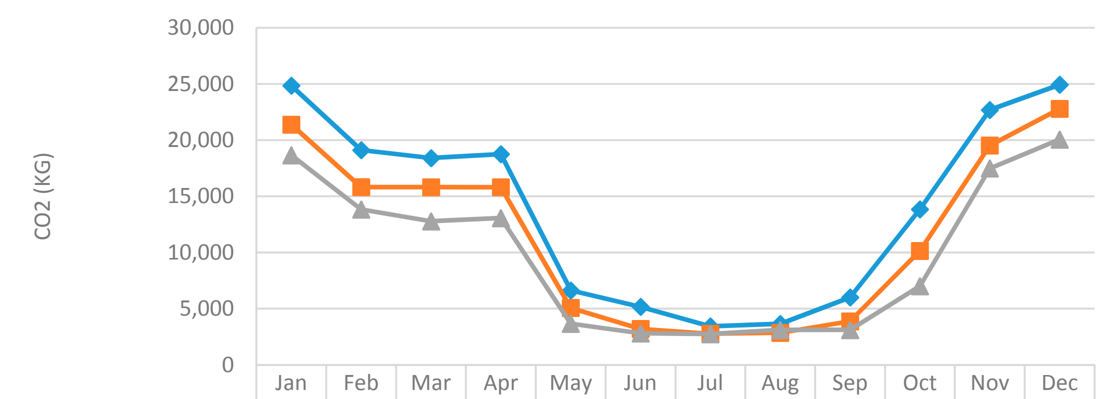
Figure 8. Cooling loads in the current, 2050, and 2080 time slices.

As Figure 8 shows, there is no requirement for active cooling devices in the present time for this case study, which shows the applied design solutions were successful in avoiding overheating risk inside the building. However, as temperatures increase in the future, there is a necessity for utilization of active cooling devices. Another factor that plays an important role in the building's overall energy consumption is the infiltration rate and ventilation strategies. For this case study, the infiltration rate has been set at 4 $m^3/h \times m^2$ @ Pa (the maximum rate is set at 10.00 $m^3/h \times m^2$ @ Pa for Part L regulations) and mechanical ventilation has also been considered, which appears to be a successful design strategy for the current summer months. [24]. In order to calculate cooling loads for 2050 and 2080, a mechanical cooling system with a COP of 4 is assumed to keep the operative temperature below 28 °C.

4.2. Carbon Emissions

Residential buildings are responsible for almost a quarter of the UK's CO_2 emissions. The 2008 Climate Change Act requires 1990 CO_2 emissions to be cut by 34% by 2020, as well as an 80% cut in emissions by 2050. It is not likely to meet the 2050 target without changing emissions from homes [25]. Therefore, the building regulations set out the Target Emission Rate (TER) as a minimum allowable standard (expressed in annual kg of CO_2 per m^2) for the building performance. The CO_2 emission rate of a building is measured on the basis of its actual specifications and is expressed as the Dwelling Emission Rate (DER) for residential buildings (excluding common areas). This is the annual CO_2 emissions of the proposed dwelling expressed in kg/m^2. A typical TER for new dwelling, on gas, is normally around 20–25 kg·CO_2/m^2 per year [26].

Figure 9 shows carbon emissions per month for the entire building. It shows that a warmer future climate will deliver lower carbon emissions, as was expected from considerable reductions in heating loads and a minor increase in cooling loads in the case study as a high-performance building. Carbon emissions also include the usage of lighting inside the building (specification is given in Table 1).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cardiff Present	24,845	19,110	18,403	18,747	6625	5163	3424	3647	6007	13,845	22,688	24,928
Cardiff 2050	21,378	15,815	15,810	15,804	5066	3201	2768	2853	3872	10,143	19,515	22,783
Cardiff 2080	18,656	13,829	12,773	13,059	3660	2809	2734	3105	3103	7007	17,481	20,050

Figure 9. CO_2 production in the current, 2050, and 2080 time slices.

As observed from Figure 9, a warmer future climate reduces carbon emissions of the studied building by almost 7000 Kg at maximum by 2080 compared to current time in the cold months. As the building benefits from a standard infiltration rate, no overheating risk exists in the current time, and by increasing the average temperature, the overall carbon emissions in July and August remain almost the same as the current time.

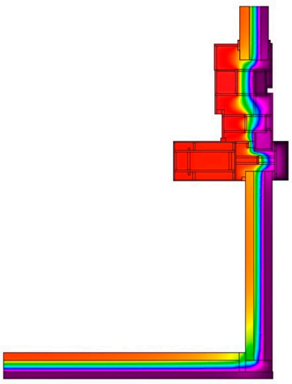
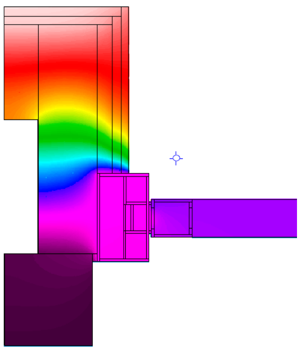
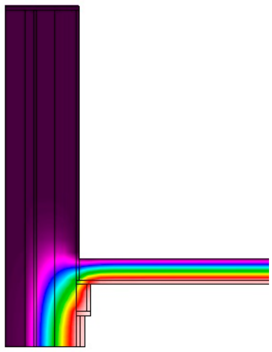
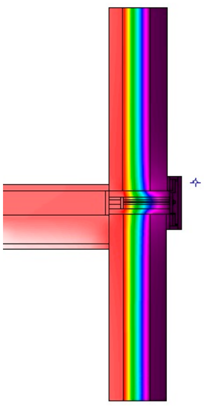
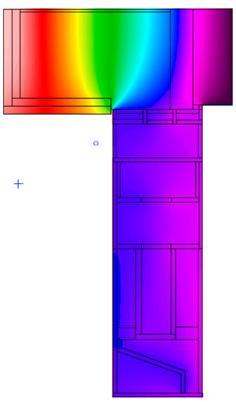
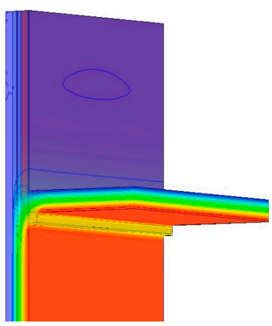
This result is comparable to Collins et al. [16] stating that the reduction in CO_2 emissions is expected by 2080 and heating loads remain dominant until 2080. The overall floor area of the case study is over 3756 m^2 and as the building exceeds the SAP requirements of DER, solar panels are used to meet regulations (the impact of PV panels are not included in the simulation results). The building used 13.6 kWp of solar panels in order to reduce CO_2 emissions.

4.3. Thermal Bridge Analysis

Further simulation works for the case study considered thermal bridge analysis. The analysis result is given in Table 2. Results are categorized into three columns for the decision-making process—junctions that are well-designed and no thermal bridge risk is identified, junctions where a thermal bridge is noticed, and junctions that are referred for further investigations.

For a parapet detail (right column), as the insulation for the wall is not brought above the underside of the roof deck, both 2D and 3D analysis were conducted and results confirm additional analysis is required for further in-situ diagnostic test by infrared camera for potential design refinement in future. For curtain walls fabricators considered thermal breaks and due to insufficient information from supplier on what materials are used as thermal breaks, thermal conductivity is assumed as 0.1 W/M °C for simulations. Figures in the left column confirm no further investigation is required for curtain walls used in the study as no thermal bridge is identified. One of the most frequent locations for thermal bridge risk is, mainly, at fenestration interfaces. Window-to-wall and door-to-wall interfaces create further challenges for energy considerations and condensation risk because of the positioning within the rest of the assembly. Figures in the middle column show thermal breaks used for doors and louvers of the project in the ground floor were unable to entirely remove the thermal bridge risk. However, this was an ignorable junction for the project because the location was not directly connected to the residential space.

Table 2. Thermal bridge analysis with Therm and Psi Therm. From top to bottom: left column curtain walls; middle column: wall-to-door and louver; and right column: Parapet 2D and 3D.

No Thermal Bridge	Thermal Bridge	Need Further Investigation
		
		

Dynamic thermal modelling accomplished in this study considered the model assuming there is no thermal bridging risk. However, further analysis reveals that such impact exists. Dynamic thermal modelling software determined the overall energy consumption of the case study on the basis of inputs on the U-values of various components.

THERM and Psi THERM are used to model the thermal bridging risk in this study and both utilise the finite-element method to model two- and three-dimensional heat-transfer problems. A thermal bridge is described by linear thermal transmittance (ψ_k) and length (l_k). Multiplying these two properties determines what thermal bridge adds to the overall transmission heat transfer coefficient of the building. The impact of the thermal bridge on the overall heat loss of the building is, therefore, a fraction of heat loss over the linear thermal bridges against the total transmission heat losses across the building envelope, this can be quantified as [27]:

$$H_t = \sum_{i=1}^{I} Ui + A_i + \sum_{k=1}^{K} \psi_k \times l_k$$

where H_t is overall transmission heat transfer coefficient of the building envelope; U_i is thermal transmittance; A_i is area which U_i applies (m^2); ψ is linear thermal transmittance of building junction k (W/mK); and l_k is where ψ applies.

This study, therefore, acknowledges the impact of thermal bridging on the overall energy consumption and carbon emissions and the intention of including such analysis was to address a holistic approach to assess building performance in the design development stage and before the translation of design details to construction details.

The quantification made by this study on the impact of climate change on overheating, increasing cooling loads, and carbon emissions implies the importance of such analysis by building developers. Furthermore, the importance of thermal bridging analysis in two- and three-dimensions to rectify design details before construction begins can have a significant impact on the building performance gap and make simulation outputs closer to the actual post-occupancy result even though the occupant factor can be referred to further studies.

5. Conclusions

This study describes a methodology on energy consumption, carbon emissions, and thermal bridge investigations in a changing climate. The worst-case scenario in climate change is chosen to evaluate heating and cooling loads, as well as carbon emissions of a 55-unit residential building in South Wales, UK. Further investigation also included thermal bridge analysis in order to avoid any unwanted heat loss during building operation. The model, which is resilient to the greatest change in future climate, is highly likely to be the most robust design. The temperature increase in the UK is likely to continue until 2080 and will have an effect on building performance and, consequently, on carbon emissions.

In Cardiff, an increase of up to two degrees (average dry bulb temperature) per month is expected which will cause a reduction in heating demand and prove overheating risks in the summer months in 2080, although the design strategies in fabric, infiltration rate, and mechanical ventilation used in the case study seem to be effective to control the loads even in 2050 and 2080. The case study shows no requirement for cooling loads in the present time even though over 1000 kWh is required to remove overheating in 2080 (assuming that a mechanical cooling system is used with a COP of 4). Carbon emissions reduction could be up to 7000 kg per month in cold months in 2080 compared to the present time and remains almost the same in summer months. Further 2D and 3D thermal bridge simulations demonstrate the capacity of the programs to rectify design details in order to avoid heat loss during building operation.

Considering the building regulations and the requirement to reduce carbon emissions, it seems that it is practical and economically feasible for building developers to reduce CO_2 emissions in order to meet the UK government target for 2050 by improving building fabric first and then using combinations of microgeneration.

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Conflicts of Interest: The authors declare no conflict of interest.

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