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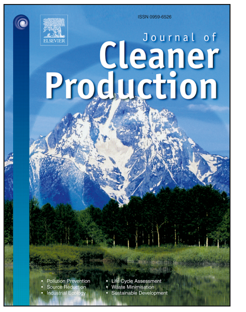

Energy effectiveness of passive cooling design strategies to reduce the impact of long-term heatwaves on occupants' thermal comfort in Europe: Climate change and mitigation

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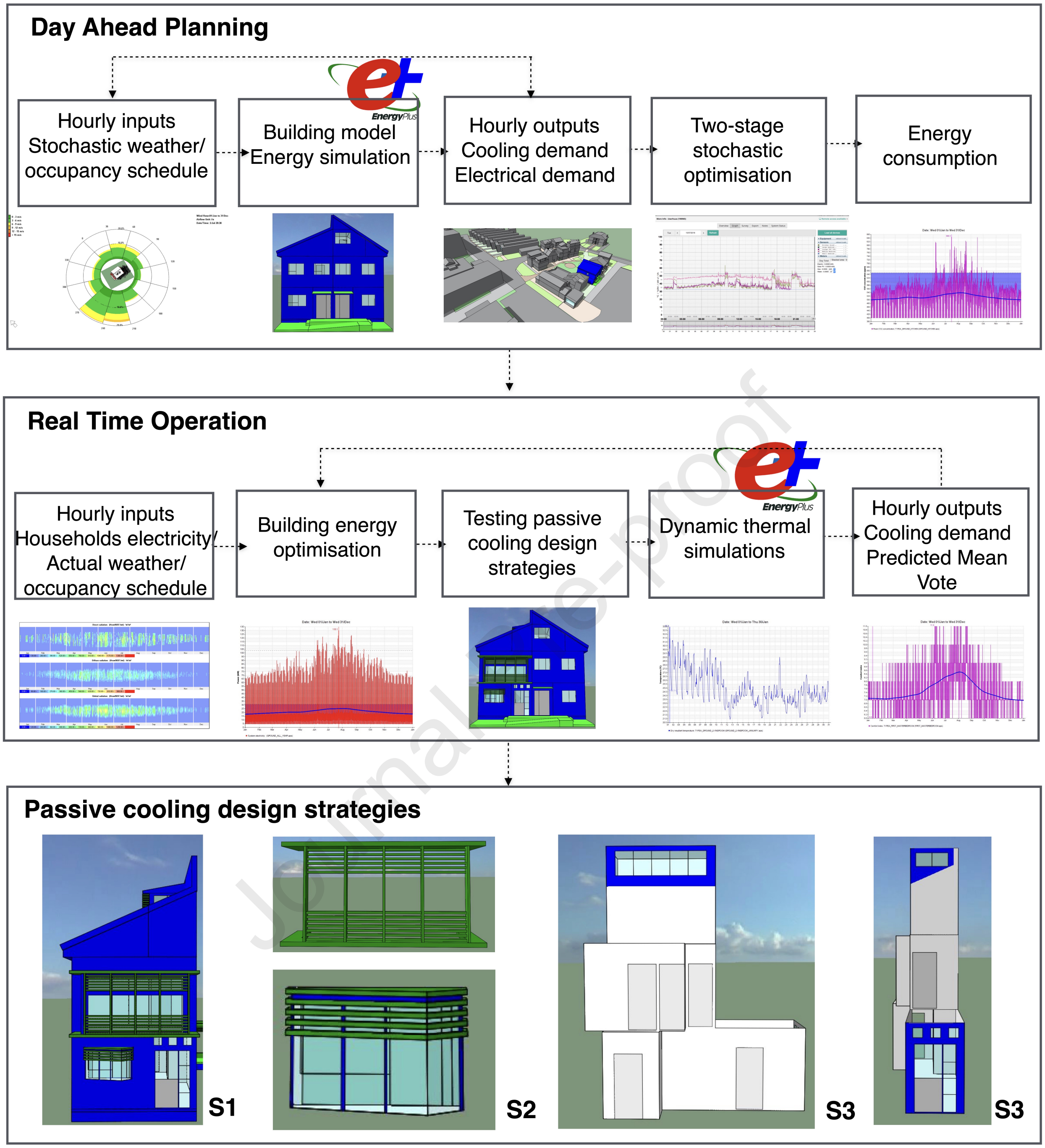

Day Ahead Planning
Hourly inputs
Stochastic weather/
occupancy schedule
Building model
Energy simulation
EnergyPlus
Hourly outputs
Cooling demand
Electrical demand
Two-stage
stochastic
optimisation
Energy
consumption
Real Time Operation
Hourly inputs
Households electricity/
Actual weather/
occupancy schedule
Building energy
optimisation
Testing passive
cooling design
strategies
EnergyPlus
Dynamic thermal
simulations
Hourly outputs
Cooling demand
Predicted Mean
Vote
Passive cooling design strategies
S1
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S3

Energy effectiveness of passive cooling design strategies to reduce the impact of long-term heatwaves on occupants' thermal comfort in Europe: Climate change and mitigation

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Review paper (19,784 words)

Abstract

Many newly built, energy-efficient terraced houses are characterised by high indoor air temperatures and thermal comfort issues, because these state-of-the-art houses were designed and built without considering the warming climate conditions in the summer. As a result, many of these residential buildings are at risk of overheating and require careful implementation of passive cooling design systems when retrofitting. This study reviews the overheating risk and energy effectiveness of six passive design strategies tested and implemented in an innovative terraced house located in southeast London during the long-term heatwaves experienced in both the UK and continental Europe in the summer of 2018. A quantitative research methodology is employed based on an extensive monitoring campaign conducted to measure environmental conditions, including indoor air temperature, relative humidity and CO_2 of each occupied space in a prototype base-case building. In the subsequent phase of the research, retrofit strategies were investigated by modelling and simulation using the Integrated Environmental Solutions (IES) software suite for data validation. The preliminary results of the modelling and simulation confirmed the survey findings of high levels of occupant discomfort and relatively high cooling loads. The internal operating temperatures of the simulated rooms remained high throughout the day and night during the long-term heatwaves, ranging from a minimum of 24.7 °C to a maximum of 32.1 °C. The results highlight significant deviations in the estimated energy consumption of the base-case building as well as in the energetic and environmental indexes of the passive cooling design strategies. The study will contribute to the strategic design of retrofit interventions to effectively reduce cooling energy consumption by considering occupants' thermal comfort, thermal adaptation and energy use.

Keywords: Building energy modelling; Energy use; Energy-efficiency; Overheating risk; Passive cooling design; Retrofit

Nomenclature

A	Area (m^2)
°C	Degrees Celsius
Clo	Insulation value of clothing
m	Mass (kg)
M	Mean
M	Thermal conductivity coefficient (kJ/m^2K)
m^2	Square meter
m^3	Cubic meter
met	Metabolic activity
N	Number of data
N_s	Number of total simulations
p	Significant level
T_a	Indoor-air temperature (°C)
T_{int}	Indoor-zone temperature (°C)
T_m	Mean air temperature (°C)
T_{max}	Maximum temperature (°C)
T_o	Outdoor-air temperature (°C)
$T_{o/u}$	Total over/underheating hours
T_{op}	Operative air temperature (°C)
T_{upp}	Upper limit of threshold temperature (°C)
U	Heat-loss coefficient (W/m^2K)
V	Wind speed (m/s)
W	Width (m)
W_s	Monthly average wind speed (m/s)

Abbreviations

.epw	EnergyPlus Weather (file format)
.gbxml	Green Building extensible markup language
.xml	Extensible markup language (file format)
A/C	Air conditioning
AMY	Actual meteorological year (weather file)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BEM	Building-energy modelling
BES	Building-energy simulation
BIM	Building-information modelling
BPE	Building-performance evaluation
BPS	Building-performance simulation
BS	British Standards
CEN	Comité Européen de Normalisation
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon dioxide
DBT	Dry-bulb temperature
DTS	Dynamic thermal simulation
EN	European Norm
EPBD	Energy Performance of Buildings Directives (standards)
EPC	Energy performance certificate
EU	European Union
GBS	Green Building Studio (Autodesk®)
GHG	Greenhouse gas
HSRS	Health and Safety Rating System
IES	Integrated Environmental Solutions (energy-simulation tool)
IPCC	Intergovernmental Panel on Climate Change
MET	Metabolic equivalent
nZEB	nearly zero energy building
NZEB	Net zero energy building

OT	Operative air temperature
PCDS	Passive cooling design strategies
PMV	Predicted mean vote
POE	Post-occupancy evaluation
PPD	Predicted percentage of dissatisfied
RH	Relative humidity
RHI	Relative-humidity index
SAP	Standard assessment procedure
SD	Standard deviation
SPSS	Statistical Package for Social Sciences (Version 25.0 software)
STS	Socio-technical systems
TMY	Typical meteorological year
TPV	Thermal-preference vote
TRY	Test reference year (weather file)
TSV	Thermal-sensation vote
UHI	Urban heat island (effect)

Superscripts/Subscripts

act	Actual
adj	Adjacent
air	Indoor air
amb	Ambient
av	Average
e	East (building envelope)
eff	Effective
eq	Equivalent
ext	External (ambient air temperature)
in	Indoor
int	Internal
min	Minimum value
max	Maximum value
n	North (building envelope)
opt	Optimal
ppm	Parts-per-million
rad	Radiation
sim	Simulation
t	Top
tot	Total
w	West (building envelope)

Greek Symbols

Δ	Difference, variation
ΔT	Time step(s)
β	Energy performance coefficient
μ	Mean value
θ	Opening/closing windows and doors (°)
ρ	Air density (m^3/kg)
ω	Weight of objective function

1. Introduction

Retrofitting existing residential buildings has been gaining increased momentum, particularly in the UK since its government established the goal of zero emission by 2050 (Iuorio, 2018; Lomas et al., 2021). The emerging issue of climate change and the increasing energy consumption of cities suggest that buildings' thermal performance should be optimised to avoid high energy bills in winter (International Energy Agency [IEA], 2015). The number of households has increased by 46% since 1970, and this trend has continued in the following decades (Gupta & Gregg, 2016). The domestic building sector's heating and cooking are responsible for more than 15% of overall carbon dioxide (CO_2) emissions in the UK, and this sector experienced a 3.6% increase in energy consumption from 2015 to 2016 (Kaveh et al., 2018; Gupta et al., 2019). Household energy consumption is generally from cooking, cooling and lighting (Julien, 2013). However, existing buildings can lower energy consumption by introducing energy-efficient technologies and passive design systems are successfully oriented when retrofitting (Gupta & Gregg, 2012; Serghides et al., 2016; Tatarestaghi, Ismail & Ishak, 2018). These effective solutions result in more environmentally friendly living and provide a significant reduction in energy bills in the residential sector (Murtagh et al., 2016).

Energy security is receiving increasing attention in academic and governmental circles in the UK due to reduced fossil fuel reserves in the North Sea, the closure of several power stations and the increasing frequency of severe weather (Pathan et al., 2017; Peacock et al., 2010). Many of the strategies that currently address energy security in the UK are directed towards the provision side of the energy chain or automated demand-side peak load reduction (Psomas et al., 2016). Measures and policies aimed at rapidly reducing energy use through changes in behaviour are discussed to a lesser extent (Verbeeck & Hens, 2005; Williams et al., 2013). At the same time, the UK government identified the residential sector as one of the most cost-effective sectors able to significantly reduce greenhouse gas emissions (Gupta, 2009; Schwartz et al., 2018). The high retrofit potential of existing housing stock is increased by the steadily improving technological innovations in this field. The UK's government has also set a number of very ambitious targets to reach in the near future. For example, according to the government's proposal, greenhouse gas emissions in existing residential buildings need to be reduced by 30% by 2030 (Pajek & Košir, 2021).

Furthermore, the government is committed to achieving zero carbon buildings on all new developments by 2030 and near zero carbon emissions from all existing buildings by 2050 (Fokaides et al., 2017; Chastas et al., 2018). These targets are likely achievable; however, approaches to these issues vary. There are 27 million existing dwellings in the UK, and 80% of this building stock is expected to still be in use in 2050. In contrast, only 120,000 new homes are built every year (Gupta & Gregg, 2018). Therefore, implementing systemic retrofit interventions plays a key role in reducing CO_2 emissions, particularly in metropolitan cities, such as London, where residential buildings contribute 36% of total carbon emissions (Gouveia et al., 2018). Therefore, enhancing energy efficiency in existing building stock is an inevitable and necessary step towards the UK's energy consumption reduction goals (Kearns et al., 2019). However, the UK government's previous 2016 carbon emission targets for domestic buildings were arguably made less stringent partially as a result of the policy of encouraging much-needed holistic retrofit schemes by reducing performance requirements on developers, which were seen as burdensome (Kalisa et al., 2018). Therefore, building envelopes did not consist of appropriate building materials that would retain heat and provide thermal comfort for the occupants without redundant energy consumption (Gupta et al., 2018). Here, it is important to note that the first radical revision of thermal standards was dated in 1976, just after the UK's energy crisis in the early 1970s (Salem et al., 2018). For the first time, the government had to put limitations on energy consumption, which meant improvements in building components' *U*-values. It is also important to remember that the changes from the 1965 standards to the 1976 standards were the first step towards energy efficiency in the residential sector (Brown et al., 2019). The IEA has published guidelines on implementing rapid electricity use curtailment (Aragon et al., 2018; Crawley, 2008), and studies have examined the significant impact of thermal properties of buildings during the long-term heatwaves frequently experienced in the summer due to climate change (Etxebarria-Mallea et al, 2021; Liu et al., 2021; Natarajan & Levermore, 2007a, 2007b). However, it has been stressed that these measures have never been assessed in the context of an overheating risk experienced in newly built housing stock (Beizaee et al., 2013; Berardi & Jafarpur, 2020). This means that, since the 1976 building regulations, these standards have been regularly updated and improved; therefore, the current 2015 *U*-value limits of thermal properties of residential buildings are considerably lower than the original ones (Brown, 2018). This is due to constant technological innovations and the need for constraints on rapidly growing, large cities' excessive energy consumption requirements (Mavrigiannaki et al., 2021).

Global energy issues are becoming more highly prioritized since the emerging realisation that the planet's resources are limited; therefore, there is now an understanding that the current level of energy use cannot be sustained in the future (Berardi, 2017; Jankovic, 2019). It is deemed an urgent concern by the local initiatives and non-governmental organisations (NGOs) that the 2016 values are considerably better than the standards set in 1976; however, these constraints only apply to new buildings and lack clarity regarding the implementation processes for existing buildings that require systemic retrofit interventions (Rodrigues et al., 2018). This study examines this socio-technical system approach in more depth but focuses on the energy effectiveness of passive cooling design strategies with respect to retrofitting efforts to concurrently reduce energy consumption and optimise occupants' thermal comfort. The main objective of this study is to develop appropriately tailored approaches for effective holistic retrofitting scenarios in policymaking decisions related to domestic energy use and occupants' thermal comfort.

The study's objectives are threefold. The first objective is to evaluate the current thermal comfort and energy performance of the prototype base-case building under investigation. To accomplish this, energy-efficient terraced houses were identified as a base-case scenario development since such structures represent the most commonly built housing typology and building construction materials considered in this study. The second objective is to evaluate the CO_2 levels of each occupied space to provide a basis for the subsequent research phase. The third objective is to develop and test the applicability of various passive cooling design strategies as potential retrofit approaches to the terraced housing typology to achieve improved thermal comfort and a reduced cooling energy load in the summer. An additional goal is to learn how passive design strategies can contribute to the retrofitting of existing residential buildings and can optimise the indoor comfort level of occupied spaces to combat exacerbated heatwaves in the summer. Further, related to the first phase findings of this research, another aim is to find an alternative applicability of the implementation of passive design strategies, which considers the geographic location, climate and shading effects from adjacent buildings in the Building Research Establishment (BRE) Innovation Park site. Figure 1 demonstrates the step-by-step development of methodological workflow developed for the study.

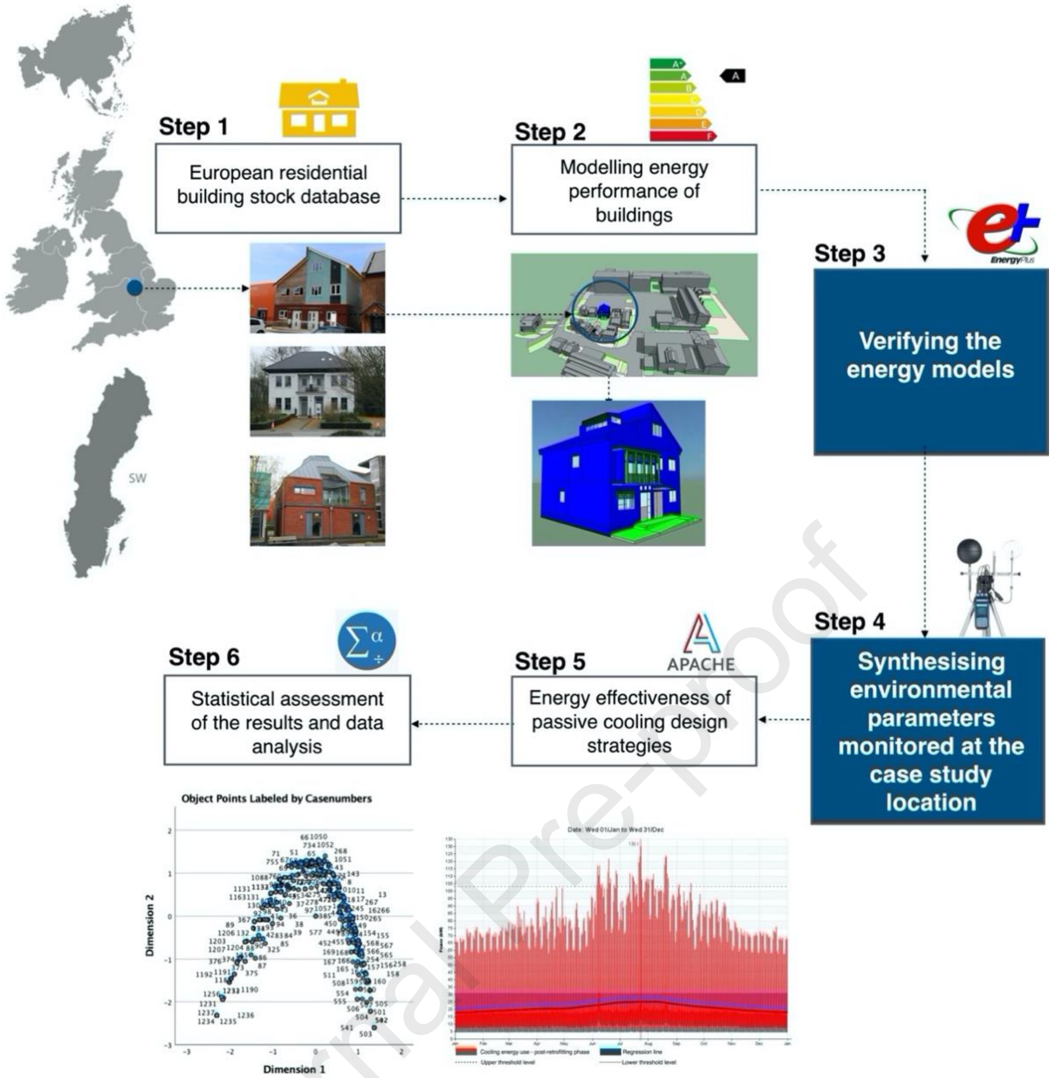


Fig.1. Conceptualisation stages of this review article. ***Image Credits:*** The flow diagram was conceptualised by the author; the images were designed in Integrated Environmental Solutions (IES) and SPSS software suites, and the images of representative buildings were taken by the author on courtesy of the Building Research Establishment.

This review paper discusses six alternative passive design systems as solutions to reduce overheating, particularly in the summer. These passive design systems show that natural ventilation systems, appropriate shading devices and fenestration designs can improve both the energy performance of a house and the occupants' thermal comfort during climate change (Congedo et al., 2020). These designs have more self-sufficient design guidelines for retrofitting this type of dwelling versus using state-of-the-art technologies and building materials (Berardi & Sprengard, 2020). Furthermore, the design approach of these systems promotes the revival applicability of effective passive cooling systems in retrofitting across the UK and other regions with similar construction practises and climates. A review of the literature on both state-of-the-art energy-efficient building systems and passive cooling design strategies is provided in the Sections between 1.1 and 1.4. The paper will first present the background of the research, followed by a literature review on current energy efficient building systems, the implementation of passive cooling design systems and criteria for assessing the risk of overheating in residential buildings. The background and literature review are followed by sections on the research methodology and results of our environmental monitoring and energy modelling simulations to provide a framework on identifying the energy effectiveness of retrofit interventions.

1.1. Energy efficient building systems in building retrofitting

Gupta and Gregg (2018) noted that, by improving occupants' thermal comfort in their homes in the winter, a number of energy efficiency measures can be implemented without using more energy to heat each indoor occupied space (e.g., thick external wall insulation, vacuum insulated panels implemented on the deficient building envelopes). These measures can vary due to building codes, regulations and the climate conditions of construction areas. Therefore, after a thorough building survey to diagnose any building envelope deficiencies, a comprehensive research method can be set up (Trotta, 2018). An effective survey method should identify issues such as cold bridges, dampness, condensation and excessive air infiltration (Gupta & Gregg, 2016; Costantino et al., 2021). These thermal anomalies generally indicate that the building is not airtight or lacks appropriate thermal insulation; some building parts might also be poorly detailed. As mentioned in section 1, systemic retrofit design strategies that are cost-effective and do not cause major intervention in the building need to be implemented. These range from draught seals around doors and windows to a more efficient heating system with smart thermostats (Tokede et al., 2018).

Gupta and Gregg (2018) also pointed out that one of the most common retrofit strategies to improve internal temperature is to inject a layer of insulation into the existing cavity of the external walls, then add 25 mm plywood and finish it with plaster boards from the inside of the property. However, in some cases, such as the prototype base-case building under investigation, the cavity injection method is not appropriate because there is no cavity insulation material amongst the steel frame skeleton, existing insulation and timber cladding (Mata et al., 2018). Therefore, another method, such as external wall insulation, is likely to be used (Jandaghian & Berardi, 2020a). This method has a number of benefits, including insulation efficiency, low price, light weight, and high installation speed and buildability (Calderon et al., 2018). Glazed areas have the lowest thermal performance in terms of thermal transmittance in the building envelope (Gillich, 2019).

UK building regulations have resulted in a vast improvement to windows' and doors' *U*-values in the past few decades. However, these openings still play a key role in overall heat loss through building fabrics (Papadopoulos et al., 2018). It should be noted that low *U-values* of glazed window's thermal properties require special attention when retrofitting residential buildings (Berardi, 2019; Roque, Vicente & Almeida, 2021). The reason is that a window system comprises three parts: the central pane, frame and window edge, including the edge effect. It is important to note that the more interactions that occur between the glass pane and the dividers, the less efficiently the window performs (Ben & Steemers, 2018).

In line with the review of energy-efficient retrofit strategies, this work attempts to evaluate whether rapid energy savings and optimisation of indoor air temperatures could effectively mitigate the warming climate in the UK, using the terraced house typology as a case study. It also seeks to identify which passive cooling strategies would be the most effective. This exploratory case study is innovative in two ways. It is the first published research to examine the revival applicability of passive cooling design strategies for building retrofitting. It also quantifies the impact of energy-saving actions on UK households, an area in which little research has been undertaken.

1.2. Passive design principles in building retrofitting

In a recent and relevant study, Lowe et al. (2018) investigated occupants' motivation to protect their residential building stock from climate-related overheating. Lowe's et al (2018) research revealed an unintended consequence: occupants assumed that retrofit measures, including implementing energy-efficient building systems, would lead to an increase in indoor air temperature and indoor overheating in summer months (Jones et al., 2017; Parker, 2021; Santamouris et al., 2010). Simultaneously, the measurements obtained in the study show that, in retrofit scenarios with night-only cooling and shading, the internal air temperatures remain above 25 °C for the majority of the time that the flats are occupied (Lowe et al., 2018). Schwartz et al. (2018) stressed that building orientation is a key element that must be considered thoroughly by the designer, as it can have a significant influence on the overall sustainability assessment of residential buildings. This can constitute an impediment in the use of passive design, resulting in a greater need for mechanical cooling and heating systems (Santamouris & Kolokotsa, 2013, 2015). Research has shown that the impact of high-rise surrounded buildings can be detrimental for the passive design outcome of a scheme, influencing solar gain, natural ventilation and, ultimately, the overall thermal efficiency of a building (Ferrari & Zanotto, 2009; Santamouris, 2016).

Several UK construction industry reports have documented that, in recent years, passive solar design principles in architecture have gained considerable popularity because it is seen as a valid way to address problems related to CO_2 emission and global temperature rise in construction (Tweed et al., 2014; Williams et al., 2013). Although passive design has great potential, it is very sensitive to the layout of the site in relation to the surrounding buildings (Dixon et al., 2018; Jandaghian & Berardi, 2020b). It is important to realise that the main drive and key to success when applying passive design principles is to take into account not only the building as a standalone structure but also the context and network of buildings in which the analysed space fits into the local climatic conditions of the construction site (Forman, 2015; Gangolells et al., 2012; Griffiths, 1990).

Notably, global, European and national policy decisions in recent years have increased the pressure to significantly reduce energy consumption and, in particular, the associated carbon emissions (Fitton, 2016). Therefore, in an urban context, passive shading systems have a significant impact on the energy demand of a space since they directly affect the need for light and mechanical temperature increases (Philokyprou et al., 2017; Porritt et al., 2013). To obtain the full benefit from structural thermal mass, it is very important that solar gains have access to the thermal mass. Coupled with this, the rapidly growing housing demand and effects on occupants' thermal comfort in relation to the implementation of passive design principles in retrofitting processes have been matters of concern and have led to relevant government initiatives for improving the thermal efficiency of residential buildings in the past decades (Ferdyn-Grygierek et al., 2021). To address this issue, the interrelation of buildings within the building network has already been discussed by Santamouris et al. (2013), who pointed out the necessity of considering the energy effectiveness of passive cooling design strategies in a building's retrofitting when assessing the building's energy performance. At the same time, many studies have been done in recent years in the field of sustainable architecture, focusing on the relationship between buildings and their local climate conditions. For example, Ozarisoy and Altan (2018) developed a computer-aided design plug used to assess the efficiency of passive measures on a building's thermal performance.

Ferraro and Zanatto (2009) further argued that passive design principles are not the only alternative options able to bring a major change to the microclimate of an occupied space. Additionally, Pisello et al. (2014) proved that reflections caused by surrounding buildings can have a major impact on the occupants' thermal satisfaction to the space. This may indicate that the shading effect, as well as influencing the thermal comfort of a space, has a direct effect on the need for cooling in the summer. Serghides et al. (2016) have, in fact, advocated that existing social housing stock in south-eastern Europe has cooling load up to 20% higher than other areas as a direct effect of high solar radiation in August. As such, some of these studies have indicated that the distance between buildings within the urban heat island (UHI) effect has a major impact on the amount of solar gain through external windows and, hence, needs to be appropriately considered when designing effective solar shading systems during the decision-making process of retrofit interventions in the residential sector (BRE, 2007; Pretlove & Kade, 2016; Sunnika-Blank & Galvin, 2012).

Reducing energy consumption and carbon emissions in housing design requires a holistic system approach, while passive design, which modifies the external climate to improve the energy performance of a building, is the foundation of this system's approach (Tatarestaghi et al., 2018). One of the main reasons this empirical study was devised in accordance with the field surveys, statistical analysis and building performance evaluation tools is that Tatarestaghi's published research project was predominantly based on assessing energy performance and occupants' thermal comfort using a prototype of a vernacular building layout in a tropical climate. Therefore, in this study, the findings highlight that the selection of energy simulation tools is important in the decision-making process of retrofit interventions in the residential sector. For that reason, this study explicitly discusses how different simulation parameters could provide significant empirical analysis on assessing the overheating risk and subsequent information for the delivery of effective retrofit interventions in south-eastern England.

In summary, passive design strategies can reduce heating and cooling demands, leading to opportunities to integrate more efficient building systems with a lower capacity throughout the year (Zahiri & Altan, 2016). This is the reason why this study explored the impact of passive design strategies on the energy performance of innovative terraced house designs in the UK. In this study, a prototype terrace house with a modelling framework was developed as a base-case scenario development. A series of building energy simulations were conducted with local climate and environmental monitoring data to evaluate the impact of a range of passive design strategies. We determined the impact of each passive design strategy on the reduction of energy consumption. These findings are discussed in Section 5.

1.3. Assessing the risk of overheating and adaptive thermal comfort

The adaptive approach is currently implemented in the main international standards, including in both the American Society of Heating, Refrigerating, & Air-Conditioning Engineers (ASHRAE), concerning thermal comfort, and BS EN 15251: Indoor environmental input parameters for the design and assessment of the energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics (ASHRAE-55, 2017; British Standards Institution, 2007; Crawley, 2008). Therefore, it is usually considered an assessment method for the summer performance of unconditioned buildings. It is worth noting that, following the work of Humphreys in the 1970s, in parallel with de Dear and Brager and many others, there has been an increasing realisation that the Predicted Mean Vote (PMV) model is not appropriate (de Dear & Brager, 1998; Humphreys & Nicol, 2003). This is especially valid in naturally ventilated buildings that are in free-running mode, including heated or cooled seasons (de Dear, 2011; Humphreys, 1979, 2005; Balvedi et al., 2018). This has led to new formulations for various standards throughout the European Committee of Standardization (CEN) and the British Standardisation of BS EN 15251, which includes 'adaptive' temperature limits for naturally ventilated or free-running buildings (British Standards Institution, 2007).

It is desirable that the International Standards Organization's (ISO) standard be concerned with indoor environments and that BS EN ISO 7730 also be an applicable benchmark to measure daytime ventilation in buildings (British Standards Institution, 2007). According to BS EN ISO 7730, it essentially provides a means to calculate both the PMV and the Predicted People Discomfort (PPD) indices, together with information for estimating some localised effects, such as shading. Independently, the Chartered Institution of Building Services Engineers' (CIBSE) Overheating Task Force has decided that a new approach to the definition of overheating is necessary, particularly for buildings without mechanical cooling (CIBSE, 2017). The new definition will follow the methodology and recommendations of BS EN 15251 to determine whether an existing occupied building can be classified as overheated or if a proposed building is in danger of becoming overheated, particularly in summer (British Standards Institution, 2007). A pragmatic way of quantifying the effects of thermal comfort is defined in CIBSE TM 52 for new buildings; that is, major refurbishments and adaptation strategies should conform to Category II in BS EN 15251, as shown in Table 1 (British Standards Institution, 2007; CEN, 2007; CIBSE, 2017).

Table 1
Overheating assessment criteria

	Assessment Criteria	**Acceptable Deviations**
Criterion 1	Percentage of occupied hours during which ΔT (ΔT = Top-Tmax rounded to the nearest whole degree) is greater than or equal to 1 °C	Up to 3% of occupied hours
Criterion 2	Daily weighted exceedance (We) in any one day > 6 °C.h (degree hours)	0 days
Criterion 3	Maximum temperature level (Tup) ΔT > 4 °C	0 hours

This section presented a systematic review of the overheating risk in buildings and its negative impact on domestic energy use and thermal comfort. As we have learnt from this review, it is important to have a deep understanding of the thermal properties of buildings and their correlation with thermal comfort (Gupta et al., 2012; Mavrogianni et al., 2012; Ozarisoy & Altan, 2018). Recent studies have investigated the overheating risk in buildings, particularly in housing stock built under social housing schemes in the 1980s and early 1990s (Ozarisoy & Altan, 2021a, 2021b). As explicitly discussed throughout the literature review, overheating can be defined as the condition in which most occupants feel uncomfortable under specific environmental control variables recorded at one point in time (Artmann et al., 2008; Santamouris et al., 2007). Thus, this period is considered in terms of the percentage of total hours that a dwelling is occupied when assessing the risk of overheating for each occupied space (Lomas & Poritt, 2017; Figueroa-Lopez et al., 2021).

Additionally, this section also discussed the major benchmarking criteria being adopted to investigate the overheating risk in base-case terraced houses during August, the hottest summer month. The static CIBSE criteria and the dynamic adaptive comfort model have been widely used in the reviewed studies and were adopted as indicators for assessing the risk of overheating in the representative base-case buildings investigated in the study presented in this paper. Another method was suggested in the 2005 CIBSE Guide, the BS EN 13779: Ventilation for Buildings, which is an applicable performance requirement for ventilation and air-conditioning systems (Mavrogianni et al., 2014). These requirements also consider basic definitions of air quality standards in occupied spaces and relates these to the fresh air ventilation rates required for each occupant (CIBSE, 2015, 2016). Other studies have focused on assessing the performance of a passive design, which may require predicting airflow through the building (Gupta et al., 2012; Mavrogianni et al., 2017; Ozarisoy & Altan, 2018). However, this review paper presented a research gap in energy research that has not been addressed previously in similar studies.

2. Systematic literature review

This section details a comprehensive literature review of adaptive thermal comfort approaches developed by previous scholars to fulfil knowledge gap in energy research. The barriers to and motivation for the energy recovery plans to tackle the issues of on-going COVID-19 and its impact on households' energy use is also presented, followed by a systematic review of the literature related to the developed energy-policymaking framework and retrofitting schemes for existing housing stock that addresses current thermal-comfort design methods, overheating risks and building energy simulation procedures.

2.1. Feeling Indices: Predicted Mean Vote and Percentage of People Dissatisfied

Climate change cannot be separated from the development of energy-performance criteria, however. In *Stern Review: The Economics of Climate Change*, climate change was identified as a determinant factor for economies and the 'greatest example of market failure' (European Commission, 2019, p. 21). It has been suggested that there is a link between economic and environmental benefits; in fact, it could be argued that every kilowatt-hour of energy used in the residential sector leads to a greater need for the development of effective policies (Hardy & Glew, 2019). Ironically, when the world experiences more frequent long-term heatwaves in the future due to the detrimental effects of climate change, the average median demand for cooling energy will increase exponentially (Mavrogianni et al., 2012; O'Sullvian & Chisholm, 2020).

In 1970, Fanger published a paper in which he described the primary parameters to assess occupant thermal comfort when conducting longitudinal and transverse surveys in different climate regions (Fanger, 1970; 1973; Humphreys, 2005). The input of certain climatic parameters, such as air temperature, air velocity, mean radiant temperature and RH; along with personal factors that were previously described by Humphreys *et al.* (2002), such as age, gender, respondent activity level and clothing insulation can be used to predict thermal comfort. The use of these experimental parameters resulted in the most widely known attempt to accomplish the above assessment: the PMV model. The first serious discussions and analyses of occupant thermal-comfort assessments emerged in the 1970s by way of a series of experiments conducted by Fanger, who adopted a statistical evaluative approach to define adaptive thermal comfort approach. Table 2 delineates the literature review that was undertaken on field investigations of occupant thermal comfort in various climate zones.

Table 2

Field-investigation studies on adaptive thermal comfort.

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Main Findings
Tuck *et al.* (2019)	Kuala Lumpur, Malaysia	To conduct a comparative analysis of OTs recorded with predicted temperature using adaptive thermal-comfort equation in hot and humid climates	Two-storey corner terraced house selected for exploratory case-study approach. Field measurements conducted; weather station installed in front yard of case-study house; thermal recorders and hot-wire anemometer installed in each occupied space; CO_2 measurements recorded.	According to ASHRAE 55 standard, recorded air temperature was 1,8°C higher than the same parameter defined by EN 15251 and 0,9°C higher than the same parameter defined by ACE hot-humid.
Pastore and Andersen (2019)	Switzerland	To analyse the thermal performance of 'Minergie'-labelled buildings	Post-occupancy evaluation (POE) conducted on four Swiss green buildings with 'Minergie' label. POE protocol recruited for winter and summer; long-term environmental monitoring campaign recruited; in-situ measurements recorded; extensive online surveys undertaken to collect long-term occupant thermal-comfort options.	According to occupants, indoor conditions never attained commonly used 80% satisfaction threshold.
Nghana and Tariku (2016)	Burnaby and Vancouver, Canada	To demonstrate the energy effectiveness of implementing PCM onto apartment building envelopes to prove the thermal-comfort effect and energy consumption of mechanical system	Field experimental study conducted: - Two prototype buildings built on-site for experimental study: One had PCMs implemented on building envelopes, the other had no PCMs. - EnergyPlus software used for numeric validation; ASHRAE 62.2 requirements used as international assessment criterion	PCM decreased peak indoor-air temperature by as much as 0,6°C and increased trough temperature by 0,8°C.
Zhang *et al.* (2018)	Guangdong Province, Southern China	To demonstrate climate-design adaption of rural folk houses and the impact thereof on household thermal comfort in hot and humid climate	Yearlong thermal-comfort survey conducted: Eleven traditional folk-house residents selected for sample size. Questionnaire survey conducted concurrently with collection of in-situ measurements; ASHRAE 55 standard adopted to identify neutral thermal-comfort assessment; statistical analysis conducted with SPSS v22.0 software suite, and all differences at 0,05 level were accepted as significant.	Thermally neutral temperature was 0,6–1,3°C lower; upper limit of 80% acceptable temperature was decreased by 0,8–4,7°C in semi-open spaces.

Based on the criteria to assess occupant thermal comfort, Carlucci *et al.* (2018) recommended several threshold limits to define the PMV index. The ISO 7730 initially proposed three categories—A, B and C—but did not specify a concise scope. At the same time, the EN 15251 standard was outlined using the same value in three categories: PMV for Category A was in interval [-0,2, +0,2], Category B was in interval [-0,5, +0,5], and Category C was in interval [-0,7, +0,7]. Similarly, the assessment of thermal-comfort criteria or an acceptability range was selected on the basis of the thermal-comfort acceptability level that is required by the ASHRAE 55 standard (2017), as shown in Table 3.

Table 3
Examples of Data Types and Collection Methods for Thermal-Comfort

Category	Data types
Thermal comfort perception[1]	Sensation, preference, acceptability, pleasure
Personal factors	
Physiological	Skin temperature[2], heart rate[2], metabolic rate, clothing insulation Sex, age, body mass index, health status
Behavioral	Turning on/off fans or heater, thermostat adjustments, Opening/closing windows
Environmental factors	
Indoor[3]	Air temperature, mean radiant temperature, operative temperature Relative humidity, air velocity
Outdoor[4]	Air temperature, running mean temperature, humidity, perception Climate, season
Other factors[5]	Time, location, context, occupancy type, thermal history Cultural expectations (i.e., dress code), mechanical system settings (i.e., thermostat setpoints), availability of occupant controls

*Frequently used data collection methods include survey[1], wearable sensors[2], environment sensors[3], weather stations[4], building automation systems[5], etc.
Source: Nicol *et al.* (2012)

A consensus exists among scientists that the key selection of thermal-comfort criterion should be considered for actual and simulated indoor operative temperatures (OTs) (Borgeson & Brager, 2010; de Dear & Brager 2002; de Dear & Candido, 2012). This is because recorded indoor OTs must be included in the OT intervals, which are constituted by the offset of a certain number of degrees above and below the recommended theoretical comfort temperatures for the adaptive-comfort models that take the PMV assessment criterion into consideration (Yao *et al.*, 2009). Furthermore, the actual and predicted simulation parameters demonstrate that occupant-related parameters, such as the temperature ranges associated with clothing and metabolic activity, which are constituted by the offset of a certain PMV value that is above and below the thermally acceptable level of neutrality (i.e., PMV = 0) should be considered in a thermal-comfort evaluation based on for the model developed by Fanger (1970).

Surveys, such as those conducted by Nicol *et al.* (2012), reveal the importance of Fanger's work in terms of a methodological approach to conduct longitudinal and transverse surveys on thermal comfort in residential buildings; because of Fanger's efforts, a universally valid technique was devised to evaluate indoor environments. Nevertheless, several critics were opposed to the formulation of this procedure because of discrepancies between recorded outdoor-air temperatures and the simulated indoor-air temperatures that were found when assessing occupant thermal comfort.

2.2. Recovery plans for energy in European Union

The significant aspect of renovating a house relates less to energy savings than to the need for certain replacements and improvements to enhance comfort (Miu et al., 2018; Ascione et al., 2019). Previous survey data on upgrading building systems and reducing energy consumption in the residential sector primarily focused on individual technologies and did not consider occupant thermal comfort or effective energy savings through passive design elements (Pajek & Kosir, 2018). The lack of control mechanisms and the uncertainty brought about by the COVID-19 pandemic could create challenges in the decision-making process of implementing holistic retrofitting schemes in the residential sector (Gonzales & Nielsen, 2020). It must be stressed that indoor environmental conditions should be considered in relation to energy-efficiency objectives, which align with intergenerational occupants, rather than with the state of the buildings (Ascione et al., 2020; Rouleau & Gosselin, 2020). Figure 2 demonstrates schematic illustration of deterministic approaches undertaken to predict households' energy use for the development of energy-efficiency guidelines.

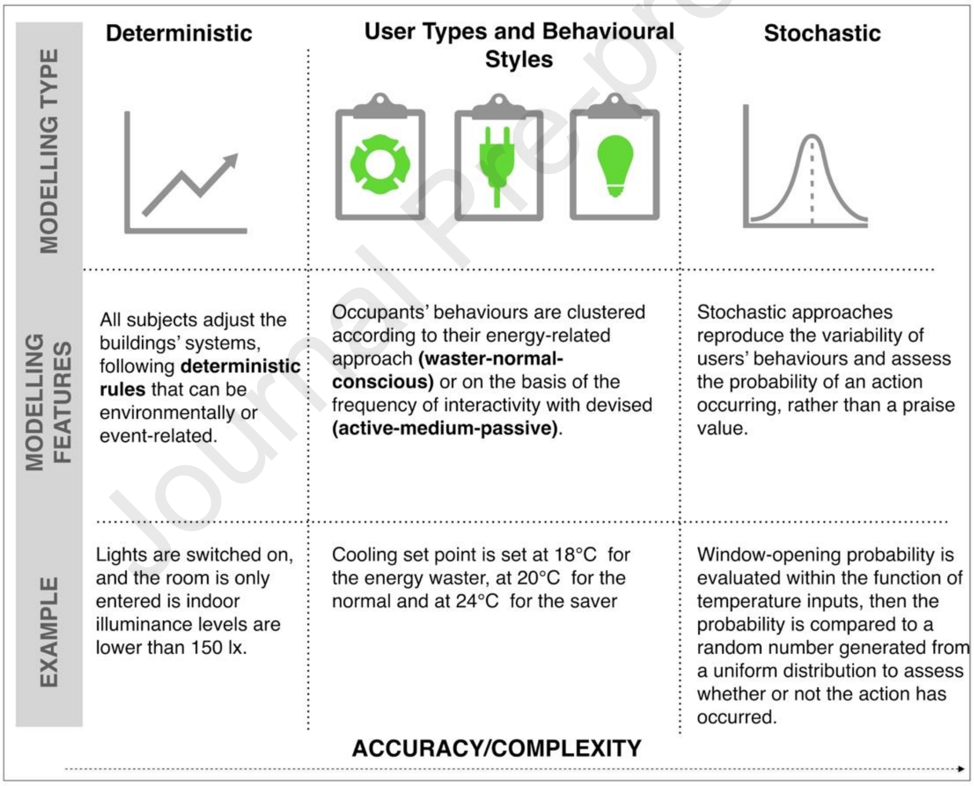


Fig. 2. Different approaches to model energy forecasting in the residential sector. ***Image Credit:*** Diagram was conceptualised by the author.

Regarding the current COVID-19 global health crisis, elderly individuals aged 65–85 years are in the at-risk group (World Health Organisation, 2020). Stringent measures and national lockdowns were put into place to minimise the spread of COVID-19 across the European continent (CIBSE COVID-19 Ventilation Guidance – Version 4, 2020; Faiella & Lavecchia, 2021); this resulted in increased occupancy hours in residential buildings and expanded domestic energy use. Studies to assess the performance of distributed energy resources in three low-energy dwellings during the UK lockdown period, which extended from March 23, 2020 to May 31, 2020, demonstrated that the combination of a solar Photovoltaic (PV) and battery reduced the average direct-grid consumption during peak hours by more than 95% (Gupta & Gregg, 2020). One pilot study also asserted that because the PV system installed for each dwelling was large at 4kWp, instantaneous self-consumption (SC), which ranged from 20–30%, was low; this study also found that energy-storage batteries increased SC by as much as 50%, which resulted in an 80% reduction in net total energy consumption over four months, even though the occupants in two of the dwellings claimed to be 'always at home' (Gupta & Gregg, 2020).

Importantly, this study noted that even before the lockdown, there was a slight increase in electricity consumption for these two dwellings, and that there was a notable increase in the other prototype terraced house (Gupta & Gregg, 2020). In order to demonstrate the impact of warming climate conditions on domestic-energy use, this study reported that heating consumption did not reflect the same impact; this is possibly due to unseasonably warm weather during the COVID-19 lockdown period (Du et al., 2021).

The methodological framework developed for this study and the findings thereof provide a pathway to understand current problems with existing post-war social housing stock and residents' thermal satisfaction with their indoor environmental conditions (Flores-Larsen & Filippin, 2021). Due to the nationwide lockdown measures in several European countries (i.e., France, Netherlands, Germany) during the 2020–2021 winter period, households are more likely to experience CO_2 acclimatisation in their homes (AiCARR, 2021). As it relates to avoiding the spread of this disease within households, there was an absence of available guidelines for effective ventilation and increased awareness of energy conservation during the lockdowns (Ascione et al., 2021).

To date, several studies have highlighted a growing body of evidence that vulnerable households in cities are disproportionately exposed to high levels of indoor air pollution due to housing location and ambient outdoor levels of pollution; housing characteristics, such as ventilation properties and internal sources of pollution; occupant behaviour; time spent indoors; and underlying health conditions (Schweiker & Wagner, 2016; Murtagh et al., 2019). These studies emphasised the need to understand the drivers of these disparities in order to design effective holistic retrofitting interventions that will improve occupant health and well-being (Poel et al., 2007; Ortiz et al., 2020). As such, passive-cooling retrofitting design strategies that neither require additional energy consumption nor further contribute to the spread of COVID-19 within households must be prioritised; where appropriate, households in residential buildings should use domestic cooling appliances or Mechanical Ventilation Heat Recovery Systems (MVHRs) to create optimum thermal environment conditions (REHVA, 2020).

3. Methodology

This study aimed to identify the potential improvements in thermal comfort and reduced energy savings associated with passive design strategies through combinations of building fabric enhancement and appropriate shading and ventilation strategies. To ensure the systematic analysis of the key aims and objectives, this research adopted a quantitative research design, undertaking building performance evaluation using dynamic thermal modelling and simulation, validated by the monitoring of indoor and outdoor environmental parameters, including the temperatures, relative humidity and CO_2 levels of each occupied space in a prototype base-case building (see **Graphical Abstract**). The investigation of the case study house modelled the energy performance of a state-of-the-art terraced house's energy demand for cooling and assessed occupants' thermal comfort during the long-term heatwave period, taking into account the effectiveness of passive design strategies (i.e. shading, ventilation) in retrofitting. The investigation also aimed to design a prototype terraced house as a climate-responsive building to improve energy efficiency using the monitoring data. To do this, six different passive design strategies were implemented in the retrofitting of this type of housing across the UK and similar climate characteristics in other European Union (EU) countries.

3.1. Technical specifications of the base-case prototype houses

The main design principle of a base-case prototype house is a volumetric unit; for example, a single unit comprised of a single bedroom apartment or a combination of units forming a two-, three- or four-bedroom house. Each unit is approximately 4.9 m wide by up to 11.4 m long, and they can be constructed into a single-storey unit, units of up to four stories in terraced, semi-detached, four-in-a-block apartments, or detached configurations (BRE, 2012). Each unit is built, serviced and finished, ready for occupation upon leaving the factory when it is transported via lorry to be laid on pre-prepared foundations, as shown in Figure 3 (a) and (b).

(a) (b)

Fig. 3. (a) The modular units are delivered to the site by lorries to reduce both the cost and time of the construction phase in the UK. **(b)** The modular units are assembled on site within 24 h, including fully fitted interior finishes. ***Image Credits:*** Tigh Grian Ltd (Scotland).

For this type of energy-efficient, state-of-the-art housing, factory production ensures high-quality, consistent construction and guarantees thermal and structural performance, particularly in the winter, to reduce the heating demands for vulnerable individuals in the UK's socially rented housing sector (BR 497:2007, 2007). Notably, each volumetric unit or combination of the units being designated as ready-for-occupation and reduced construction costs and time upon leaving the factory due to reduced on-site construction costs and sped-up construction time in remote project site locations, such as very densely built, urbanised areas or inaccessible rural project sites (Bribian et al., 2009). It is important to note that these innovative housing typologies use the Scottish Building Standard's Gold Level as its design benchmark, and the units are produced within the ISO 90001:2008-Quality Management Systems Standards and the ISO 14001:2004-Environmental Management Systems (EN ISO 10077-2:2012, 2012).

As previously mentioned, the units arrive on-site via lorry (Royal Institution of British Architects [RIBA], 2011). When the unit arrives, it is lifted onto a pre-prepared foundation with the service connections waiting. The units are secured onto the foundations and, in the case of two- to four-storey units, are fixed to each other (RIBA, 2013). The units are then site-tested to measure how airtight the buildings are before the occupants move into the property (McLeod & Hopfe, 2013). This initial operation takes no more than a few days, after which the units are sealed and external enveloping can commence (Construction Industry Council, 2007). The final testing takes place when the utility services are set up at a time closer to the occupation date (Langmans et al., 2010). The units come with all fixtures and connections necessary for external cladding and roofing, without the need to re-enter the building after occupation.

There is also the option to replace the tiled roof with a building integrated photovoltaic (BIPV) panel system (Feist et al., 2013). External cladding and roofing adhere to the local built environment and/or the local planning authority (HM Government, 2013). The units are designed to comply with the Housing for Varying Needs standards and the Stationary Office guideline specifications, which are indicated by the RIBA (Dengle & Swainson, 2012). The space standards compare favourably with the recommended space standards advised by the RIBA's' The Case for Space report, as shown in Table 4. It is important to note that the space and storage standards of the case study building under investigation exceeded those specified by the Scottish Building Standards.

Table 4

Recommended space standards from RIBA and the space standards implemented for the prototype base-case under investigation.

	RIBA Case for Space*	**Prototype base case**
1 bedroom/2-person	50 m^2	49.8 m^2
2 bedroom/4-person	83 m^2	86.9 m^2
3 bedroom/5-person	106 m^2	106.7 m^2

*The Case for Space, Royal Institute for British Architects, September 2011.

The volumetric units are set at a general maximum width of 4.8 m, which is just below the threshold for a transport permit or prior authorisation by the Department for Transport in the UK (McLeod et al., 2012). There is flexibility in the length, depending on customer specifications, and there is allowance for considerable space and specification determination. The enclosed space within the perimeter dimensions can accommodate a variety of floor plans. The current plans have been developed to ensure that the houses and development meet the Barrier Free Design objectives and are designed to meet the Scottish Homes Housing for Varying Needs standards (McLeod et al., 2012).

In this prototype base-case demonstration, the house's tiled roof was replaced with an entirely photovoltaic roof. This roof has been developed to generate electricity from renewable sources, and it represents a unique way of mounting high-performance, thin-film PV panels in roof colours, but without the usual frames and features commonly seen on roofs throughout Europe.

The demonstration roof can generate up to 5 kWh of electrical energy at the solar azimuth (DIN 4108-2:2013, 2013; BRE Global, 2014). In the demonstration prototype house, the prototype base-case house stores the energy in ion-lithium batteries, which, if this were an occupied house, would be available for use once the sun sets. It is worthwhile to note that the real value of this roof, with its energy capture option, is that it opens up possibilities for community energy schemes in order to promote the revival applicability of renewables in parallel with raising the awareness of households about energy saving. Figure 4 illustrates the renewable energy technologies installed on the roof surface and energy battery storage's location in the prototype house.

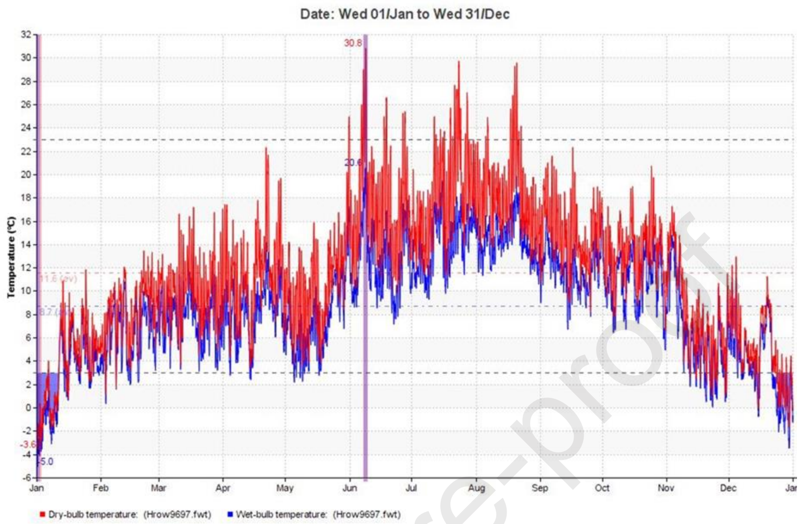
Fig. 4. (a) 3D rendering model of the prototype case study building. **(b)** The integration of terra-cotta photovoltaic panel systems on the south facing inclined roof surface. **(c)** The installation of energy batteries into the battery room which is located beneath the staircases in the case study building. **(d)** The installation of the photovoltaic generation meter to monitor the renewable energy stored.

Image credits: **(a*)*** the case study building was re-modelled by the author using the Autodesk® Revit® software suite. **(b)** the photovoltaic panels were developed by the Userhuus AG (Switzerland). **(c)-(d)** The energy batteries were installed in collaboration with Tigh Grian Ltd (Scotland) and Building Research Establishment (England and Scotland) as part of the demonstration of show-houses at the BRE Innovation Park.

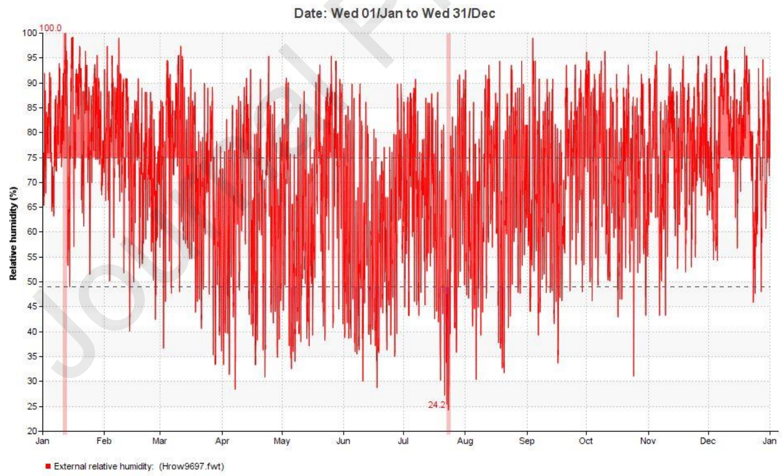
It has been stressed that the floor plans include a scope for future proofing, where practical, while the stairs are straight and open to allow a future staircase to be fitted. The floors are designed to sit directly on top of an insulated concrete ground floor slab, incorporating a low-pressure hot water (LPHW) under-floor heating system powered by roof-mounted solar panels via the Ecocent hot water and heat recovery system (McLeod et al., 2014). The walls are 150 mm thick structural insulated panels (SIPs) with an internal, air-reflective vapour barrier. Internally, they are battened out with 25 × 38 cm timbers to provide a services void and are then faced with Fermacell thin insulation board. Additionally, the external face has a low e-breather membrane that is applied before leaving the factory (McLeod et al., 2013). Notably, the ceiling cassette varies depending on whether the house is a single storey or two or more storeys. For example, the cassette could be comprised of a Fermacell internal finish, joists with Earthwool infill, chipboard decking and, in the case of the uppermost cassette, a wall plate with an ethylene propylene diene monomer (EPDM) waterproof membrane to ensure that the unit remains weatherproof until roofed (EN ISO 10211:2007, 2007). All external doors and windows are Secure by Design certificated (DIN EN 13947:2006, 2006). Ventilation is provided by a whole-house heat recovery ventilation system linked to an unvented integral air source heat pump and a direct hot water cylinder (BS EN 15643:2011, 2011). Heating is provided by wall-mounted electric panel heaters. They are thermostatically controlled with an illuminated temperature read-out and an extra heating override, should circumstance demand it (BS EN 15804:2012, 2012).

3.2. Climate and Research case study

The prototype base-case building investigated is adopted for both running extensive monitoring campaigns and undertaking dynamic thermal simulations in the temperate climate zone according to the Köppen-Geiger climate classification. Figure 5 (a) and (b) demonstrate the climate parameters of case study location in order to provide accurate information for the assessment of overheating and thermal comfort criterion in Sections 4 and 5.



(a)



(b)

Fig. 5. (a) Average hourly air temperature fluctuations of the study context. **(b)** Average relative humidity fluctuations. ***Image Credits:*** Fluctuation diagrams extracted from the Integrated Environmental Solutions (IES) software suite version 2021.1.0.

As shown in Figure 5 (a) and (b) the sub-type for this climate is (Cfb) – marine west coast climate (Kottek et al., 2006). The archetype house is located in Watford, in the southeast England, at the Building Research Establishment Innovation Park (latitude 51° 42’ N, longitude 0° 22’ W), as shown in Figure 6 and Figure 7 (a) and (b). The suburban district of Watford is situated 50 m above sea level, close to city of London. It is one of the suburban regions most affected by the urban heat island (UHI) effect, which has led to increased temperatures in the surrounding areas of London due to the subsequent effects of climate change.

Fig. 6. The national representativeness of archetype housing stock, geographical location of prototype case study house, climate characteristics and interior images of show-house located in the Innovation Park site in Watford, United Kingdom. ***Image credits:*** Interior images were taken by the author on courtesy of the Building Research Establishment; Climate diagrams were extracted from the IES software suite – version 2021.1.0.

(a) (b)

Fig. 7. (a) The prototype case study building – Userhuus (an energy-efficient Swedish housing prototype with photovoltaic solar panels on the roof surface) facing northeast – with the high albedo surface of the car park area at the BRE Innovation Park. The Victorian terraced house is located on the left and is currently used as a marketing office suite. The prototype Passivhaus building (an energy-efficient German housing prototype with thick insulation and brick external walls) on the right demonstrates exemplar innovative housing typologies. **(b)** The case study building facing the landscaped garden area with a southwest orientation at the prototype house's demonstration site. ***Image credits:*** Outdoor perspective images were taken by the author on courtesy of the Building Research Establishment.

In this innovative terraced house, the external walls of different thicknesses are made with lightweight panels and, in some cases, are insulated with expanded polystyrene (EPS); the finishing layer is either lime and gypsum plaster or composite external cladding. The slab on the ground has a concrete structure with 7.0 EPS for a global thickness of 39 cm. The other floor surfaces are made of pedalled elements with a thickness of 24 cm and are insulated. In order to evaluate the insulation level, the building is subjected to the standards required for undergoing systemic retrofitting (Phillips & Forman, 2018). Figure 8 (a) through (d) demonstrates the elevations of archetype house with the articulation of different innovative construction materials installed on the external wall surfaces.

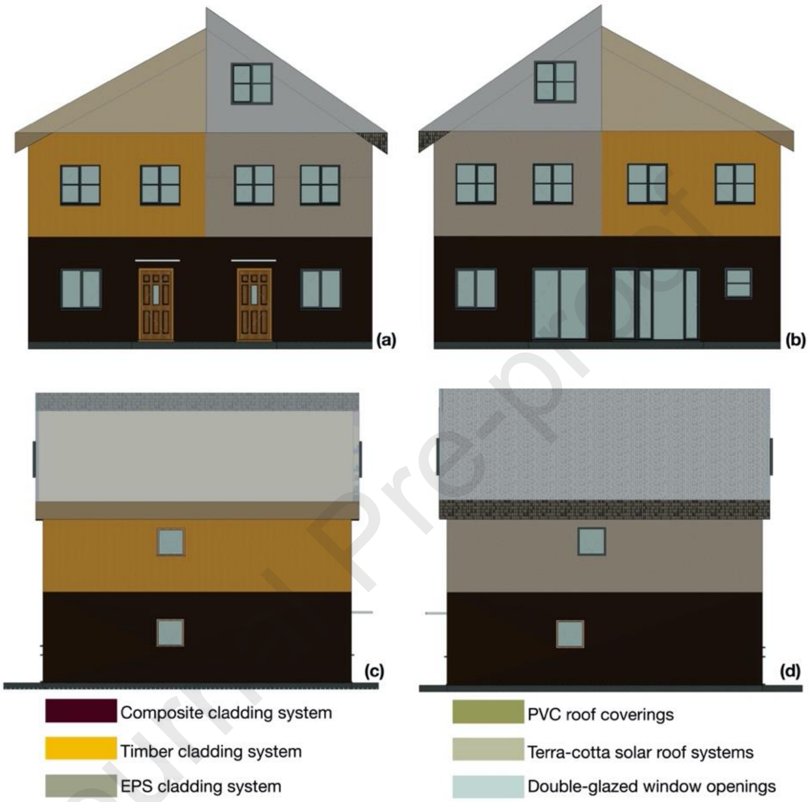


Fig. 8. 3D Renderings of elevations: **(a)** south-east facing front view; **(b)** west facing back view; **(c)** south-west facing side view; **(d)** north facing side view. ***Image credits:*** 3D renderings were modelled by the author using the Autodesk® Revit® software suite.

According to the Standard Assessment Procedure (SAP) criteria recommended by the government for assessing and comparing the energy and environmental performance of residential buildings, the value of the thermal transmittance of building envelopes should be less than 0.26 W/m^2K or 0.29 W/m^2K for roof surfaces (International Organisation for Standardisation, 2006b). Thus, in its present state, the prototype base-case building is more insulated than the existing terraced houses built in the UK (Ren & Sunikka-Blank, 2019). One of the main reasons is that this innovative housing typology was designed to reduce heating consumption, rather than considering the detrimental changes of climate and its impact on indoor air temperature fluctuations in the summer. It is worth mentioning that periodic thermal transmittance does not always demonstrate the limits set by the regulations; consequently, the opaque envelope does not prevent overheating during long-term heat peaks in the summer (Figueiredo et al., 2018). Notably, the building provides a representation of an average three-bedroom property in the UK, which was built for social housing purposes by the developer (British Property Federation, 2013). Figure 9 (a) demonstrates the ground floor plan layout of the prototype house.

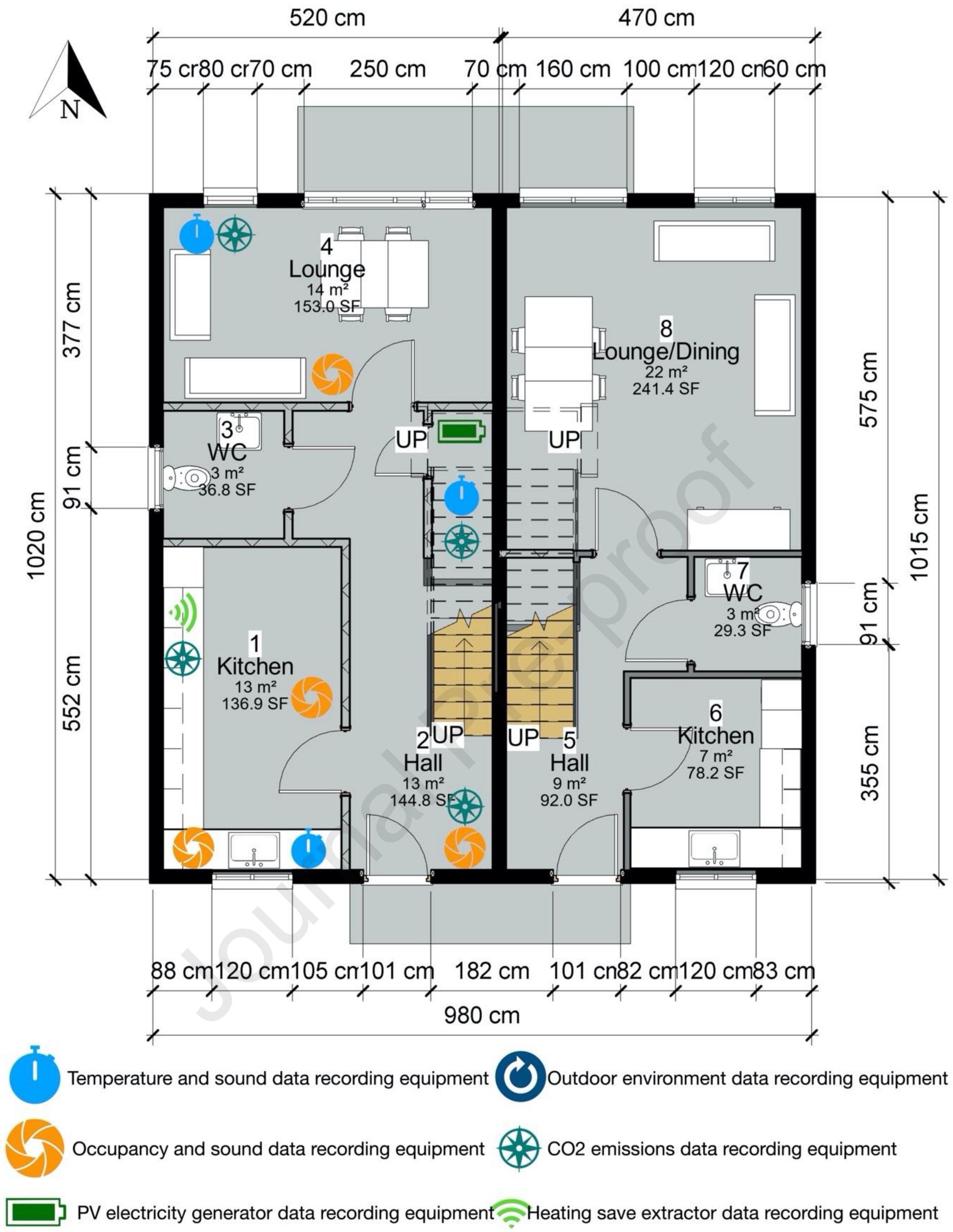


Fig. 9. (a) The floorplan of ground floor area of the base-case prototype house, including the monitoring equipment installed in the property. ***Image credit:*** Floor plan layout was modelled by the author using the Autodesk® Revit® software suite.

The geometric characteristics of the case study building were taken from documents made available by the technical office of the Building Research Academy, and these were verified in the field. The building has a rectangular floor plan with the floor plan dimensions of 4.6 m and 9.8 m. It is composed of two floors. Additionally, there is a cold roof space designated as an attic. The net height of all rooms is 2.60 m. The net conditioned area is 86.9 m^2, and there are three bedrooms with a mean surface area of 9.50 m^2. The global window-to-wall ratio (WWR) is equal to 30%

(International Organisation for Standardisation, 2006a). Notably, the main characteristics of the building envelope have been found in previous studies aimed at energy labelling. However, these have been verified by means of non-intrusive diagnostic techniques, such as infrared thermography and *in-situ* measurements of thermal transmittance. Figure 9 (b) demonstrates the first-floor plan layout of the prototype house and Figure 9 (c) illustrates the section drawings of case study building to demonstrate the construction details and building components.

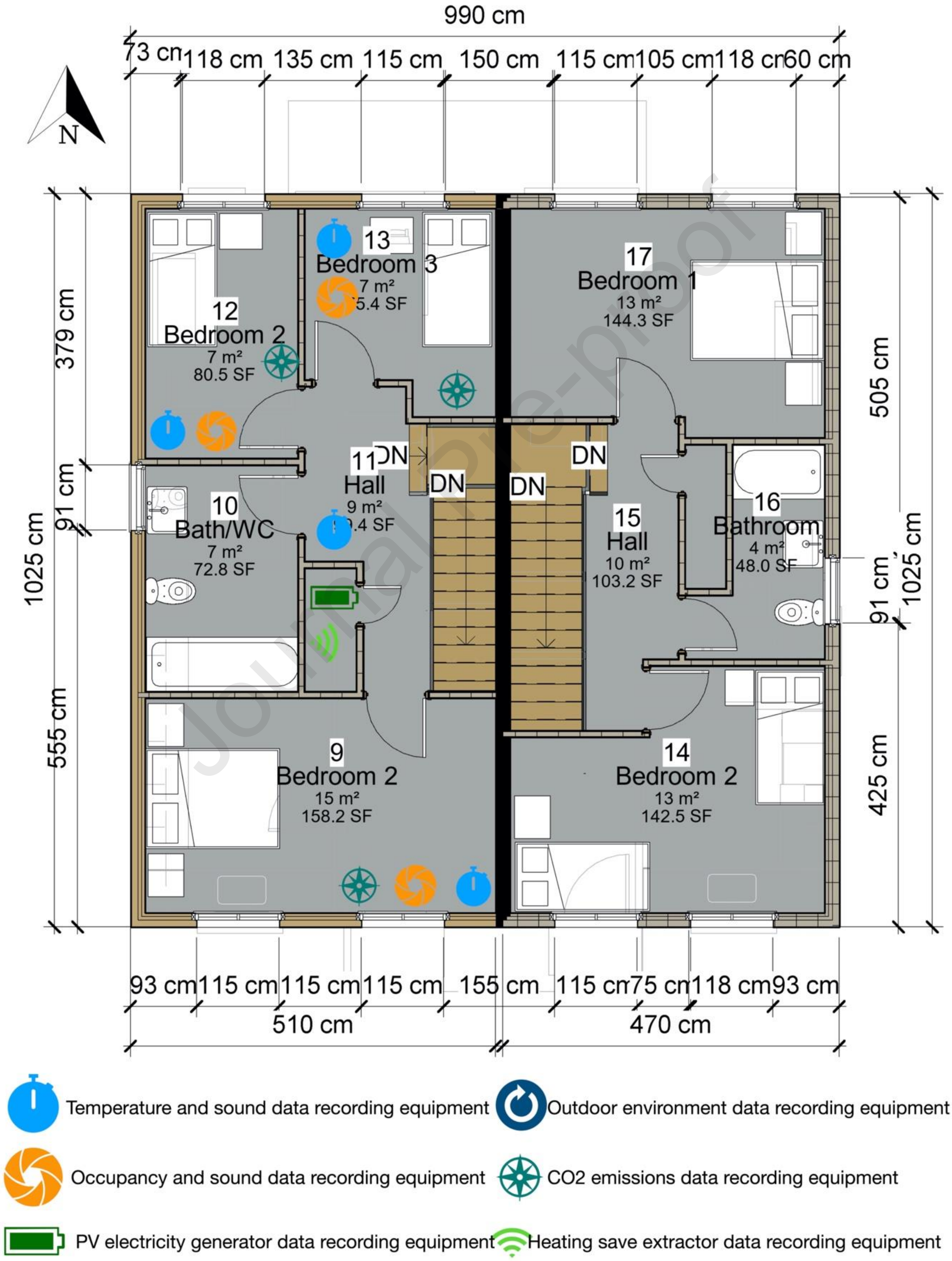


Fig. 9. (b) The typical floor plan of the first-floor level of the terraced house for base-case scenario development. ***Image credit:*** Floor plan layout was modelled by the author using the Autodesk® Revit® software suite.

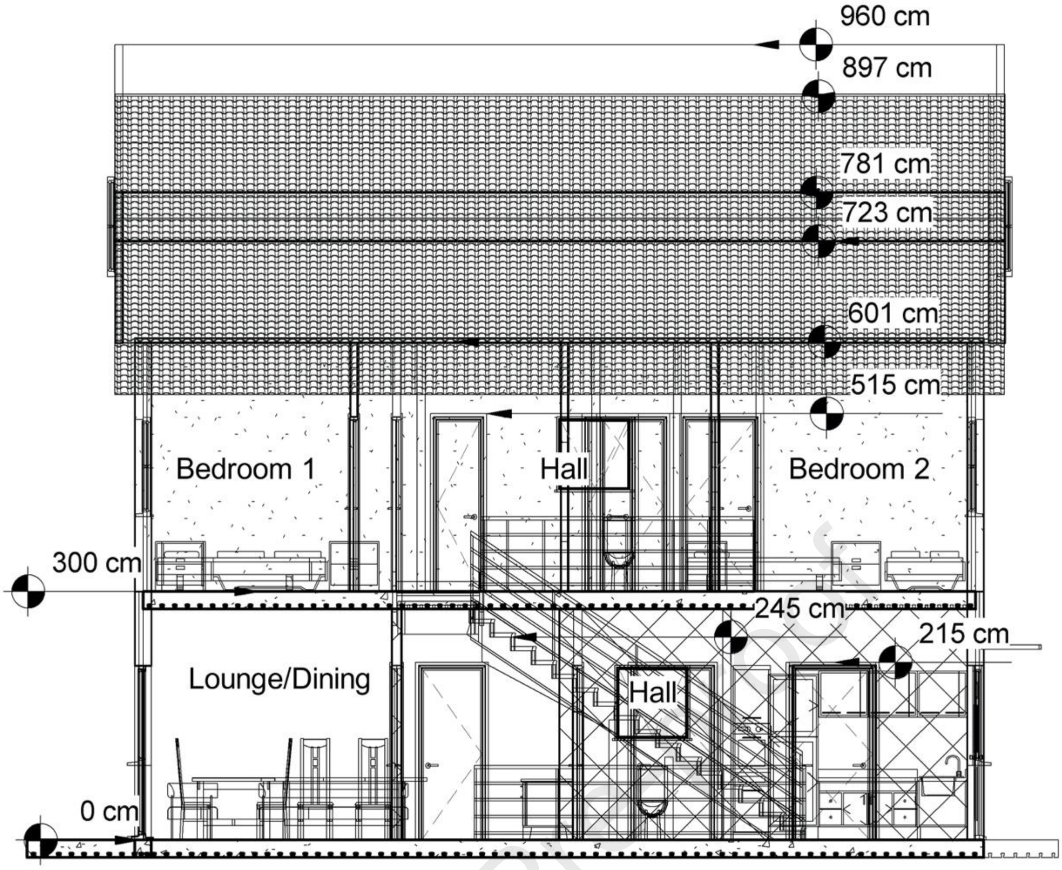


Fig. 9. (c) The section drawing of the terraced house for base-case scenario development. ***Image credit:*** The construction drawing was modelled by the author using the Autodesk® Revit® software suite.

In this innovative terraced house typology, there are two types of glazed components installed to provide various natural ventilation strategies to cool occupied indoor spaces. The first type concerns external walls made of EPS board and steel-framed structure components, as shown in Figure 10 (a). The second type concerns all the windows, including the translucent windows on the entrance door and the large, glazed door windows in the living room on the ground floor (Figure 10 (b), (c) and (d), respectively). The windows in and around the living room door are a double-glazed system with an aluminium frame and controllable side windows. The whole window thermal transmittance values are reported in Figure 10 (c). At the same time, a mechanical ventilation heat recovery (MVHR) system was installed in the property (Dengle & Swainson, 2013).

The building was occupied during the extensive environmental monitoring campaign, and from 25 June to 19 July 2018. The residence was unoccupied on weekends, and no previous occupancy was recorded at the time of prototype house constructed at the Innovation Park site, because the property had been used as a showroom to demonstrate several innovative technologies during the construction process of this base-case building at the BRE Innovation Park. For this reason, the findings could be an exemplar model to provide subsequent basic information for other scholars in the building engineering field.

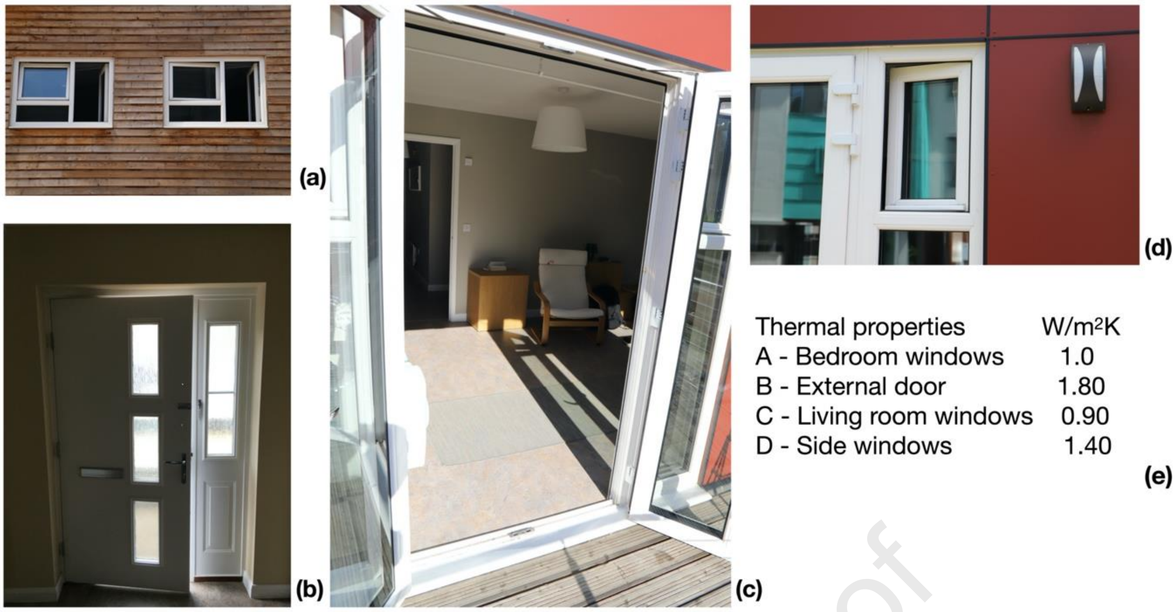


Fig. 10. (a) The typical window openings installed in the bedrooms within timber cladding surfaces. **(b)** The translucent window openings installed on the door. **(c)** The operable large, glazed door openings which allow 100% natural ventilation of the living room space. **(d)** The side window openings installed with the doors in the living room space increase the frequency of infiltration rate. **(e)** The thermal transmittance values of windows implemented in the prototype base-case building. ***Image credits:*** Outdoor and interior images were taken by the author on courtesy of the Building Research Establishment.

In order to provide absolute accuracy for the building energy modelling phase of the study, the occupancy profiles of each room have been verified. On the ground floor are the entrances to the hall, kitchen and living room, including a water closet (WC). The battery storage space is located just underneath the staircase; there is no direct source of natural ventilation allowed into this space, as shown in Figure 11 (a) and (b). Within the first-floor area, there are large, medium and small bedrooms allocated off the hallway. A medium-sized bathroom is included. A separate space is allocated to accommodate the MVHR system in the property; the mechanical duct systems are routed into the cold roof space area in the attic, as shown in Figure 11 (c).

(a) (b) (c)

Fig. 11. (a) The battery storage space is located beneath the staircase. **(b)** The electrical circuit system and the central wireless router for the monitoring equipment are positioned in the battery room. **(c)** The MVHR system, hot boiler tank and ventilation duct system are located in the storage room on the first-floor level in the base-case prototype building. ***Image credits:*** Interior images were taken by the author on courtesy of the Building Research Establishment.

In order to identify the realistic occupancy schedules in the building energy model, a building occupancy inventory survey was recorded by the researcher at the time of residency (see **Supplementary Material – A**). It was reported that the most dominant occupancy profile was between Monday and Friday, with the occupant leaving the residence from 9:00 a.m. to 5:00 p.m. to work in an office. The living room was occupied from 5:00 p.m. to 11:00 p.m. by the sole occupant, and the large bedroom space was occupied between 11:00 p.m. and 8:00 a.m. It is worth noting that the bedrooms on the first floor, as well as the living room on the ground floor, were naturally ventilated during occupancy hours to reduce the high temperatures experienced at the property. Figure 12 (a) demonstrates typical representative occupancy profile recorded at the time of extensive monitoring campaign recruited and experimental building performance evaluation undertaken at the case study house and Figure 12 (b) depicts representative window occupancy schedules recorded during experiments conducted for the study.

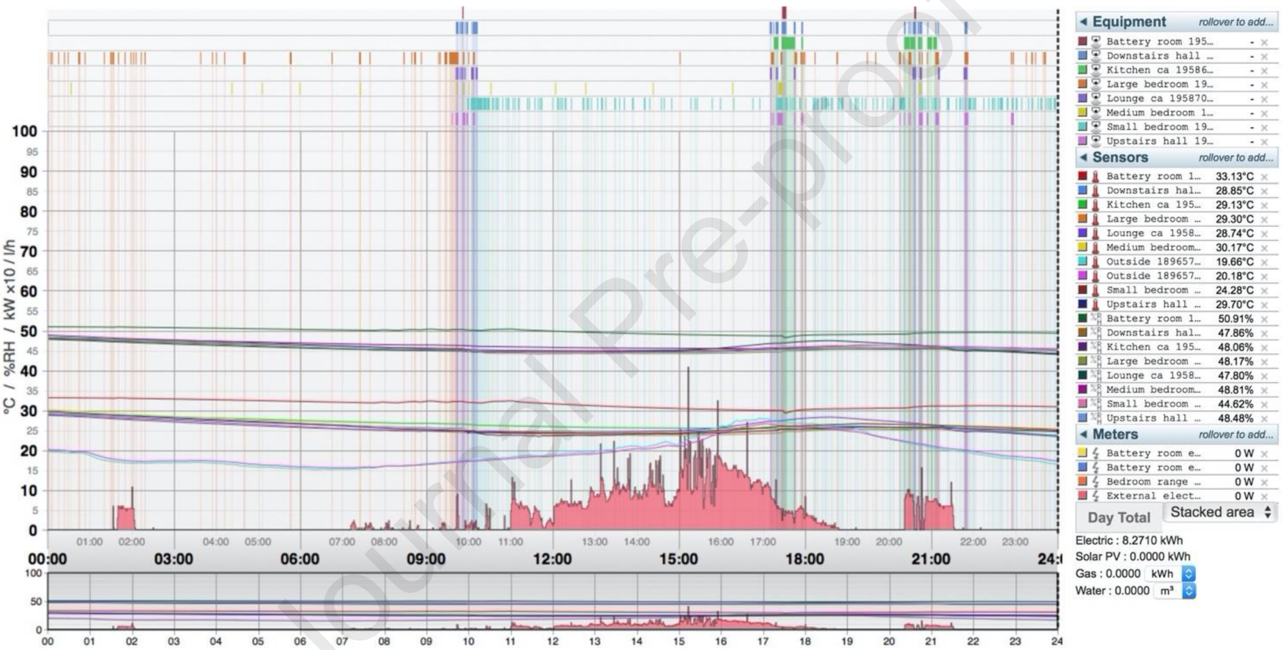


Fig. 12. (a) In-vivo occupancy profiles recorded at the case study building, including energy used by sole user during the occupancy hours. ***Image credit:*** The data extracted from Energy Saver dashboard platform developed by Tensor Ltd and access permitted by the Building Research Establishment.

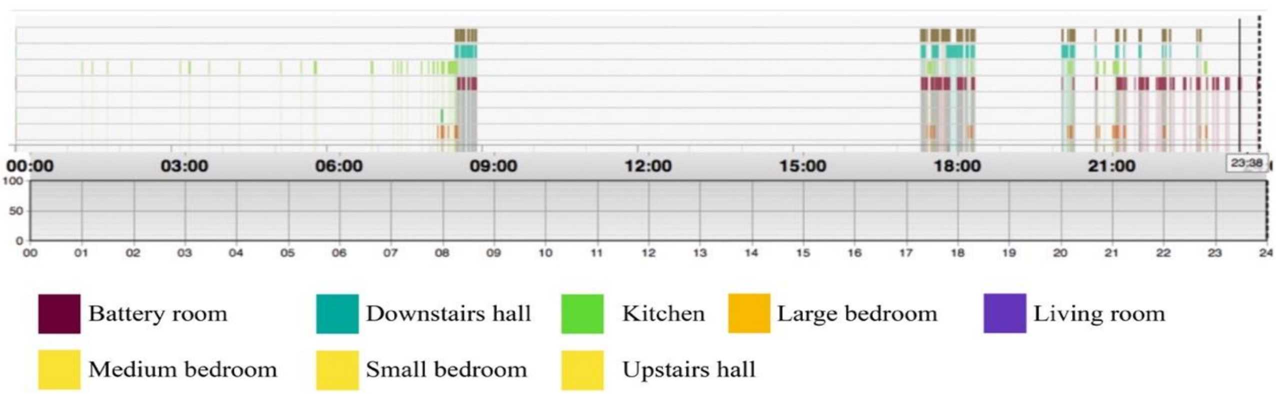


Fig. 12 (b). The representative window opening schedules recorded during the building performance evaluation for base-case scenario development. ***Image credit:*** The data extracted from Energy Saver dashboard platform developed by Tensor Ltd and access permitted by the Building Research Establishment.

The property uses a mixed air-water system for heating, cooling and ventilation; the emitters are ceiling mounted fan-coils, and there are two air handling units installed in the attic space. When occupied in the summer, hot water for sanitary uses is also produced by three premixed condensing boilers with a global nominal power of 284.7 kWh; the efficiency at full load is equal to 98.2 kWh. An electric chiller with a nominal power of 137 kWh supplies cool water. Figure 13 (a) through (g) demonstrates the location of temperature sensors and weather station installed to record *on-site* environmental conditions.

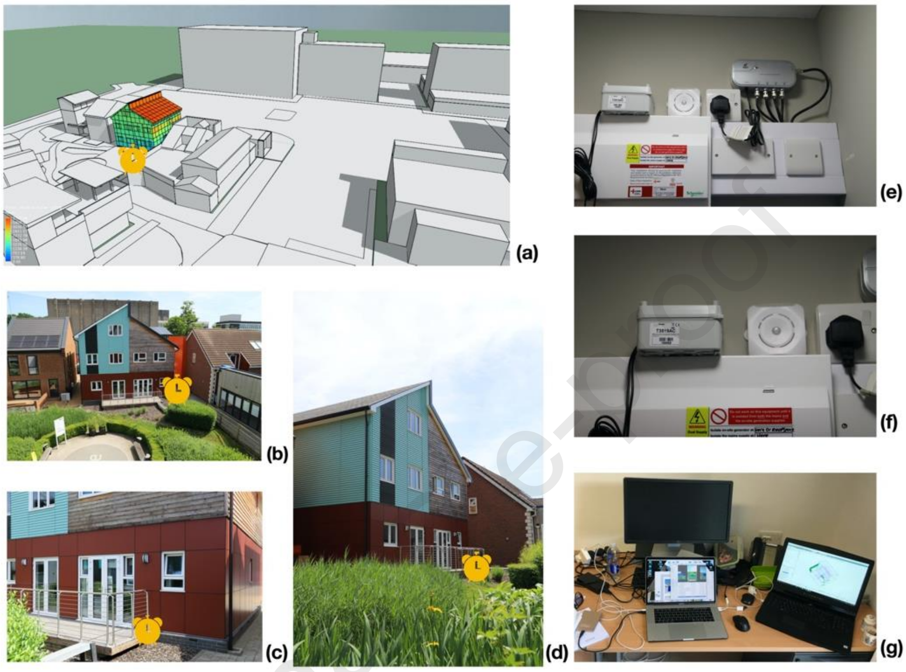


Fig. 13. (a) 3D rendering model of archetype house and surrounding built environment. **(b)** The location of weather station installed in the Innovation Park site. **(c)** The weather station was installed beneath the decking space. **(d)** The position of weather station installed in the property. **(e)** The location of environmental monitoring device mounted on the wall in the battery room. **(f)** The main environmental recording station. **(g)** The environmental recordings were monitored and data extracted for experimental analysis by using highly efficient custom-made computers provided by the author.

Image credits: **(a)** 3D Rendering model was constructed by using IES software suite's ModelIT application. **(b)-(d)** Outdoor images were taken by the author on courtesy of the Building Research Establishment. **(e)-(f)** Interior images were taken by the author on courtesy of the Building Research Establishment. **(g)** The image was taken by the author to demonstrate the research environment at the time of extracting date from the monitoring devices.

A crucial detail is that a temperature sensor was located on the outside of the building, on a north-facing wall, to avoid the effects of high levels of solar radiation and provide absolute accuracy for the environmental analysis. The sensor was wired to the internal controls of the boiler and chiller and recorded information about outside environmental conditions, including temperature and relative humidity. We observed that when temperature changes occur outside, the boiler responds by increasing or decreasing the water temperature to optimise the indoor air temperature. With regard to the optimisation of the occupants' thermal comfort, only rooms with mixed ventilation systems were considered. At the same time, in the less frequently occupied spaces (e.g. the battery room or storage room), there is no control over indoor conditions. Therefore, overheating problems can sometimes occur in the winter or people may experience lower temperatures than are comfortable (McCartney & Nicol, 2012; McLeod et al., 2013).

3.3. Environmental monitoring

This paper presents two different design approaches to quantify the impact of the passive design strategies implemented in the building envelopes of a prototype terraced house. The first approach involved placing data loggers in the rooms, enabling us to collect information related to temperature, relative humidity and CO_2 emissions in each occupied space for the duration of the summer of 2018. The second approach primarily considered a simulation analysis software suite of IES to calibrate indoor environmental conditions for each occupied space and the thermal behaviour of the base-case building when experiencing long-term heatwaves in the UK. As previously mentioned, the main objective of this study is to assess the risk of overheating and optimise occupants' thermal comfort by using energy-effective passive design systems. To satisfy the research aims and objectives, monitoring equipment was installed on the property to evaluate the current building performance of the base-case building in order to provide subsequent information for the optimisation studies described in Section 5. Table 5 illustrates the types of monitoring devices used as building diagnostic tools that were installed in the property to run the extensive monitoring campaign.

Table 5
Types of monitoring devices installed in the prototype house.

Monitoring Device	**Technical Specifications**	**Monitoring Device**	**Technical Specifications**
 **Heating Save wireless sound, occupancy sensor, and ambient temperature sensor**	Detection range: up to 6 m and 120 °C Temperature measurement range: 0–60 °C Temperature accuracy: +/–0.5 °C Humidity range: 0–100% Humidity accuracy: +/–4%	 **Heating Save wireless internal temperature sensor**	Operating range: –40 to 125 °C Accuracy: +/–1% Permissive operative current: 0.38 mA Rated electric power: 15 mW Dissipation constant: 1.5 mW/°C Time constant: 7 sec Resistance: 10 K ± 1%
 **Heating Save CO_2 wireless concentration sensor**	Range value: 0 to 100,000 ppm Accuracy: ±100 ppm Accuracy: ±5% of reading + 100 ppm Accuracy: ±10% of reading Accuracy: ±15% of reading Resolution: 2 ppm	 **Victron energy storage battery – PV generator meter**	Input voltage range: 187–265 VAC Input frequency: 45–65 Hz Temperature compensation: –16 mV/°C to –32 mV/°C Operating temperature range: –20 to 50 °C Humidity (non-condensing) max: 95%
 **Heating Save RF signal range extender**	Storage temperature range: –50 to 150 °C Ambient temperature: min. 40 °C/max. 125 °C Operation frequency range: min. 2,400/max. 2,483.5	 **Tinytag ambient temperature and relative humidity sensor**	Operating temperature range: –40 to 85 °C Standard range: –50 to 300 °C Accuracy: ±1 °C from 0 to 150 °C Resolution: 0.43 °C at –200 °C

Note: Monitoring devices, sensors, weather station and data loggers were provided by the Building Research Establishment

To fill the knowledge gap in the building performance evaluation method, the data loggers were installed both on the ground and first-floor levels in the building to concurrently record real-time environmental conditions to determine the validity of results while was undertaking building energy simulations, as shown in Figure 14 (a) and (b). This allowed us to compare the actual indoor air temperature and relative humidity levels for each occupied space against the acceptable international assessment criteria and graphically represent this for further analysis and discussion. This provided an early diagnostic methodology to find occupied spaces that would require improvement or further investigation to optimise occupants' thermal comfort.

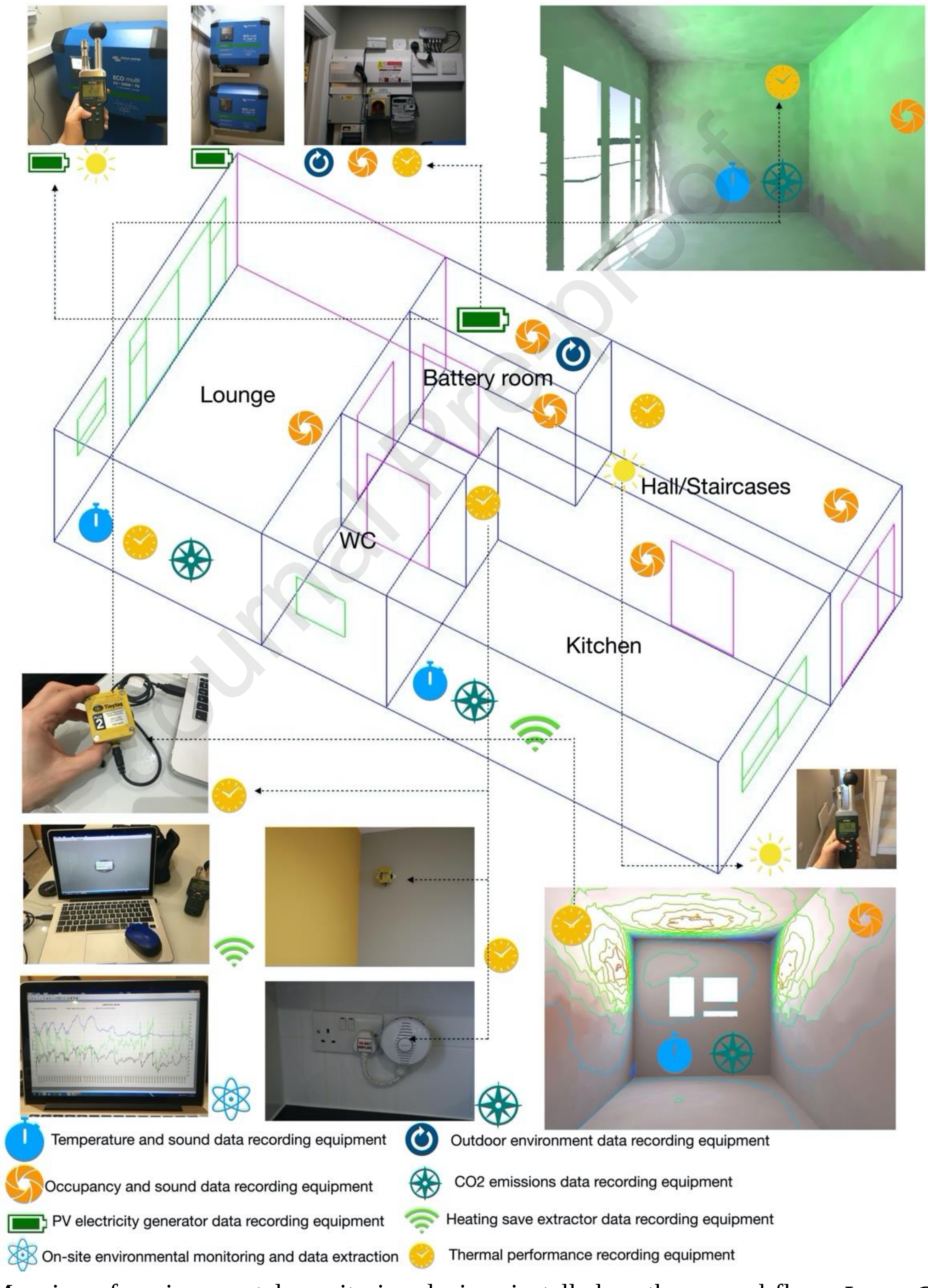


Fig. 14. (a) Mapping of environmental monitoring devices installed on the ground floor. ***Image Credits:*** 3D Analytical energy model was constructed by the author using the IES software suite – version 2021.1.0. Interior images were taken by the author on courtesy of the Building Research Establishment. The specialised software suite purchased by the author to extract the data gathered from the monitoring devices.

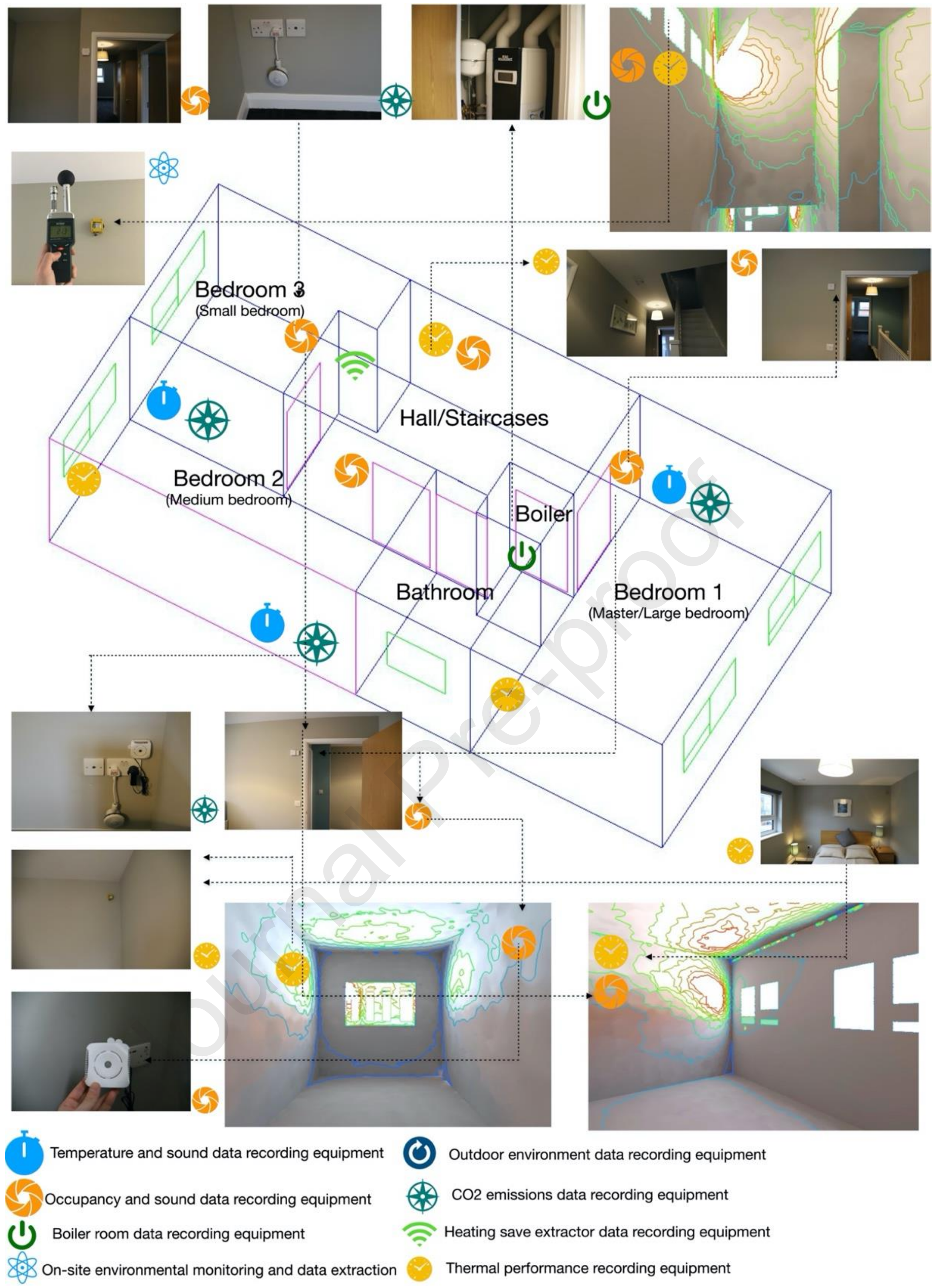


Fig. 14. (b) Mapping of environmental monitoring devices installed on the first floor. ***Image Credits:*** 3D Analytical energy model was constructed by the author using the IES software suite – version 2021.1.0. Interior images were taken by the author on courtesy of the Building Research Establishment. The mobile monitoring device was purchased by the author to record *in-situ* temperature recordings of each occupied space at the case study building.

In order to assess the current energy performance of the base-case prototype building, each occupied space was monitored by seven data loggers from June to August 2018. The extensive monitoring campaign aimed to measure the impact of significant indoor air temperature fluctuations on the thermal performance of a building and the occupants' thermal comfort concurrently during the summer period in order to calibrate a worst-case scenario as the basis for the development of effective passive cooling design strategies.

As previously indicated, Figure 14 (a) and (b) illustrates the location of the data loggers installed in the case study building. The physical parameters were measured at 10-minute intervals in order to record the environmental conditions with absolute accuracy. Simultaneously, five additional data loggers were installed in the occupied spaces, including the living room, kitchen and bedrooms 1, 2 and 3, to record the CO_2 emissions of densely occupied spaces in the home. Three of them were positioned on the first-floor, in bedroom 1 (the large bedroom) facing northeast and bedrooms 2 (the medium bedroom) and 3 (the small bedroom) facing southwest. One was positioned in the kitchen, and the last one was installed in the living room on the ground floor level, which is often one of the most problematic rooms due to high gains from domestic home appliances. The data loggers remained in place throughout the summer to gain an overall picture of the thermal comfort in this state-of-the-art terraced house typology. Figure 15 (a) through (d) demonstrate the solar shading analysis of prototype case study building to demonstrate the importance of mutual shading impact factor on building fabric thermal performance.

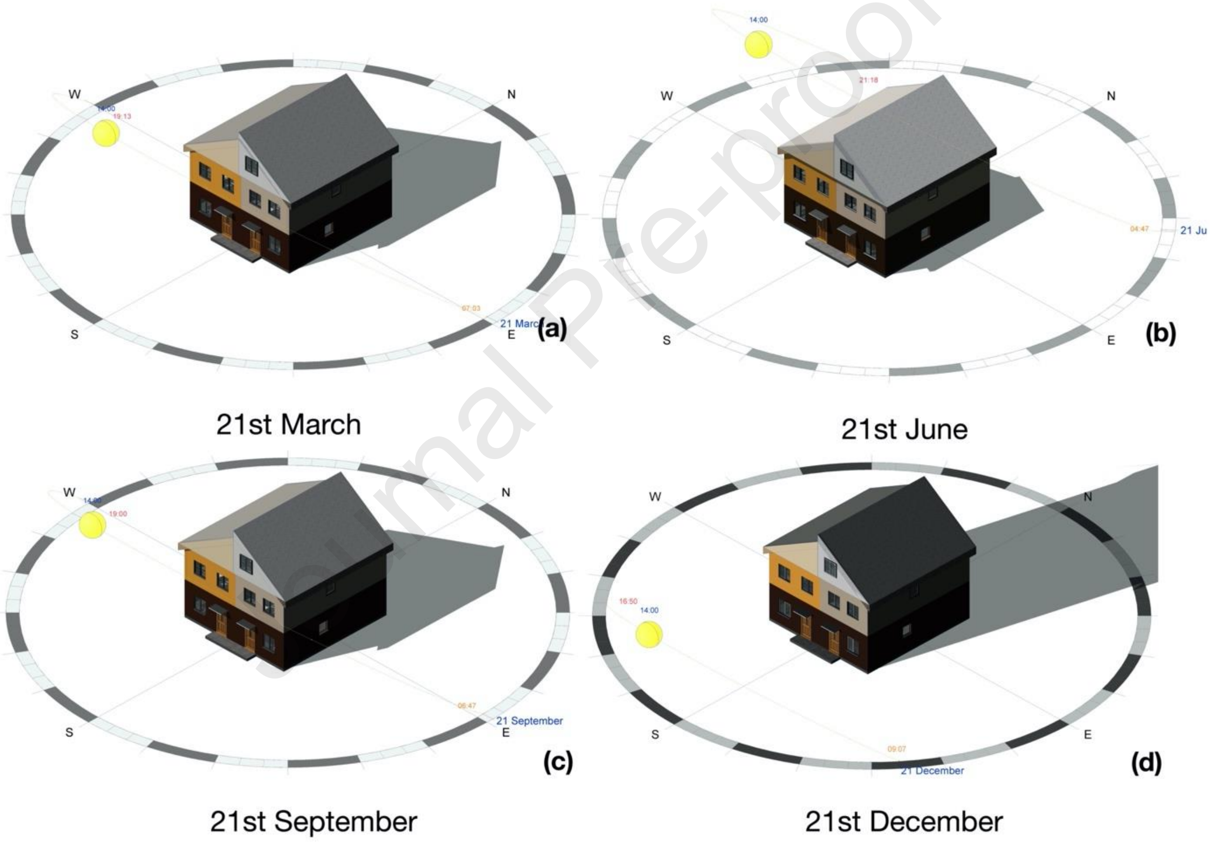


Fig. 15. (a)-(d) Solar shading analysis with taking into account summer and winter solstices and equinox. ***Image credits:*** The case study building was re-modelled by the author using the Autodesk® Revit® software suite.

The location of the instruments plays a major role; for accuracy, it is preferable to place them at head height and away from heat sources or direct solar radiation. Notably, as the both medium and small bedrooms were characterised by the same window-opening schedules, any difference in the recorded temperatures could be associated with different solar exposure and/or the user's internal heat gain. This helped us to quantify the impact of the mutual shading from the surrounding buildings (more descriptive information about the research design approach can be found online at **Supplementary Material** – Inventory Proforma of the case study building). Once the data were extracted, the minimum and maximum hourly temperatures were plotted and compared with each other with the aid of visual representation, as described in Section 4.2.

3.4. Building modelling simulation

All information acquired during the extensive monitoring campaign was used to define the numerical model by means of the IES software suite and the graphical interface of ModelIT. It is important to note that, during the energy modelling, all other surrounding buildings and vegetation were taken into account to improve the accuracy of the dynamic thermal simulation results. The detailed landscape elements were also included in the base-case energy model in more detail; for example, the nearest both woodland and forested region about 10 m from the case study building. Figure 16 illustrates the conceptual framework developed to determine building characteristics, contextual parameters and local climate conditions.

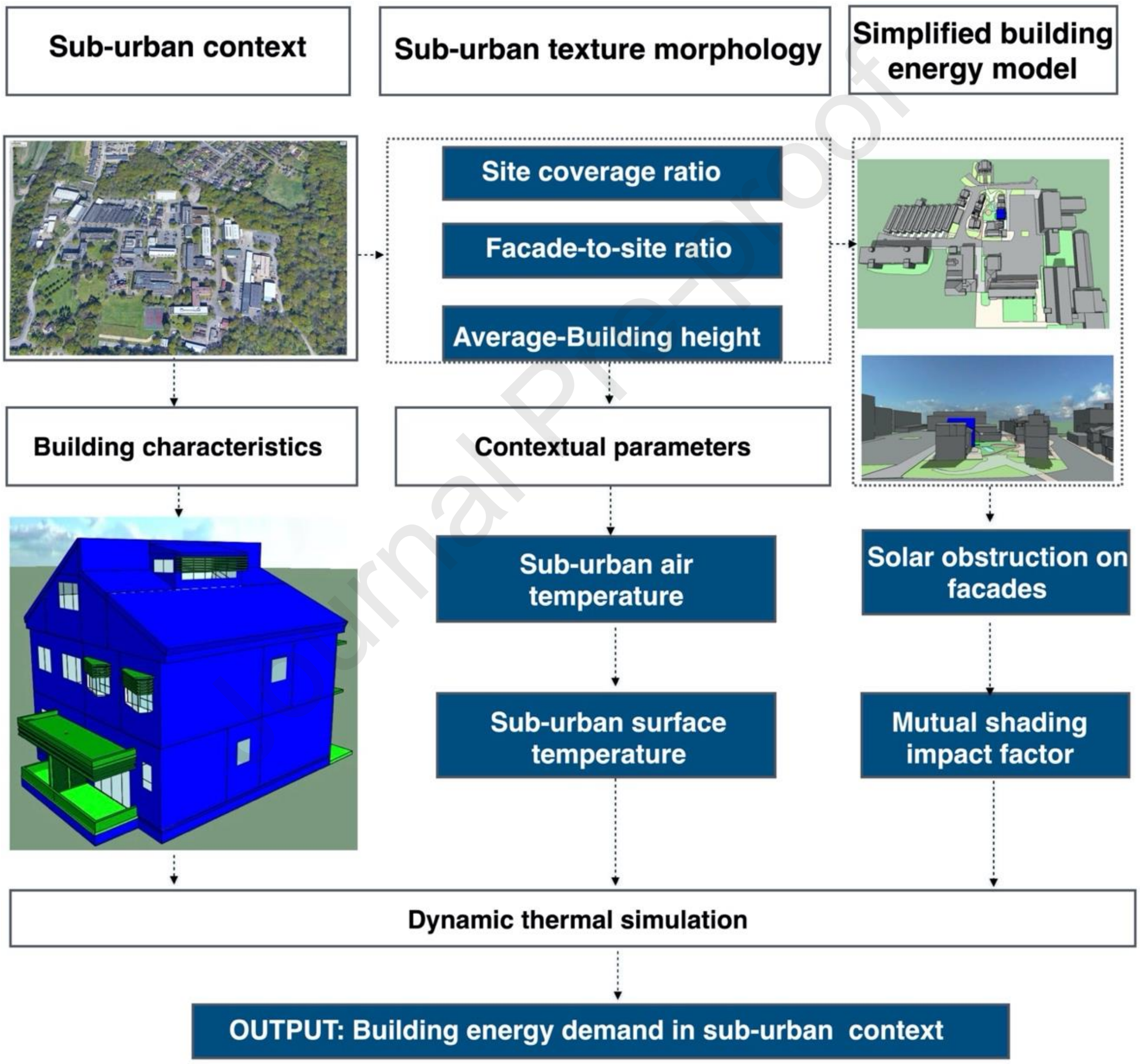
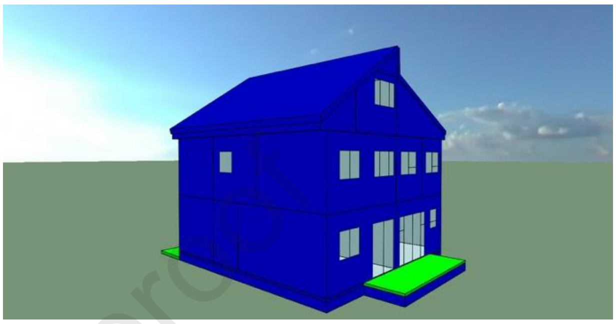


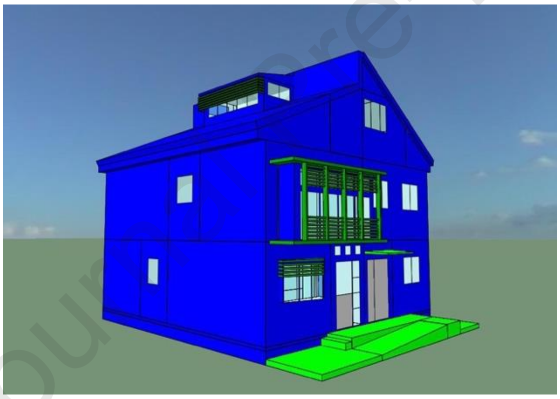
Fig. 16. Development stages of building energy modelling. ***Image credits:*** The flow diagram was conceptualised by the author – the 3D rendering model of case study location and prototype house was modelled in IES software suite by using ModelIT application.

To assess the risk of overheating experienced from May and September 2018, the IES building performance evaluation tool with the Apache-Sim assessment application for dynamic thermal simulation (DTS) was used. Cooling load calculations using IES Apache-Constructions' database and Apache-Loads in the IES software suite were performed in order to calibrate the current energy performance of the prototype base-case building (Firth et al., 2010; Schünemann et al., 2021). In this base-case scenario, as the goal was to design a suitable holistic retrofitting of the innovative terraced house typology, a replicable research design approach was adopted by concurrently combining both experimental and analytical methods. It successfully demonstrated the impacts of the adoption of energy-efficiency technologies in a real-world context and allowed us to understand the discrepancies between the predicted and actual energy use in the residential sector. For this reason, detailed energy models were developed to measure the impact of mutual shading resulting from the surrounding buildings and the implementation of shading systems in the building envelopes. Figure 17 (a), (b) and (c) illustrates the analytical energy model of the base-case prototype building.

(a)



(b)



(c)

Fig. 17. (a) The rendering of the prototype case study building and its surrounding environment used to measure the impact of mutual shading effect on occupants' thermal comfort and energy use – Category A. **(b)** The base-case building without surrounding environment for calibration studies – Category B. **(c)** The tested and implemented passive shading systems in the existing building envelope – Category C. ***Image credits:*** 3D renderings were modelled by the author using IES software suite – ModelIT and VistaPro applications.

In this study, the base-case model was simulated using the weather file defined with data gathered from May to September 2018 from the closest weather station, located in the BRE Innovation Park. Hence, the output of the dynamic thermal simulations was compared with the energy consumption of the building measured in August 2018, to predict the demand for cooling in each occupied space in the home by determining the deviation and the relevant uncertainty parameters in the simulation model. As previously mentioned, Test Reference Year (TRY) weather files were used to undertake the Dynamic Thermal Simulations (DTS) for a period of one year. It is important to mention that several modifications were implemented during the calibration phase to avoid any risk of data loss while generating actual meteorological year (AMY) weather files to assess the overheating risk of each occupied space in the property (Ascione et al., 2021). These modifications mainly concerned the inner load and the occupancy schedules, which had been updated with information provided by the building occupancy survey. Figure 18 illustrates the step-by-step development of simulation set-in put parameters for building optimisation studies.

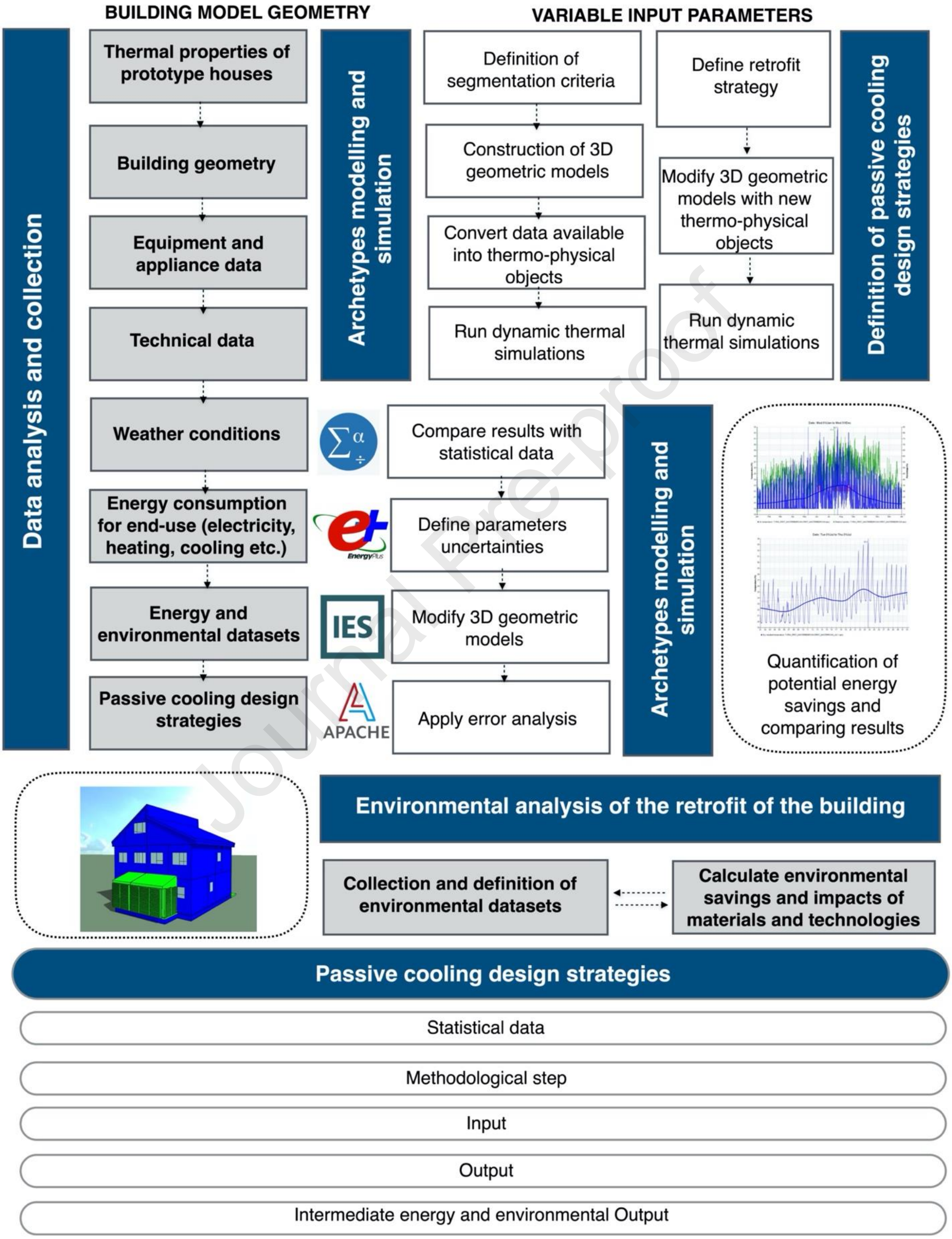


Fig. 18. The methodological workflow developed for building optimisation studies. ***Image credits:*** The flow diagram was conceptualised by the author – the 3D rendering model of prototype house was modelled in IES software suite by using ModelIT application and the dynamic thermal simulation graphs were produced by using the VistaPro application.

Notably, both the calibrated energy model and the optimisation studies were developed to provide further information for establishing the effect of simulation set-in put parameters for building energy modelling (BEM). This means that the base model was simulated with input from weather files created with data available from the closest station for the same year or with weather files from the typical reference year carried out to the algorithm recommended by the EN ISO 15927-4:2005 standard (Hygrothermal performance of buildings – Calculation and presentation of climatic data – Part 4: Hourly data for assessing the annual energy use for heating and cooling). In this study, the available data sets were generated with IES weather file extensions using the Weather Analytics software suite in order to assess the overheating period from May to September. For each configuration, deviations of the calibration criteria from the threshold value and calibrated model had to be evaluated. These weather files were also used to simulate the model of the current state of the building and the energy efficiency of implemented passive cooling design strategies, considering as a base-case the model of state of fact simulated with the same weather file. The comparison of these assessment criteria allowed us to estimate the frequency of errors committed in the decision-making process of retrofit interventions in the residential sector. In order to design absolutely accurate information for dynamic thermal simulations, three groups of internal heat gains, i.e. the lighting, appliances, and occupancy profile “professional single”, were modelled, as shown in Table 6.

Table 6
The list of tabulations of internal heat gains, external loads and recorded occupancy profiles for each occupied space during the building performance evaluation analysis.

Space	Internal Gain Category	Sensible Gain	Latent Gain	Occupancy Profile and Number of Occupants
Large Bedroom	People	50.2 W/person	23.6 W/person	10:00 p.m.–7:00 a.m. daily 1 person
	Lighting	18 W		6:00 a.m.–7:00 a.m., 9:00 p.m.–11:00 p.m. daily
	Appliances	20 W		6:00 a.m.–7:00 a.m., 10:00 p.m.–11:00 p.m. daily +10% best gains for background and/or standby use 24 hr/day
Medium/Small Bedrooms	People	50.2 W/person	23.6 W/person	10:00 p.m.–7:00 a.m. everyday 1 person
	Lighting	18 W		6:00 a.m.–7:00 a.m., 9:00 p.m.–11:00 p.m. daily
	Appliances	20 W		6:00 a.m.–7:00 a.m., 10:00 p.m.–11:00 p.m. daily +10% best gains for background standby use 24 hr/day
Living room	People	75 W/person	55 W/person	6:00 a.m.–9:00 a.m., 5:00 p.m.–11:00 p.m. daily 1 person
	Lighting	36 W		8:00 p.m.–11:00 p.m. daily
	appliances	120 W		6:00 a.m.–9:00 a.m., 5:00 p.m.–11:00 p.m. daily +10% heat gains for background standby use 24hr/day
Kitchen	People	75 W/person	55 W/person	7:00 p.m.–8:00 p.m.
	Cooking appliances	1000 W		7:00 p.m.–9:00 p.m.
	Fridge/freezer	31 W		24 hr/day

In this research, the occupancy pattern was assigned as a generic template for the use of window opening schedules. These opening schedules were assigned using the VistaPro software interface tool to validate this type of opening system in the simulation model (see **Video A** – The demonstration of natural ventilation frequency of case study within the research context). Additionally, it was important to simulate the opening pattern of the operable windows in accordance with the occupancy profiles of the case study building. The IES software suite was chosen for the empirical case study analysis to assess the impact of solar radiation on building envelopes and the thermal behaviour of building materials on occupants' thermal comfort. After the initial stage, in which the buildings were modelled, paying particular attention to inserting all the thermal properties (*U*-values) related to the construction materials, the Apache-SIM application interface was run for all necessary dynamic thermal simulations using the occupancy patterns and the cooling settings, which had to be manually inserted into the simulation software to customise the generic occupancy schedules provided by the IES software suite's databases, as shown in Figure 19.

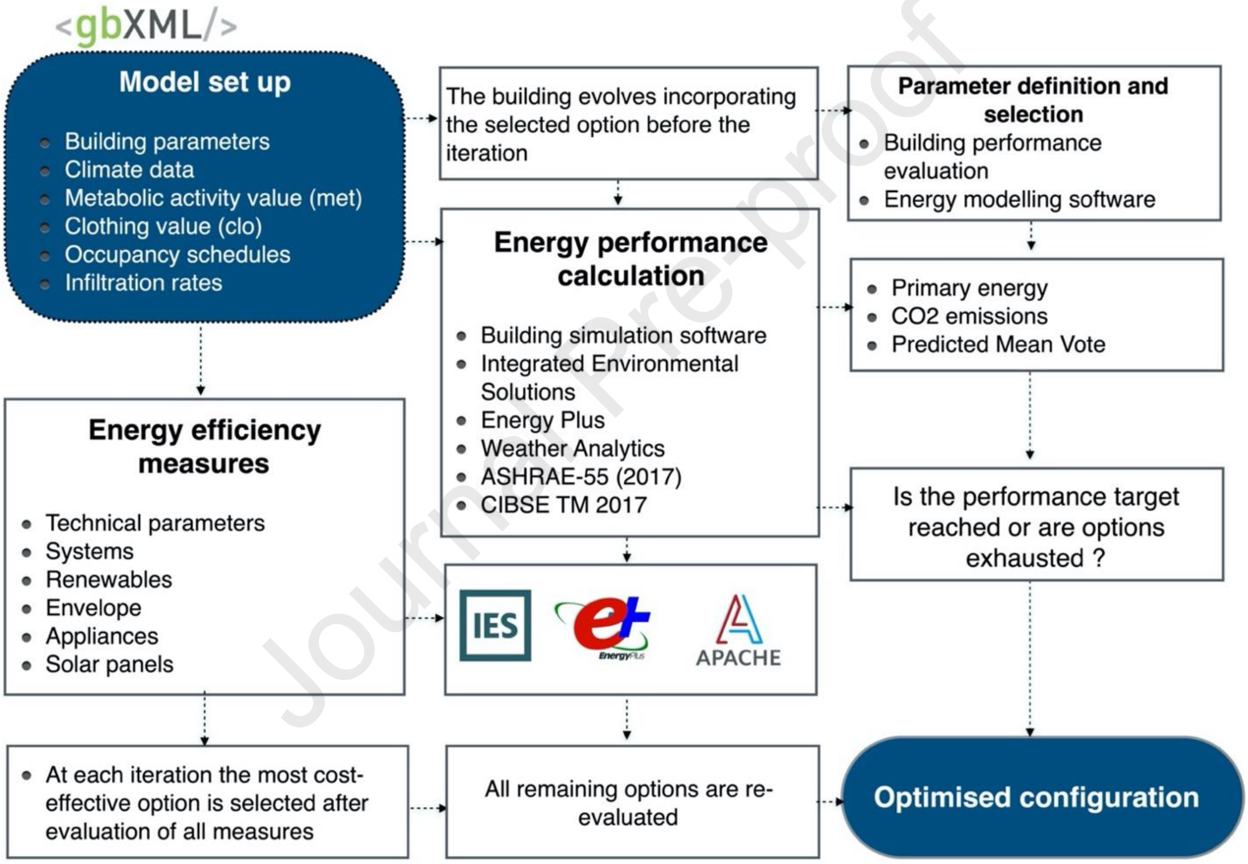


Fig. 19. The step-by-step development of analytical energy model developed to assess energy performance. ***Image credits:*** The flow diagram was conceptualised by the author.

In order to analyse the impact of mutual shading from the adjacent buildings in the case study location, three different thermal simulation scenarios were carried out to identify worst-case scenarios related to the implementation of passive cooling design strategies. In the first simulation model (Category A), the real building network was considered; the prototype base-case building and the surrounded buildings of the Passivhaus and Victorian detached houses at the BRE Innovation Park were analysed with the aim of understanding the implications and mutual effects the buildings have on each other and especially the result this has on the occupied spaces, which, as already mentioned, were distracted by the surrounding buildings, as shown in Figure 17 (a). The second simulation (Category B) was carried out by omitting the surrounded buildings. The base-case building was analysed to calibrate the indoor air environment of each occupied space with considering direct solar radiation (which was not distracted by the surrounding buildings), as shown in Figure 17 (b). The purpose of this simulation analysis was to understand the mutual impact of shading effect. The last simulation (Category C) was carried out to determine the effectiveness of passive cooling design strategies to understand the design applicability of those measures in retrofitting for policymaking decisions on energy use, as shown in Figure 17 (c). Comparing discrepancies between Categories A and B allowed us to quantify the impact of mutual shading within the UHI effect factor of surrounding buildings. We found that these two simulation concepts demonstrate different indoor environmental conditions related to direct solar exposure throughout the day. These findings helped us to devise appropriate shading systems for worst-case scenario development, which is discussed in Section 5. This research approach can be applied while comparing simulation results and quantifying the implications of having solar shading systems in building envelopes in terms of considering occupants' thermal comfort in the analysed occupied spaces.

3.5. Correlation analysis

Correlations among two parameters (indoor air temperature and relative humidity) were collected by environmental monitoring to investigate the relationship among the different parameters, using the Statistical Package for the Social Sciences (SPSS) version 25 (IBM, Armonk, NY, USA). The descriptive analysis was used to illustrate the monitored environmental conditions and occupants' thermal comfort level, and then correlation analysis methods were applied to the findings to evaluate the correlations among the different parameters. Inferential statistics (or inductive statistics) are techniques, are employed to make generalisations or inferences about the sample size. The main inferential statistical techniques used in this study included Pearson's correlation coefficient and linear regression analysis. The results for all statistical tests were as follows: 95% was the assumed degree of confidence, 0.05 was the level of confidence and the p-value was 0.000. The findings from the variables were further tested to determine relationships with the actual environmental conditions that were monitored in order to gain more reliable data to validate the results in the building modelling simulation phase of the study.

4. Data and summary statistics

This section focuses on reporting the collated data, along with its analysis and interpretation. The intent here is to explain the findings of the methodological approach adopted in this paper for evaluating variations in the prediction of energy performance, with the integration of the findings of extensive monitoring analysis. The proposed research design is based on the on-site monitoring of each occupied room rather than on the outdoor environment, with a comparison between the monitored data in different weather files and data diffused for the simulation in an online database. In more detail, two main phases can be distinguished. In the first, the effect of the monitored environmental parameters was taken into account to evaluate the current energy performance of the base-case building. The decision to use these data sets was made based on the statistics decision chart for parametric tests, as described in Section 4.2. The second stage consisted of an optimisation analysis of the simulation results with six different passive shading systems implemented in the building envelopes.

4.1. Environmental monitoring and assessing the risk of overheating

The collection of the mean air temperature, relative humidity and CO_2 level of each occupied space in the property was used in our evaluation of the indoor conditions from June to August 2018 to assess the risk of overheating due to the state-of-the-art energy efficient building materials implemented to reduce heating demand in the winter (see **Appendix A**). We found that these conditions led to an increase in indoor air temperature in the summer. The following graphs show the maximum indoor relative humidity (RH) and temperature, and the outdoor maximum temperature used to measure the peak time of the environmental conditions so that the worst-case scenario for the building could be identified, which would give us the maximum heat stress impact factor of the building. The following graphs also demonstrate the findings of long-term environmental monitoring for each occupied space, including outdoor air temperature fluctuations, to provide subsequent information for energy-effective retrofit interventions described in Section 5.

Fig. 20. (a) The monitoring results of all interior occupied spaces and the external environmental monitoring in June 2018. ***Image credit:*** Data was extracted from the Energy Saver online dashboard platform by the author.

Figure 20 (a) depicts how the fluctuations in outdoor air temperature affected the fluctuation of indoor air temperature and RH during the heatwave in June 2018. In the first week, the outdoor air temperature reached 30 °C, and the indoor spaces' temperature fluctuated from 23 °C to 28 °C. From the second week to the end of the third week, the outdoor temperature fluctuated from 19 °C to 28 °C, but the findings showed that the indoor spaces' air temperature ranged from 23 °C to 25 °C. The final week, which contained the heatwave peak period, the outdoor air temperature was 27 °C to 30 °C. The indoor RH remained stable from 45 to 50 on the relative humidity index (RHI) for all of June 2018, regardless of external air temperature fluctuations (see **Data set 1** – Readings of humidity for each occupied space during the cooling period between May and September). This shows that indoor spaces have warm and dry weather conditions that affect the comfort levels of the occupants. Overall, the temperature fluctuations remained above the acceptable thermal comfort level benchmark (Nicol et al., 2009, 2012). It must also be highlighted that the battery room, though not a habitable temperature, always remained between 30 °C and 34 °C, which resulted in a further increase in the discomfort level of the surrounding living spaces.

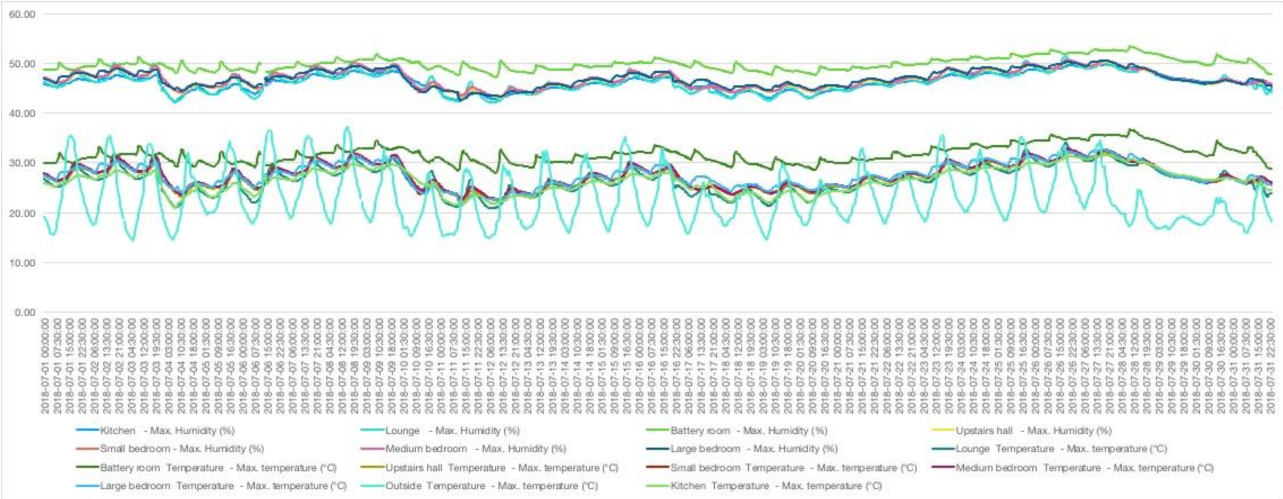


Fig. 20. (b) The monitoring results of all interior occupied spaces and external environmental monitoring in July 2018. ***Image credit:*** Data was extracted from the Energy Saver online dashboard platform by the author.

Figure 20 (b) demonstrates the fluctuations in the outdoor air temperature and the indoor air temperature and fluctuations within the Relative Humidity Index (RHI) during July 2018, which was the peak of the heatwave. From 1 to 9 July, the outdoor air temperature ranged from 30 °C to 36 °C while the indoor air temperature was between 28 °C and 32 °C. This indicates a high level of discomfort in indoor spaces. In addition, it was observed that from 7 to 10 July, the occupied spaces' temperatures ranged from 29 °C to 32 °C, while the battery room was measured from 30 °C to 32 °C. These environmental conditions highlight the fact that, in extreme peak heatwaves, the indoor spaces' air temperature was 2 °C below the battery room temperature, even though they had sufficient natural ventilation (CIBSE, 2013; Farahani et al., 2021). From 10 to 23 July, the outdoor air temperature fluctuated from 28 °C to 32 °C, while the indoor air temperature oscillated from 23 °C to 30 °C. This shows that the indoor air temperature was again above the acceptable benchmark of 23 °C (CIBSE, 2017; Lomas, 2021).

From 23 to 28 July, the outdoor temperature was measured between 30 °C and 34 °C; all occupied spaces were measured at 30 °C to 32 °C, and the battery room was between 34 °C and 36 °C. From 28 to 31 July, the outdoor temperature plummeted from 32 °C to 18 °C while the indoor spaces' temperature hovered around 25 °C, which is the maximum temperature for an acceptable comfort level (CIBSE, 2014). At the same time, the battery room ranged from 30 °C to 32 °C. The RH fluctuated from 48 to 52 on the RHI for the entire month of July 2018. This displayed a pattern similar to that of June 2018, even though the outdoor temperatures were much higher at that time; this was due to the indoor temperature fluctuating at a level comparable to June 2018, which was a result of the highly insulated external wall materials and the building's composite cladding systems. The overall monitoring results indicated that during the peak time of the heatwave, the indoor spaces' temperatures increased to levels that led to a high discomfort level for the occupants. Hence, as these prototype buildings are intended to reduce energy demand, it can be concluded that they are not applicable for use in long-term heatwave conditions (Ozarisoy & Altan, 2021a).

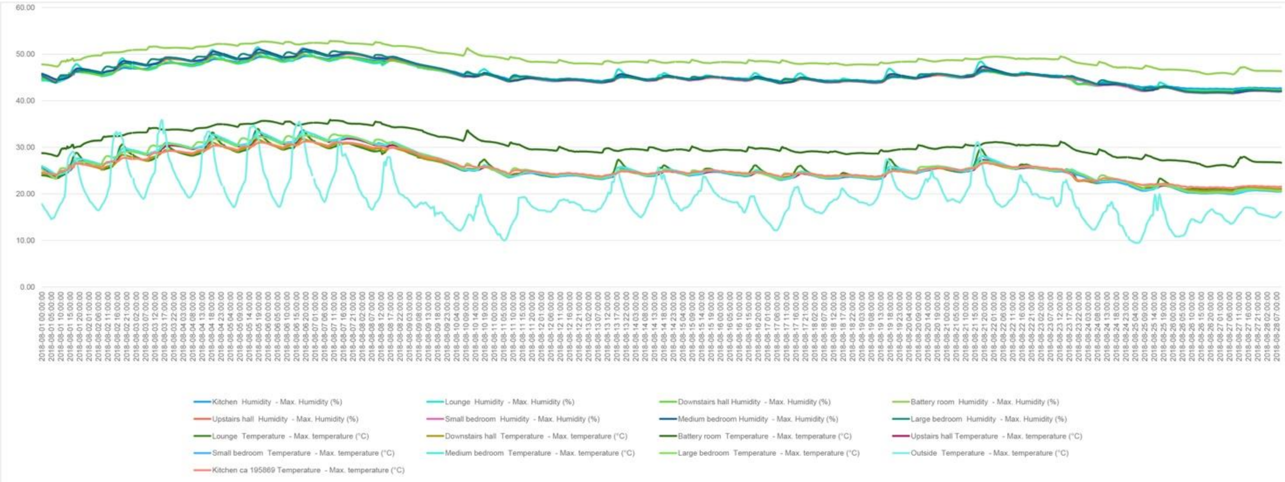


Fig. 20. (c) The monitoring results of all interior occupied spaces and external environmental monitoring in August 2018. ***Image credit:*** Data was extracted from the Energy Saver online dashboard platform by the author.

Figure 20 (c) displays the fluctuations in the outdoor air temperature, the fluctuations in the indoor air temperature, and the RH for the duration of August 2018. From 1 to 9 August, the outdoor temperature was between 32 °C and 36 °C, while the indoor spaces' temperatures ranged from 29 °C to 33 °C. This was due to a severe heatwave during this period. An indoor temperature range of 29 °C to 33 °C is well above the acceptable benchmark of 23 °C (Mavrogianni et al., 2015; Nicol & Humphreys, 2010). Therefore, this resulted in a high heat stress index. From 9 to 13 August, the outdoor air temperature plummeted from 30 °C to 12 °C, but during this fluctuation period, the indoor space temperature hovered between 23 °C and 25 °C, which is the acceptable benchmark temperature for thermal comfort levels (Guerra-Santin et al., 2013; Martínez-Mariño et al., 2021). Then, from 13 to 24 August, the outdoor air temperature fluctuated from 24 °C to 30 °C; however, on 21 August, the outdoor temperature reached its final peak of 30 °C, before falling to 9 °C on 25 August.

The outdoor temperature remained at around 9 °C until 28 August. During this same period, the indoor temperature dropped from 25 °C to 18 °C, which is an acceptable thermal comfort level (CEN, 2007; CIBSE, 2015). From 1 to 12 August, which was still in the heatwave period, the battery room temperature ranged from 32 °C to 36 °C. Then, from 12 to 24 August, it remained around 30 °C. From 24 to 28 August, it decreased slightly to around 28 °C. The RH fluctuated from 45 to 50 on the RHI from 1 to 24 August; it then decreased slightly from 45 to 41 on the RHI (see **Data set 2** – Readings of humidity of each occupied space at the peak day in August and **Data set 3** – Readings of humidity of each occupied space during the peak cooling month of August).

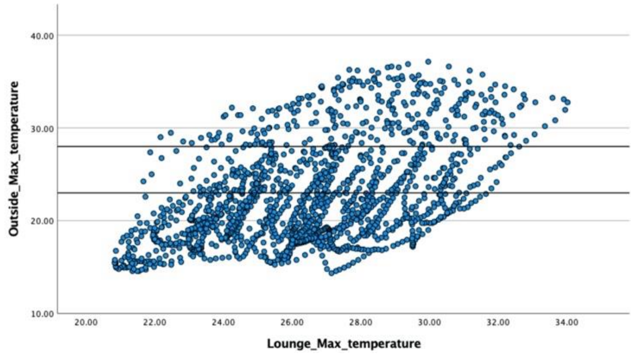
The impact of the varying outdoor temperature levels (e.g. high, moderate, and low) on the temperature and comfort level of the indoor spaces can be clearly seen from the monitoring measurements on the August 2018 graph (see **Data set 4** – Readings of indoor air temperatures of each occupied space during the peak cooling month of August). At the beginning of August 2018, during the heatwave, the indoor spaces' temperature was between 28 °C and 32 °C. These temperatures caused a high level of discomfort in this prototype building (see **Data set 5** – Readings of indoor air temperatures of each occupied space during the peak cooling month of August). Then, when the outdoor air temperature became moderate, the indoor air temperature decreased to the range of 23 °C to 25 °C, which barely meets the acceptable comfort level benchmark (CIBSE, 2016, 2017). These temperature measurements also place this prototype building at a high discomfort level benchmark.

When the outdoor temperature was moderate, the indoor air temperature decreased to between 23 °C and 25 °C, which barely meets the acceptable comfort level benchmark (Nicol et al., 2009). Towards the end of August 2018, when the outdoor temperature plummeted to a range from 10 °C to 18 °C, the indoor air temperature levelled off at 20 °C and remained stable throughout the remainder of August, which follows the CIBSE TM 52 guideline indicated for the optimum thermal comfort level when the heat is turned on during the winter (Sadeghi et al., 2021). However, with this prototype house, the optimum indoor thermal comfort level was achieved when the outside air temperature was 18 °C, while the inside temperature remained stable at 20 °C without the need for any type of heating system. This important finding could be the optimum benchmark for the indoor thermal comfort level of this particular prototype house (Homaei & Hamdy, 2021). The data gathered from this environmental monitoring analysis were intended for use in subsequent building simulations for dynamic thermal studies to validate the overheating risks of the prototype house described in Section 5.

4.2. Correlation analysis between indoor and outdoor environmental conditions for occupied spaces

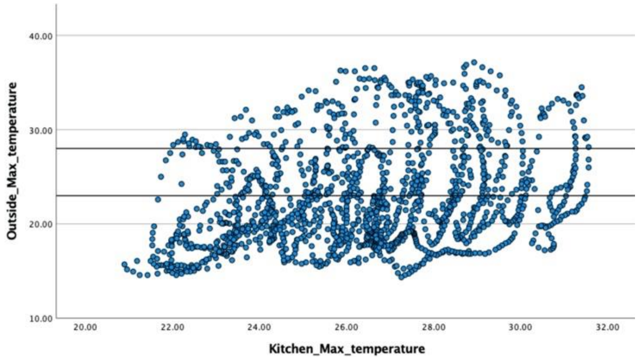
As previously mentioned, the thermal comfort variables of the case study building, including the indoor air temperature and indoor RH levels, were monitored by data loggers both on the ground and first-floor levels of the building during the summer of 2018 (see **Data set 6** – It consists of extracted data during the peak cooling period at the time of experiencing long-term heatwaves). This is because this study aimed to assess and optimise the building's performance and the occupants' thermal comfort (see **Appendix B**). This section presents the results of August, the hottest summer month to demonstrate the worst-case scenario for providing subsequent information on the implementation of the passive cooling design strategies outlined in Section 5.

The graphs in Figure 21 (a) through (f) show the correlations between maximum indoor and outdoor temperatures gathered from the data loggers. The data sets were prepared with IBM SPSS software version 25.0, and the relevant parametric tests were undertaken to assess indoor thermal comfort levels according to CIBSE TM 52 – Technical memorandum on overheating risk assessment of buildings, and the international benchmark of EN 15251 – Adaptive thermal comfort theory, as discussed in Section 1.3. These graphs were plotted to average the data logger records, since the data loggers recorded the temperature every 10 minutes. The mean constitutes the average hourly temperature of each occupied space (see **Appendix C**). The graphs reveal a common trend between indoor and outdoor temperatures throughout the monitoring period (see **Appendix D**). This was due to the fact that the monitoring period overlapped with the longest heatwave recorded both in the UK and across continental Europe at the time of undertaking this study.



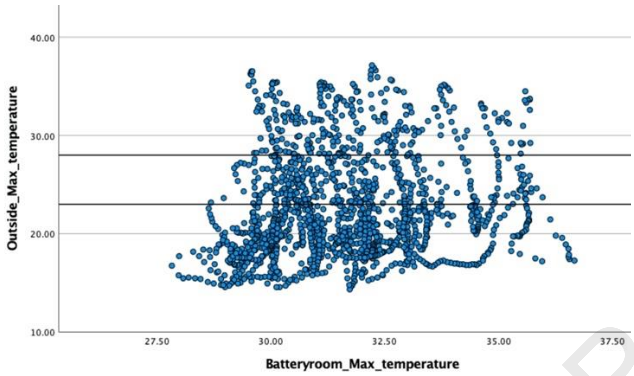
(a)

Fig. 21. (a) Correlation analysis between the outside maximum temperature and the living room maximum temperature during the heatwaves.



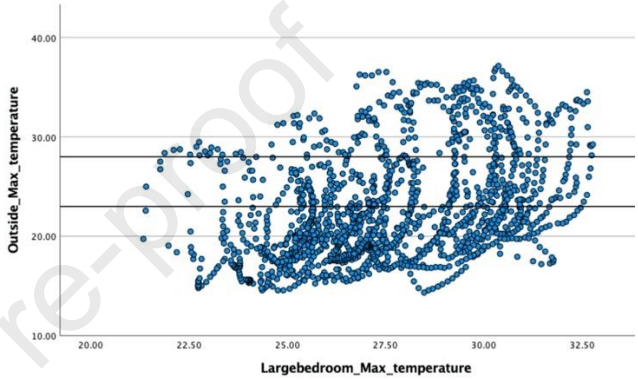
(b)

Fig. 21. (b) Correlation analysis between the outside maximum temperature and the kitchen maximum temperature during the heatwaves.



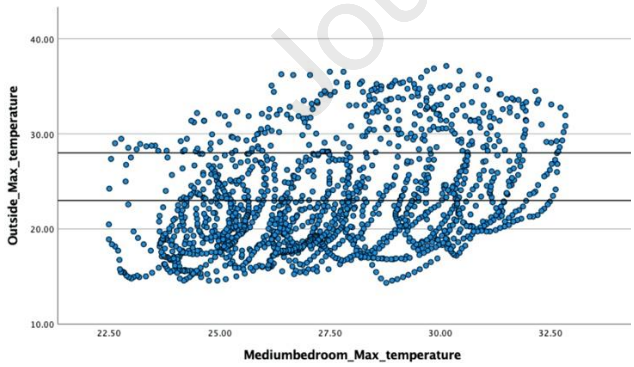
(c)

Fig. 21. (c) Correlation analysis between the outside maximum temperature and the battery room maximum temperature during heatwaves.



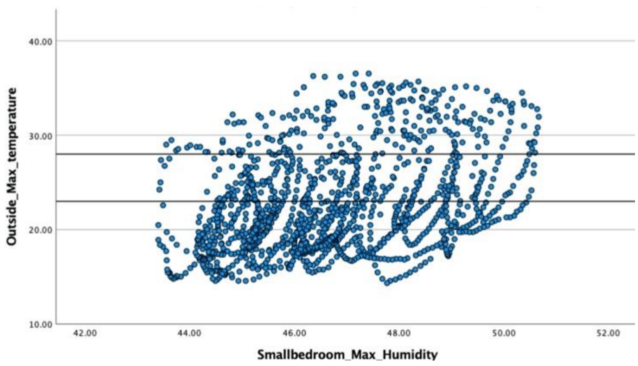
(d)

Fig. 21. (d) Correlation analysis between the outside maximum temperature and the large bedroom (bedroom 1) maximum temperature during heatwaves.



(e)

Fig. 21. (e) Correlation analysis between the outside maximum temperature and the medium bedroom (bedroom 2) maximum temperature during heatwaves.



(f)

Fig .21. (f) Correlation analysis between the outside maximum temperature and the small bedroom (bedroom 3) maximum temperature during heatwaves.

Image credits: Data was extracted from the Energy Saver online dashboard platform by the author. The scatter plots were constructed by using SPSS software suite by the author.

Overall, six rooms were monitored across the base-case building, including the living room, kitchen and battery room on the ground floor, and three bedrooms on the first-floor level, to assess the degree of overheating risk experienced in the summer. Figure 21 (a) through (f) illustrates the temperatures within each occupied space during the monitoring period. Throughout monitoring, the temperature in the occupied rooms was above 19 °C (dotted grey lines), and was often above 25 °C (solid black line).

Furthermore, the average mean temperature across all monitored occupied spaces was 24.5 °C, which is above the recommended thermal comfort levels (CIBSE Guide A, 2015). In relation to the static comfort range (CIBSE Guide A, 2006) for non-air-conditioned living rooms, the temperatures in the large bedroom were not generally in the recommended lower limit of the comfort range (25 °C), although there were some instances of temperature above 28 °C and below 22 °C. Notably, in the battery room, temperatures were significantly higher throughout the monitoring period, and at several points the temperature was above 28 °C and never below 22 °C. The average mean temperature across the six rooms monitored was 25.5 °C.

The monitoring findings revealed that, when cross-relating the indoor temperatures to external temperature data, these fluctuations happen during periods of long-term heatwaves. As Figure 21 (a) through (f) indicates, the indoor temperatures increase specifically as a result of the state-of-the-art insulation materials used for the building envelopes, suggesting that the ventilation and cooling strategies do not provide adequate overnight cooling to reduce indoor temperatures and perhaps even a lack of adequate preparation for heatwaves in terms of heat and ventilation management (Abdalla & Peng, 2021; Sakiyama et al., 2021). Figure 21 (c) demonstrates that the battery room, a non-naturally ventilated space, was generally always above 26 °C, meaning that it could not be used as a 'cool area', as recommended by the Heatwave Plan for England, without additional heat management strategies" (Yang, Javanroodi & Nik, 2021).

4.3. CO_2 emissions on building-fabric thermal performance

In order to validate the data from the monitoring study, as described in section 4.1, DTSs were undertaken to assess the CO_2 concentration level of the occupied spaces in the prototype house. These DTS studies were run from January to December to determine the overall CO_2 concentration and to create more reliable data sets for this study. As shown in Figure 22 (a), the CO_2 emissions from the prototype house were monitored from 22 June to 20 July 2018. The extracted data were from the wireless data loggers, which had been installed in the living room and kitchen on the ground floor and the large, medium and small bedrooms on the first floor (see **Data set 7** – Readings of CO_2 emissions for each occupied space during the peak cooling period in August in .sav file formatting). The aim of this investigation was to assess the impact of CO_2 concentration in indoor spaces during the longest heatwave since 1976 on the thermal comfort level of the occupants (MET Office, 2018). Figure 22 (a) through (e) demonstrate the CO_2 emissions recordings of each occupied space to understand the impact of building fabric thermal performance of archetype house.

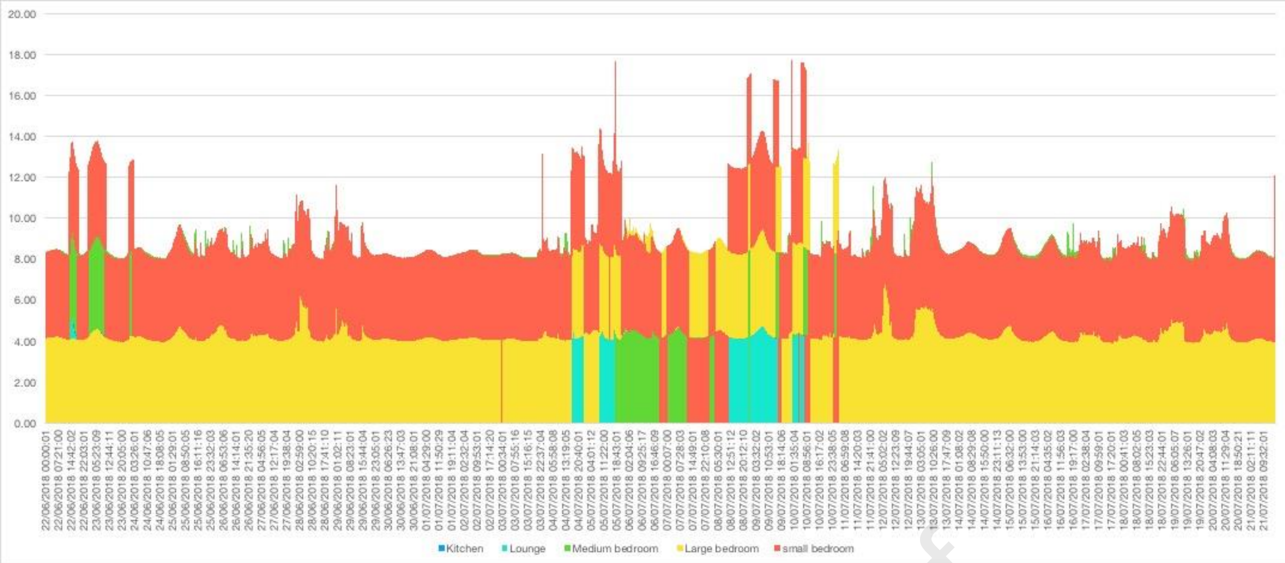


Fig. 22. (a) The monitoring results of CO_2 concentration of all occupied spaces during peak occupancy hours from 22 June to 20 July. The graph illustrates the findings generated from the data loggers that were installed in the prototype base-case. ***Note:*** Reading of recordings are equivalent as per rate x 100. ***Image credits:*** Data was extracted from the Energy Saver online dashboard platform by the author.

As shown in Figure 22 (a), the most problematic room for CO_2 emissions was the small bedroom. On 22 July, the CO_2 was 1,200 ppm, which decreased to 800 ppm before fluctuating between 800 and 1,100 ppm until 4 July. At that point, CO_2 emissions peaked at 1,400 ppm on 5 July before decreasing to 800 ppm on 7 July. Between 7 and 9 July, CO_2 emissions peaked at 1,800 ppm, which is attributable to the simultaneous peak in outdoor solar radiation to which the house was exposed. From 10 to 20 July, CO_2 emissions fluctuated from 800 ppm to 1,200 ppm.

The large bedroom showed a similar trend in its CO_2 emissions to that of the small bedroom, but the overall numbers were slightly lower. This was attributed to its southeast orientation, its two large windows (twice the size of those in the small bedroom) with 100% opening ratios, which permitted natural ventilation in the occupied spaces. As can be seen in Figure 22 (a), the CO_2 emissions from both bedrooms were above the acceptable level of 1,000 ppm. This leads to night-time sleep disruption and impacts the health of the occupants (Beckmann, Hiete & Beck, 2021).

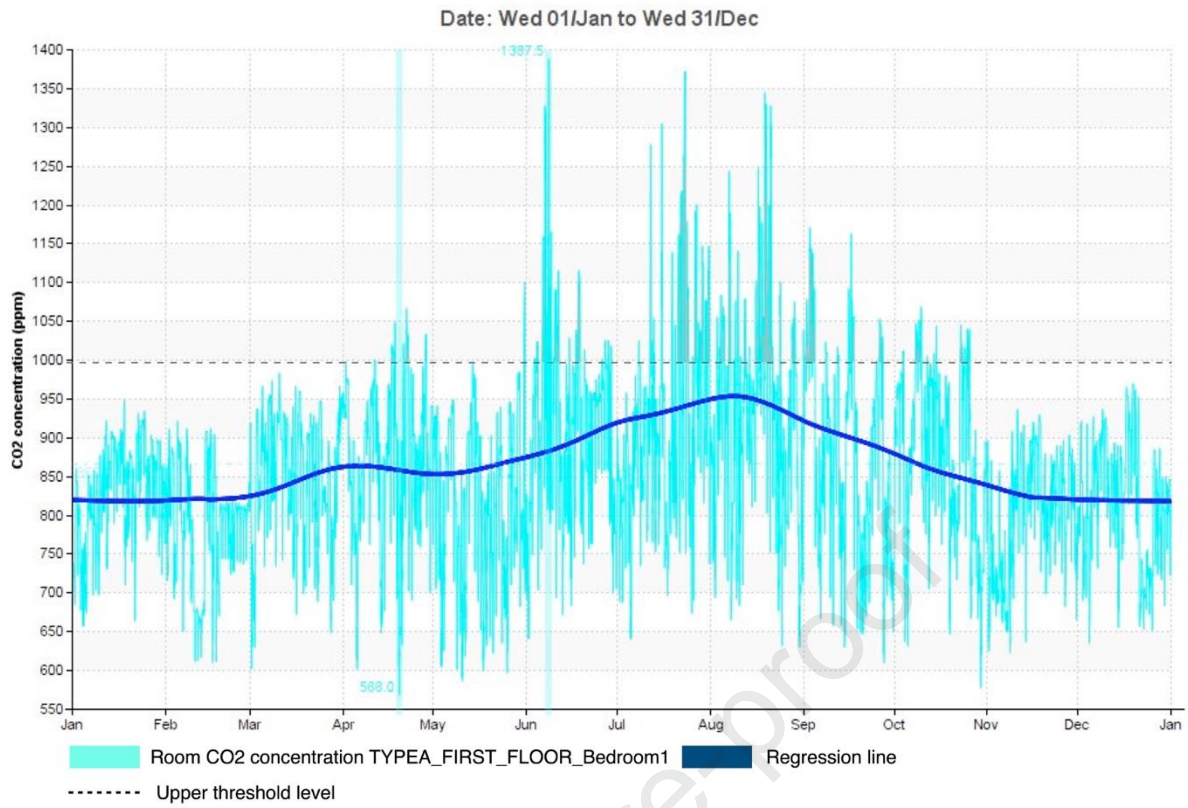


Fig. 22. (b) The annual CO_2 concentration results from the medium bedroom on the first floor. ***Image credit:*** The diagram was conceptualised by the author by using the IES – ApacheSim and VistaPro applications.

The medium bedroom, demonstrated in Figure 22 (b), showed CO_2 concentration fluctuations starting in January that ranged from 850–1,000 ppm up until the first week of June. The concentration peaked in June at 1,387.5 ppm and then plummeted to just below 1,000 ppm in mid-July. After this, it peaked at 1,300 ppm in mid-August and continued to show small fluctuations between 1,000 and 1,300 ppm until September, before decreasing slightly and fluctuating from 900 to 1,000 ppm until the end of December. The benchmark CO_2 emission for this bedroom was found to be 1,000 ppm. This is an acceptable CO_2 concentration level benchmark, as defined by the CIBSE TM 59 guidelines (CIBSE, 2017). At the same time, the regression line hovered around 800 ppm and reached its peak in August at 950 ppm, which was just below the acceptable comfort level. It then dipped down and fluctuated at the 800 ppm margin line. These results show that the data from CO_2 emissions simulations and building modelling were similar when compared; hence, they validated each other. The results from the building modelling simulation at peak CO_2 concentration levels were recorded in mid-July and were found to be 1,387 ppm. Also, monitoring of the peak CO_2 concentration level at the same time found a concentration of 1,400 ppm on 9 July.

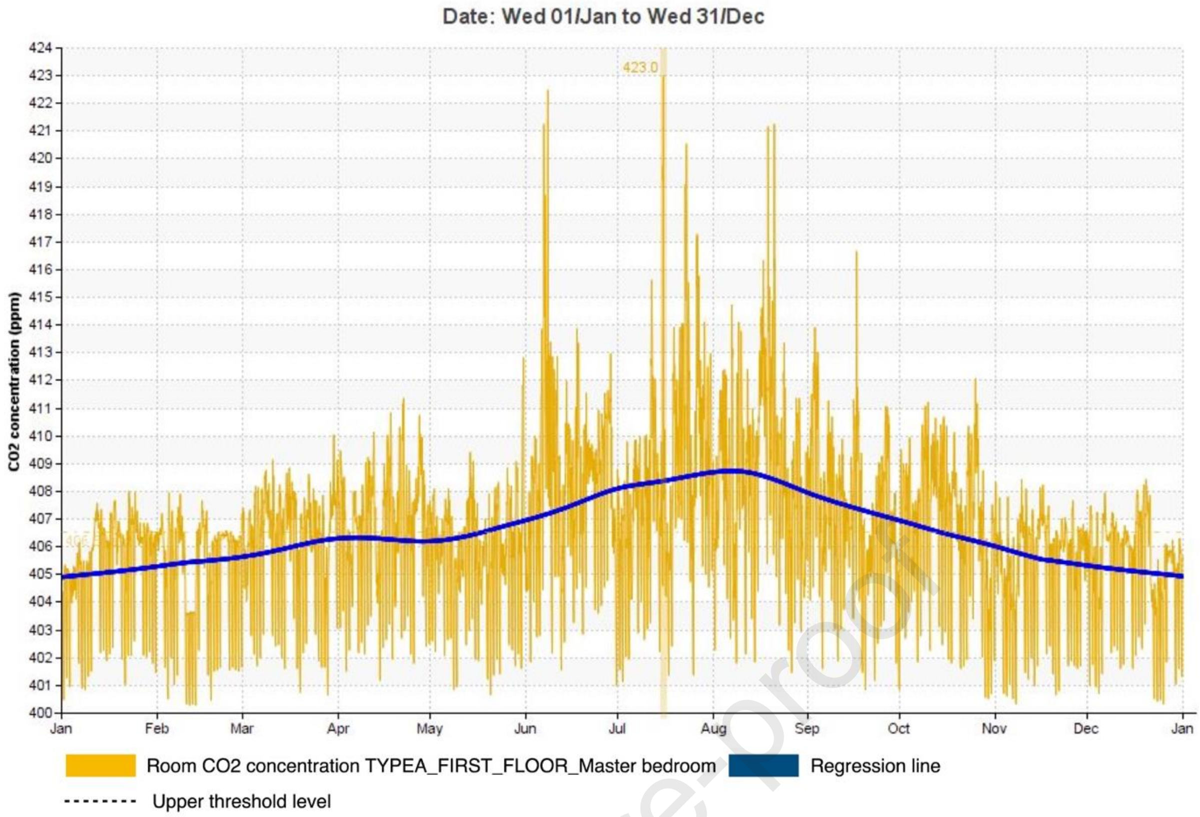


Fig. 22. (c) The annual CO_2 concentration results of the large bedroom on the first floor. ***Image credit:*** The diagram was conceptualised by the author by using the IES – ApacheSim and VistaPro applications.

Figure 22 (c) shows that CO_2 emissions in the large bedroom fluctuated from 405 to 411 ppm between January and June, at which point emissions peaked at above 422 ppm before dipping to 408 ppm in mid-July. The highest peak was recorded in mid-July, at 423 ppm. From mid-July to September, it remained at around 412 ppm. From mid-September to January, it decreased slightly, from 416 to 407 ppm. The benchmark level for the CO_2 emissions for the large bedroom was 408 ppm, and it peaked at 423 ppm in mid-July; however, the benchmark level according to CIBSE guidelines is 1,000 ppm. Hence, the CO_2 emissions of the large bedroom, even at its peak, were just below the CIBSE Guide A benchmark level (CIBSE, 2016). It can be concluded that, at peak heatwave temperature, this large bedroom's thermal comfort level would be above the necessary benchmark level for occupants' night-time sleep and health (Brimicombe et al., 2021). This can also be validated by monitoring CO_2 concentration measurements of the peak heatwave temperature in mid-July when the CO_2 concentration was 900 ppm.

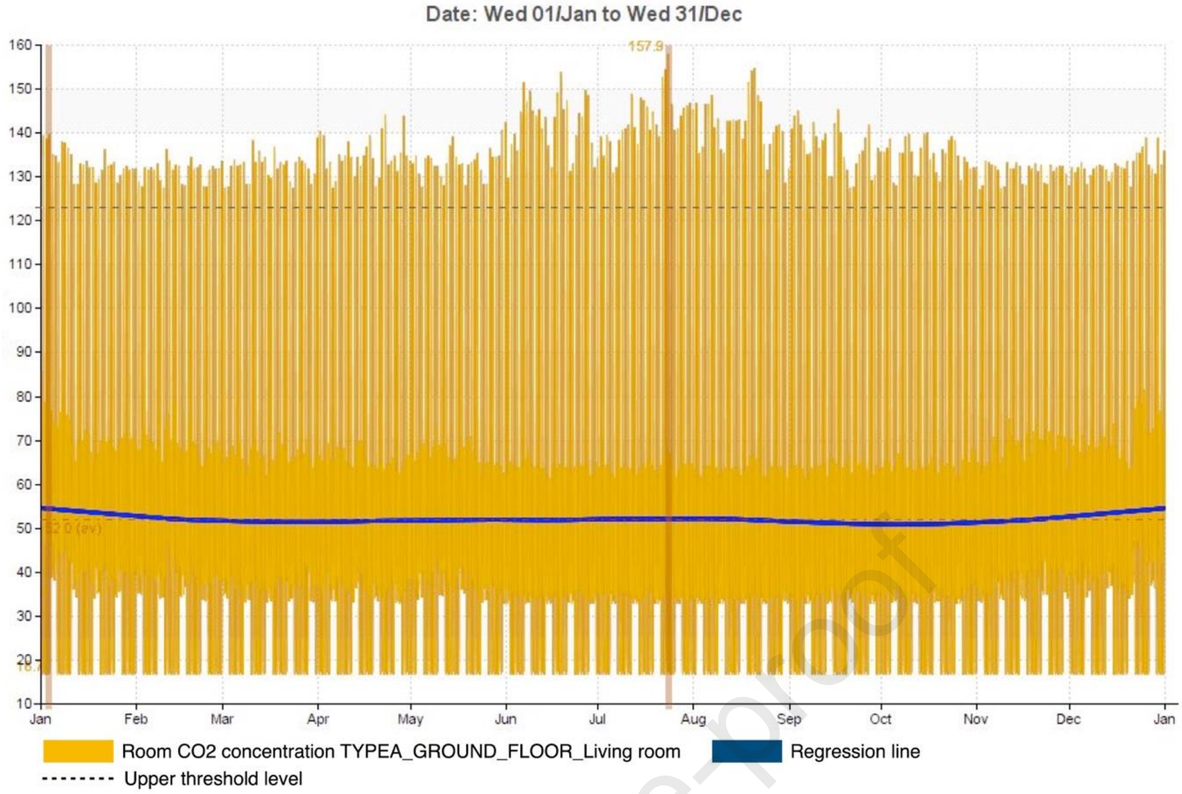


Fig. 22. (d) The annual CO_2 concentration results from the living room on the first floor. ***Image credit:*** The diagram was conceptualised by the author by using the IES – ApacheSim and VistaPro applications.

Figure 22 (d) demonstrates the CO_2 concentration in the living room starting in January. It was at 139 ppm, which fluctuated in a similar trend like one of the bedrooms until June, when it reached 150 ppm. From June to November, it peaked at 157.9 ppm and remained near this level. From November to January, it dipped again to 130 ppm. The living room benchmark level of CO_2 concentration was determined to be 122 ppm. Interestingly, this study deduced that, based on the simulation measurements, the CO_2 concentration in the living room always remained above the generated benchmark. However, according to CIBSE Guide A, the benchmark level should be 1,000 ppm for existing terraced houses in the UK (CIBSE, 2016). During the monitoring at the peak of the heatwave, we found the CO_2 concentration in the room to be 400 ppm. This data shows that there is a contrary finding to the CIBSE TM 52 technical memorandum on the overheating risk for European buildings (Gonzalez-Trevizo et al., 2021). This is because CIBSE guidelines are meant for existing terraced housing in the UK, while our findings are specifically attributed to this innovative, state-of-the-art, prototype terraced house typology (CIBSE, 2016). Hence, it is recommended that new guidelines be written for this type of building (Vettorazzi et al., 2021).

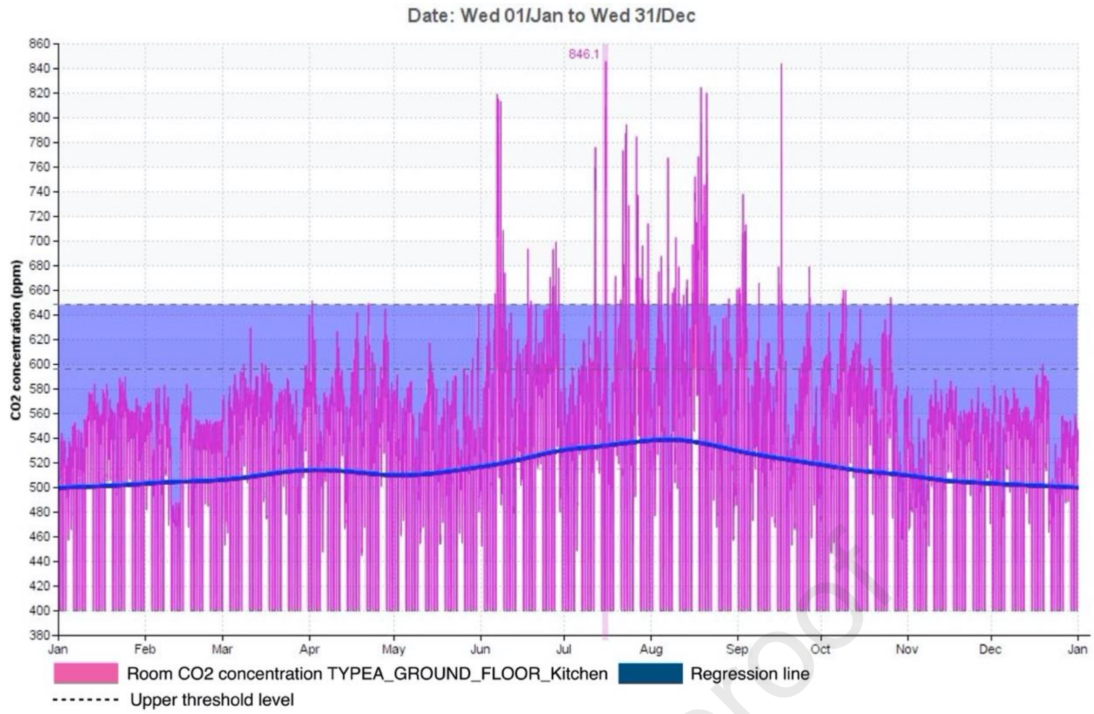


Fig. 22. (e) The annual CO_2 concentration results from the kitchen on the ground floor. ***Image credit:*** The diagram was conceptualised by the author by using the IES – ApacheSim and VistaPro applications.

Figure 22 (e) shows the CO_2 concentration in the kitchen, which started at 540 ppm in January and fluctuated from 540 to 640 ppm until June. In June, it peaked at 820 ppm and then plummeted to 660 ppm in mid-July. The highest recording, 846 ppm, was in mid-July, and then it fluctuated at near 780 ppm until mid-August. In early September, it decreased to 650 ppm and continued to fluctuate at the same level until the end of December. When comparing the graph in Figure 22 (e) to graphs in Figures between 22 (a) and (d), a significant change in the pattern can be observed due to the internal heat gains from domestic appliances. The generated benchmark for the kitchen was found to be 600 ppm. The graph shows that the overall CO_2 concentration of the kitchen was above this generated benchmark, and from June to November, it was well above this level. In the monitoring measurements during the peak of the heatwave, the kitchen was found to be above 800 ppm. Hence, the findings of the CO_2 concentration during the peak time heatwave were validated.

The results reveal that the medium bedroom was susceptible to reaching 1,387.5 ppm, which is well above the acceptable threshold limit. This trend was similar to that of the large bedroom situated on the first-floor level. What is interesting about these findings is that high outdoor temperature fluctuations led to changes in the thermal transmittance of building materials. Because of this physical change, the CO_2 level increased significantly in those rooms. Notably, the findings related to the change in thermal transmittance of the building materials were from the first-hand experience of the occupant, which was validated using monitoring data and simulations. We observed that, during this heatwave monitoring period, the battery room temperature ranged from 30 °C to 36 °C due to its position and location on the ground floor of this prototype house. This room provided secondary heat gains to adjacent spaces, which led to further increases in their heat stress index. The CO_2 concentration in the battery room was not monitored, but it can be assumed to be high due to the presence of a battery storage system in this room. Hence, in order to avoid the abovementioned negative effects, it should be recommended that the battery room's location be moved to another part of the building, which would provide space for ventilation to cool it down.

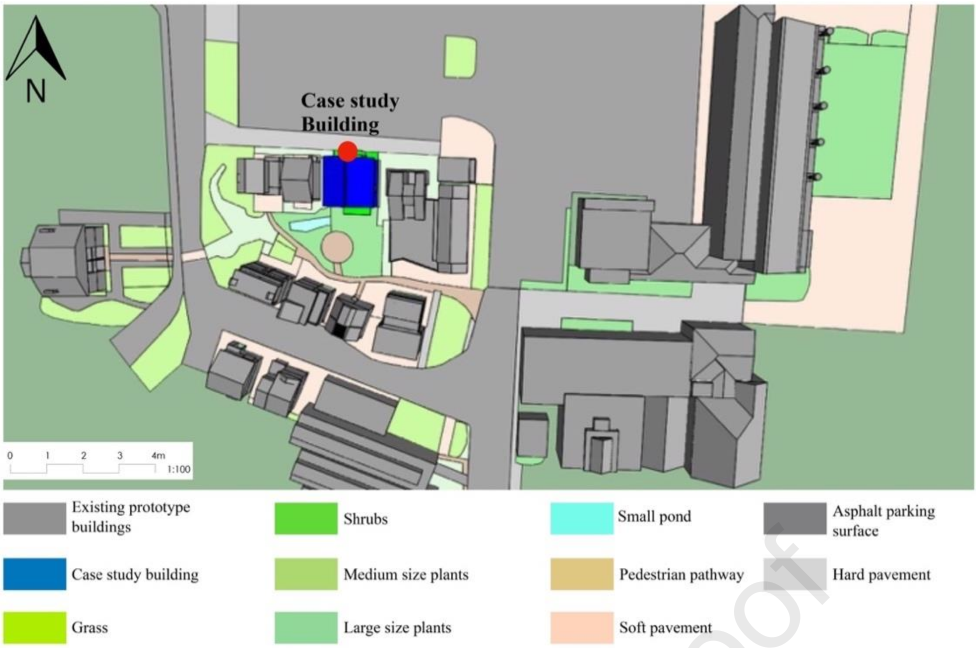
5. Empirical results

This section discusses the impact of both the state-of-the-art, energy-efficient building systems and passive cooling design strategies' applicability on retrofitting base-case representative buildings for optimising occupants' thermal comfort and reducing the risk of overheating in summer. The innovative terraced house was modelled in IES' software suite, including the extensive modelling of the surrounding environment, to predict the impact of the mutual shading factor, high albedo surface frequency and vegetation at the BRE Innovation Park (as described in section 3.4), as shown in Figure 23 (a), (b) and (c). (See **Video B**, which illustrates the solar exposure analysis of the base-case buildings within consideration of surrounding buildings in order to measure the impact of the mutual shading factor on the overheating risk assessment).

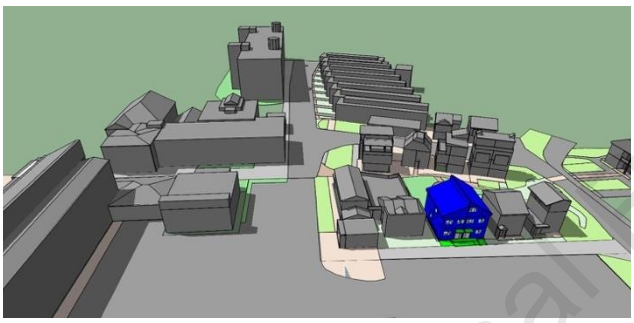
5.1. Analysis of the retrofit strategies investigated for base-case scenario development

In order to calibrate the energy performance of the representative terraced house typology accurately, the recommended new *U*-values of the building fabric enhancements, occupancy patterns, window opening schedules, lighting and equipment loads, and ventilation on the internal temperature were embedded in the set of input parameters of the building energy simulation model (see **Data set 8** – Analytical building energy simulation model constructed in IES software platform in .gbxml file formatting). This section also describes the most sensitive building fabrics in terms of the corresponding percentage of time of comfort temperature. The goal here is to establish the specifications of a resilient building envelope to effectively deal with the changing excessive outdoor air temperatures, as the current building envelope assigned to the simulation model presented poor performance in the current climate (TRY) (Nicol et al., 2009; Nicol et al., 2012).

The state-of-the-art, energy-efficient building systems of different building envelopes, with respect to the wall, roof, floor and window properties was carried out. The calibration studies were retained from the TRY and AMY weather files included in the construction material details and thermal properties of the base-case building to predict the energy efficiency of the passive cooling design systems (Zou et al., 2021). The results of the dynamic thermal simulations were analysed in terms of the percentage of hours of thermal comfort in order to validate the occupants' thermal sensation findings in line with the previously undertaken statistical tests described in section 4.2. The recommended adaptive thermal comfort limit is 23 °C to 28 °C according to the CIBSE Guide A; thus, any temperature below 23 °C is considered a thermally comfortable indoor environment, and if the temperature is above 28 °C, it is considered that space, when occupied, is at risk of overheating during the summer (Pajek & Košir, 2021).



(a)



(b) (c)

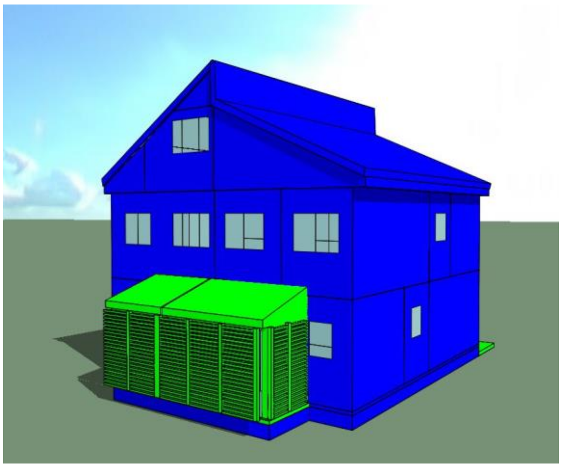
Fig. 23. (a) The site map of the energy analytical model of the BRE Innovation Park with the detailed adjacent buildings and landscape elements. **(b)** The location of the case study building and its integration within the BRE Innovation Park – the front façade of the building is towards the high albedo surface of the car park area (northeast). **(c)** The loggia space faces the landscaped garden area (southwest), which receives high levels of solar radiation throughout the day. ***Image credits:*** 3D renderings were modelled by the author using IES software suite – ModelIT and VistaPro applications.

The following steps describe the evaluation of potential passive cooling design strategies for reducing the risk of overheating and optimising the occupants' thermal comfort within the prototype house (Cillari, Fantozzi & Franco, 2021; Nicol, 2017). To assess the overheating risk and thermal comfort of the passive design retrofitting when there was no heating, ventilation or air-conditioning (HVAC) system for each scenario, the thermal performance of the prototype house was studied (see **Video C** – Analytical model of prototype house), comparing the hours of discomfort by using the CIBSE TM 52 as described in Section 1.3. For this analysis, six design alternatives were tested to assess the efficiency of each as a potential retrofit scenario. It is important to highlight that the tested passive design strategies were applied to purpose-built structures and then to the prototype building without changing the assigned construction material characteristics from their current state (Reis, Figueiredo & Samagaio, 2021). This type of application was intentionally implemented to test both the feasibility and the applicability of the various passive design strategies without altering of the existing envelope of buildings (de la Flor et al., 2021). A list of the strategies in this building performance evaluation and optimisation study, including the methods for analysis and descriptions, are shown in Table 7.

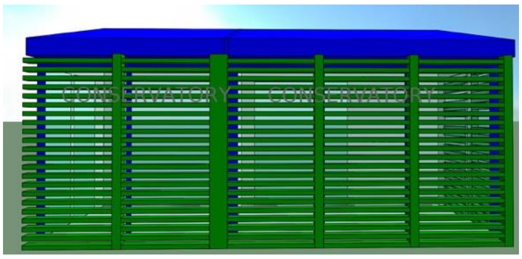
Table 7
The design scenario development of energy-efficient retrofit strategies investigated for the existing base-case.

Strategy	Strategy Description	Analysis Method	Dynamic Building Simulations
Base-case	Base-case design	Thermal performance	Current assigned construction materials
Strategy 1 (S1)	Proposed design	Thermal performance in the living room	Base-case design + volumetric sunspace addition Base-case design + operable pine wood external shutters Base-case design + BIPV systems on the roof
Strategy 2 (S2)	Natural ventilation analysis	Thermal performance in both the ground- and first-floor circulation areas	Base-case design + wind catcher system Base-case design + skylight Base-case design + operable pine wood external shutters
Strategy 3 (S3)	Natural ventilation analysis	Thermal performance in the kitchen, medium and small bedrooms	Base-case design + window opening projections Base-case design + overhang window canopy Base-case design + horizontal external pine wood louvers
Strategy 4 (S4)	Natural ventilation analysis	Thermal performance in the large bedroom	Base-case design + volumetric window opening projection Base-case design + folded window system Base-case design + overhang window canopy Base-case design + operable pine wood external shutters
Strategy 5 (S5)	Floor plan layout reconfiguration	Thermal performance in the kitchen	Base-case design + open plan layout design Base-case design + folded internal partitions
Strategy 6 (S6)	All proposed designs	Thermal performance	Base-case design in the combination of S1+S2+S3+S4+S5

The aim was to make the prototype house more comfortable thermally for the occupants and to combat exacerbated heatwaves in the summer in a given geographic location in south-eastern England, Watford, United Kingdom (see **Video D** – Solar shading analysis of baseline prototype house). The strategies, i.e. S1, S2, S3, S4, S5 and S6, were first applied separately, and the required results were obtained. Then they were applied together to test the effectiveness of the design strategies as a whole. S1 was a volumetric sunspace with operable external shading devices added to the living room's southwest-facing decking area. This addition was in the form of a room extension, with measurements of 3.2 (length) x 1.5 (width) x 3 (height) m, and a slanted roof with terra cotta BIPV solar panel systems, as shown in Figure 24 (a) through (c). The external walls were made of double-glazed glass with folded windows. The whole of the exterior had operable pinewood shutters. The living room was chosen because, based on the monitoring findings, it was the worst-performing room under the threat of overheating. The aim of this strategy was to assess by how much the overheating risk could be decreased in the living room simply by applying this passive design application. The simulation findings revealed that there was a significant decrease in energy consumption and a simultaneous increase in stored electricity, with an added factor from the increased solar panel roof area of this intervention (Gainza-Barreencua et al., 2021).



(a)



(b)

Fig. 24. (b) The operable horizontal louvres were installed to avoid excessive solar radiation throughout the day (0.6 x 2.10 m) – (0.10 x 0.6 cm).

(c)

Fig. 24. (a) The volumetric sunspace addition was installed on the southwest-facing existing decking area of the prototype house in S1.

Fig. 24. (c) The volumetric room addition allowed for more liveable space and provided more natural ventilation (1.8 x 2.10 m).

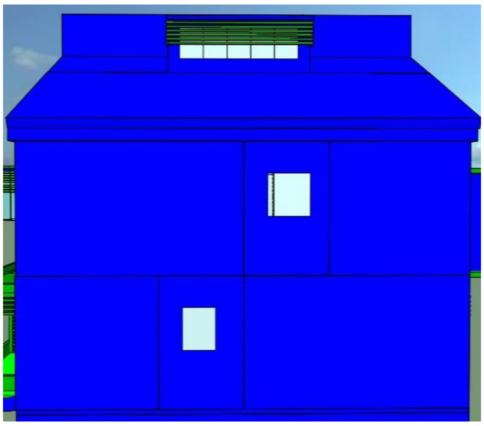
Image credits: 3D renderings were modelled by the author using IES software suite – ModelIT and VistaPro applications.

Table 8

The results of the overheating risk assessment for the implemented S1.

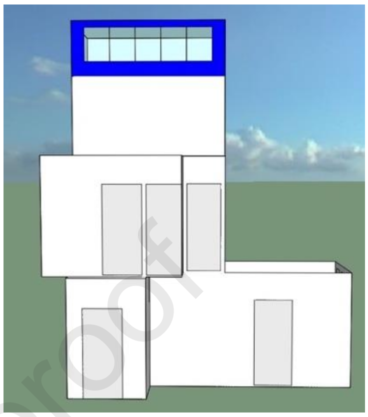
Room Name	**Criterion 1** (%Hrs Top-Tmax ≥ 1K)	**Criterion 2** (Max. Daily Deg. Hrs)	**Criterion 3** (Max. ΔT)	**Criterion failing**
TYPEA_FIRST_LARGEBEDROOM	1.4	10	4	2
TYPEA_FIRST_MEDIUMBEDROOM	0	0	0	-
TYPEA_GROUND_KITCHEN	9.9	40	11	1&2&3
TYPEA_GROUND_LIVINGROOM	4.2	19		1&2&3
TYPEA_GROUND_CIRCULATION	0.1	2	1	-
TYPEA_FIRST_SMALLBEDROOM	0	0	0	-

This building was already constructed to be energy efficient, but the application of this passive design increased its energy-efficient potential and reduced the risk of overheating, as shown in Table 8. The heating energy consumption before the intervention was measured at 163.97 kWh/m^2. After the implementation of S1, the annual heating consumption was 83.73 kWh/m^2. The annual electricity consumption of these purpose-built, energy-efficient terraced housing units with three bedrooms in the UK is 638.45 kWh/m^2. It has been found that the use of a combination of energy-efficient, purpose-built prototype housing with a passive design strategy result in decreased energy consumption and optimised thermal comfort (Porritt et al., 2012; Psomas et al., 2016). The amount of available excess energy from the terra cotta roof panels was 157.35 kWh/m^2 before this intervention. After the implementation of S1, the excess energy from the BIPV systems was 196.6 kWh/m^2. Therefore, the addition of another 5 m^2 of BIPV solar panel systems to the roof of the retrofitted space led to a 10% increase in excess storable electrical energy. This volumetric sunspace addition was chosen because it is a very simple, cost-effective way to increase the volume of the indoor living space, with an added increase in the occupants' thermal comfort, and a decrease in energy costs (Shrubsole et al., 2014; Sunikka-Blank & Galvin, 2012).



(a)

Fig. 25. (a) The windcatcher system was installed on the roof in order to harness more daylight and to provide natural ventilation in the occupied spaces (1.2 x 2.10 m) in S2.



(b)

Fig. 25. (b) The traditional windcatcher system provided an effect driven by 'air buoyancy' in the occupied spaces (1.2 x 2.10 m).

Image credits: 3D renderings were modelled by the author using IES software suite – ModelIT and VistaPro applications.

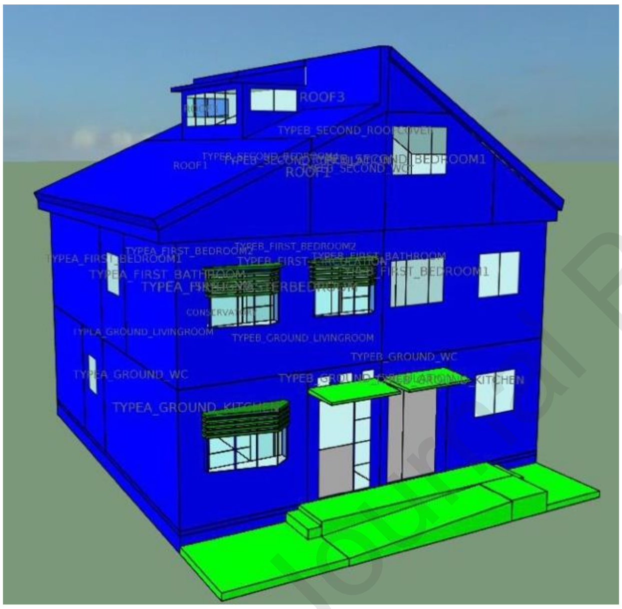
Table 9

The results of the overheating risk assessment for the implemented S2.

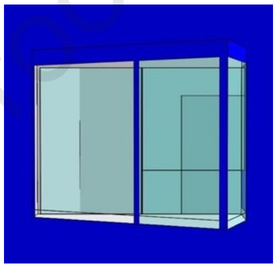
Room Name	**Criterion 1** (%Hrs Top-Tmax ≥ 1K)	**Criterion 2** (Max. Daily Deg. Hrs)	**Criterion 3** (Max. ΔT)	**Criterion failing**
TYPEA_FIRST_LARGEBEDROOM	0.9	7	3	2
TYPEA_FIRST_MEDIUMBEDROOM	0	0	0	-
TYPEA_GROUND_KITCHEN	9.5	33	8	1&2&3
TYPEA_GROUND_LIVINGROOM	4.5	25	7	1&2&3
TYPEA_GROUND_CIRCULATION	0	0	0	-
TYPEA_FIRST_SMALLBEDROOM	0	0	0	-

In order to combat the overheating risk for all living spaces, S2 was chosen to test the efficiency of the passive ventilation system in the building, as shown in Figure 25 (a) and (b). A traditional windcatcher system was applied to the roof, wherein one part of the roof was elevated with a rectangular wedge, measuring 3.6 (length) x 2.00 (width) x 1.2 (height) m, as shown in Figure 25 (a). The construction design was such that the roof design remained comprised of terra cotta BIPV solar panel systems, and the south-facing area of this intervention was constructed out of double-glazed glass with window panels with a 100% opening ratio. For the exterior of this window surface, horizontal, external fixed pinewood shutters were designed for shading. The side-opening surfaces were constructed out of double-glazed window panels. The aim of S2 was to provide natural ventilation to the inside spaces from above, or the air-buoyancy driven natural ventilation effect, whereby the accumulated heat of the indoor air temperature circulates to the outside; this lowers the indoor temperatures.

The main aim of applying the S2 retrofitting design system to this prototype house was to reduce the overheating risk during heatwave periods and to decrease electricity consumption for energy efficiency, as shown in Table 9. Most importantly, the cooling effect from this natural ventilation proved sufficient to eliminate the need for energy use in cooling systems. The calibrated cooling energy consumption was measured at 163.97 kWh/m^2 after this retrofitting intervention, and the cooling energy consumption was 57.8 kWh/m^2. There was a 62% reduction in energy consumption. It is important to also highlight that, after this intervention, the indoor thermal comfort of the downstairs hallway, staircase circulation areas, living room, medium bedroom and small bedrooms was within the acceptable limits as defined by CIBSE Guide A (CIBSE, 2016; 2017). However, the indoor air temperature of the master bedroom and kitchen remained slightly higher than the acceptable thermal comfort level benchmark.

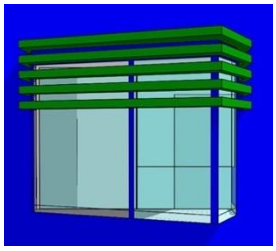


(a)



(b)

Fig. 26. (b) The operable window openings with a 100% opening ratio (0.6 x 0.9 m), a 50% opening ratio (0.4 x 0.9 m), and a 20% opening ratio (0.3 x 0.9 m).



(c)

Fig. 26. (a) The overhanging window projections were installed in all customised window openings on the external wall surfaces within the fixed horizontal louvre systems to reduce the impact of excessive solar heat gains in S3.

Fig. 26. (c) The fixed horizontal louvres were installed on the overhanging window projections.

Image credits: 3D renderings were modelled by the author using IES software suite – ModelIT and VistaPro applications.

In S3, the standard PolyVinyl Chloride (PVC) windows, which were situated in the kitchen, master bedroom and medium and small bedrooms, were replaced with volumetric, modular, overhanging windows made of double-glazed glass with panels that have 100% opening ratios, as shown in Figure 26 (a) through (c). For these windows, an angular overhanging shading system was applied approximately halfway down from the top. These operable shading systems were constructed out of pinewood and were fixed. The functions of this shading system are to absorb wind from different angles and to circulate natural ventilation to indoor spaces.

This simultaneously reduces excessive incoming solar radiation and the risk of overheating, as shown in Table 10. These two effects, when combined, led to a 2 °C decrease in the indoor air temperature. However, when these are implemented, the results show that the indoor air temperature remains slightly higher than the acceptable benchmark (Brown et al., 2019). It is also important to highlight that the calibrated cooling consumption before this intervention was 163.97 kWh/m^2. After this retrofit intervention, the cooling consumption was 76.54 kWh/m^2. This shows a 32% reduction achieved through the use of overhanging window projection design systems.

Table 10
The results of the overheating risk assessment for the implemented S3.

Room Name	**Criterion 1** (%Hrs Top-Tmax ≥ 1K)	**Criterion 2** (Max. Daily Deg. Hrs)	**Criterion 3** (Max. ΔT)	**Criterion failing**
TYPEA_FIRST_LARGEBEDROOM	1.2	8	3	2
TYPEA_FIRST_MEDIUMBEDROOM	0	0	0	0
TYPEA_GROUND_KITCHEN	9.7	35	9	1&2&3
TYPEA_GROUND_LIVINGROOM	4.9	26	7	1&2&3
TYPEA_GROUND_CIRCULATION	0	1	1	
TYPEA_FIRST_SMALLBEDROOM	0	0	0	0

(a)

(b)

Fig 27. (b) The top window openings with a 20% opening ratio (0.6 x0.4 cm).

(c)

Fig. 27. (a) The modular volumetric space projection was installed in the large bedroom area to regulate both exposure to solar radiation and natural ventilation at night in S4.

Fig. 27. (c) The overhanging roof projection and operable horizontal louvres were installed on external surface of the folded window openings.

Image credits: 3D renderings were modelled by the author using IES software suite – ModelIT and VistaPro applications.

S4 required the large bedroom (a room with a high risk of overheating, particularly during heatwaves) to be retrofitted with an overhanging window space using the fenestration design in Figure

27 (a) through (c). This was done by removing the two existing windows, opening the space between them, and lowering the opening to the room's floor level. This retrofitted window protruded beyond the building's wall. The window openings were constructed from double-glazed glass with folded window panels. At the same time, these window panels were divided into upper and lower parts; the top part had small openings to the outside, while the lower part had long opening sections. The aim was to acquire natural ventilation as needed at night; with this extended window opening, a large surface area was gained to provide natural ventilation for the indoor space, which was intended to cool the room and lower the indoor air temperature. However, this enabled the direct entry of solar radiation into the large bedroom, which was southeast-facing and received direct sunlight throughout the day, leading to the overheating of the space.

Table 11

The results of the overheating risk assessment for the implemented S4.

Room Name	**Criterion 1** (%Hrs Top-Tmax ≥ 1K)	**Criterion 2** (Max. Daily Deg. Hrs)	**Criterion 3** (Max. ΔT)	**Criterion failing**
TYPEA_FIRST_LARGEBEDROOM	0	0	0	-
TYPEA_FIRST_MEDIUMBEDROOM	0	0	0	-
TYPEA_GROUND_KITCHEN	9.1	27	7	1&2&3
TYPEA_GROUND_LIVINGROOM	3.2	8	3	1&2
TYPEA_GROUND_CIRCULATION	0.1	1	1	-
TYPEA_FIRST_SMALLBEDROOM	0	0	0	-

In order to combat the problem of heat mitigation caused in S4's window design, the overhanging roof projection was implemented, in addition to placing the volumetric window with horizontal pinewood louvres on the upper part and the lower part of this window, leaving an open space in between. The intent of this retrofitting was to decrease the master bedroom's exposure to excessive solar radiation. The top window openings were designed so that they could be opened at night to allow for natural ventilation and lower indoor air temperatures during sleep. This design had a significant impact on the indoor air temperature of the master bedroom. According to the measurement figures from the monitoring and simulation studies, the indoor temperature was 30.6 °C.

After the implementing this strategy, the indoor air temperature was 23.4 °C. The data validated that applying this retrofitting strategy allowed the indoor air temperature to be lowered sufficiently to reduce the risk of overheating and provide optimal thermal comfort for the occupants, as shown in Table 11. Additionally, the calibrated cooling consumption of the large bedroom was 163.97 kWh/m^2 before retrofitting. After retrofitting, it was lowered to 42.78 kWh/m^2. Therefore, an 53% reduction in cooling consumption was achieved.

The S1, S2, S3 and S4 strategies were applied and tested using step-by-step applicable retrofit strategies in addition to the base-case. S2 proved to be the most effective in addressing the three criteria for overheating (CIBSE, 2016, 2017). After the implementation of these step-by-step strategies, the overall effect achieved a reduction in the indoor air temperature in all rooms except the kitchen. The next implementation was S5, which was the combined application of all four preceding strategies for the overall effects of these retrofitting implementations, as shown in Figure 27 (a). The DTS measurements of the combined strategies in the prototype house show that indoor air temperatures for all rooms were at an acceptable benchmark comfort zone level, ranging from 23 °C to 25 °C (Nicol, 2017; Nicol et al., 2009). In spite of this favourable result for the indoor living space, the kitchen's indoor air temperature remained high, at 29.5 °C, due to the impacts of both internal and external environmental conditions. One factor was the floor plan layout design, which was small and compact, with composite cladding panel systems for its external walls. There were also internal heat gains from the domestic appliances and their position in the building, which faced both southeast and southwest, as both surfaces were exposed to long hours of solar radiation during the day.

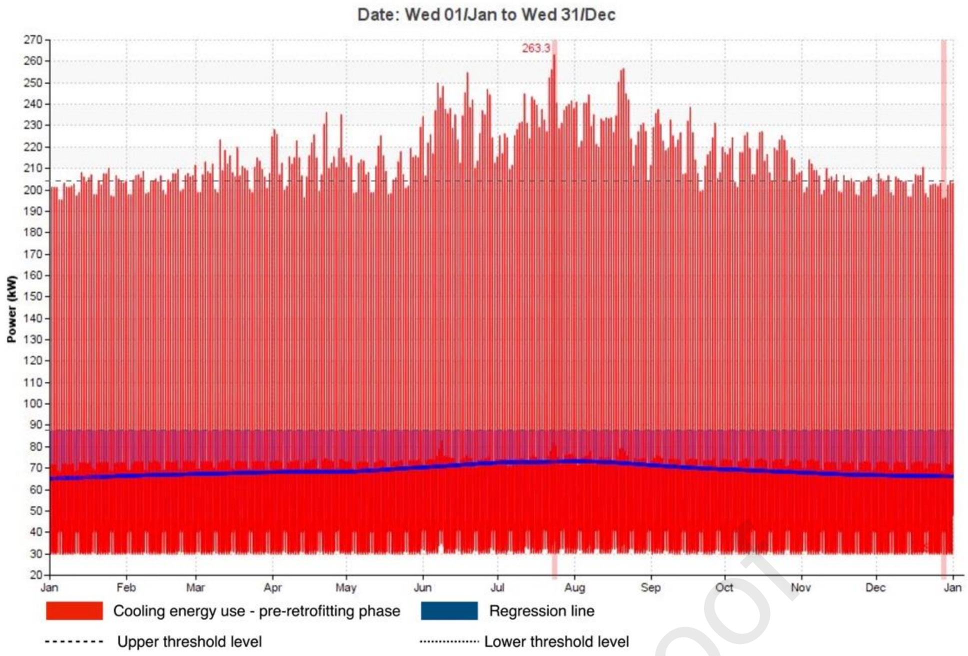
In order to achieve the optimum indoor air temperature for all living spaces, including the kitchen, another strategy was devised. This time, rather than retrofitting just the existing base case of the prototype building, an internal floor plan layout reconfiguration was applied, whereby the wall between the kitchen and the entrance hallway area was removed to capture more daylight and ventilation. The entrance door was also changed to include glass and opening window panels on the top portion. Through the application of this strategy, the kitchen indoor air temperature was lowered by 5 °C to 24.5 °C, which is the optimum comfort level temperature. This shows that, in parallel with the aforementioned passive design strategies, which were all volumetric and modular, maximising the effects of the spatial configuration must be considered as part of the retrofitting of this prototype house. Table 12 displays the results of these overheating risk assessments based on the six proposed design strategies implemented in the base case design for the prototype house.

Table 12

The overall overheating risk assessment after implementing six passive design strategies on the existing base.

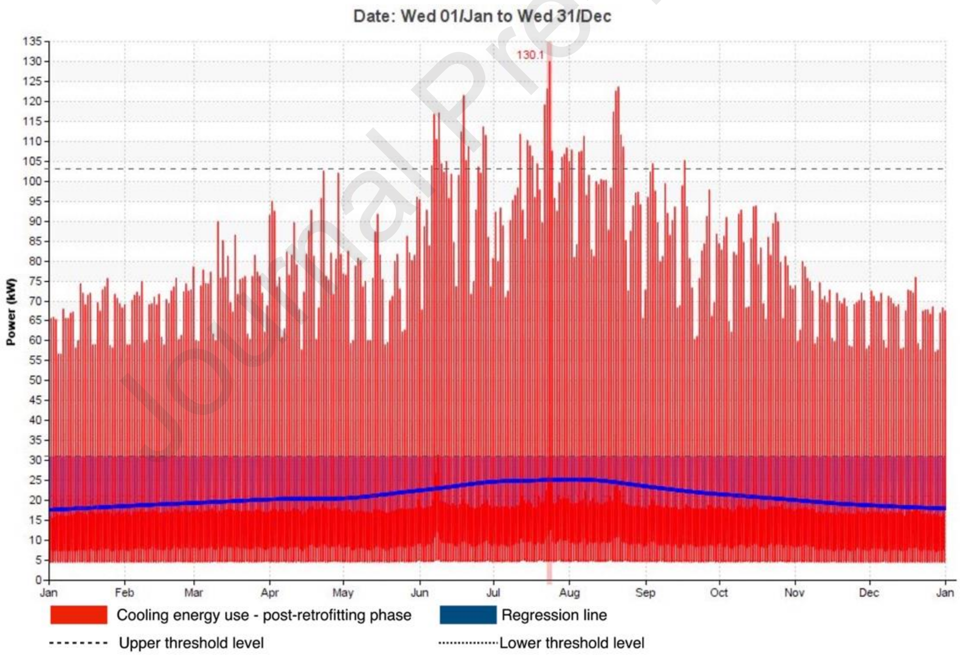
Room Name	**Criterion 1** (%Hrs Top-Tmax ≥ 1K)	**Criterion 2** (Max. Daily Deg. Hrs)	**Criterion 3** (Max. ΔT)	**Criterion failing**
TYPEA_FIRST_LARGEBEDROOM	0.2	2	1	-
TYPEA_FIRST_MEDIUMBEDROOM	0.1	1	1	-
TYPEA_GROUND_KITCHEN	0	0	0	-
TYPEA_GROUND_LIVINGROOM TYPEA_GROUND_CIRCULATION	0.1	1	1	-
TYPEA_FIRST_SMALLBEDROOM	0.2	1	1	-

The energy performance simulations and investigation and the optimisation of the different building components' structures demonstrated that there were significant differences in cooling loads in the base-case prototype houses. The results of the simulations were analysed to understand the existing energy use conditions and, thereby, to calibrate the energy consumption patterns, primarily the cooling demand of the occupied indoor spaces during long-term heatwave periods in the summer (Wang et al., 2021). In terms of examining the energy consumption with respect to specific heat losses, the prototype house consumed 174.4 kW/m^2 of its energy during the pre-retrofitting phase and 17.1 kW/m^2 during the post-retrofitting phase through its HVAC system, as shown in Figure 28 (a) and (b).



(a)

Fig. 28. (a) The total electricity consumption of the base-case prototype house pre-retrofitting.



(b)

Fig. 28. (b) The total electricity consumption of the base-case prototype house post-retrofitting.

Image credits: Diagrams were conceptualised by the author by using the IES – ApacheSim and VistaPro applications.

Based on the analysed and tested passive design measures, representative of all occupied indoor spaces of the prototype house, the efficiency of these systems in the southeast-facing occupied spaces was evaluated. The results indicated that using the windcatcher systems to harness natural ventilation with the external Venetian blinds in S2 was the most efficient passive design system for the summer; in particular, the blinds were most effective when tilted at 30°. To maximise these benefits, combining the shading system with a building automation system that manages the openings in a dynamic way might be useful. Additionally, in both S2 and S3, the insertion of the shading system into the existing window openings or the addition of a volumetric space to the existing building provided effective results, especially when combined with horizontal blinds tilted to a 30° angle. The depth of the window opening projection (analysed for dimensions between 0.8 and 1.2m) had a limited effect on the amount of solar radiation the room was exposed to.

The shading system that was perpendicular to the façade with horizontal blinds in S3 and the opaque horizontal overhang in S5 had a similar performance but far lower cooling energy consumption than previously analysed (on the order of 50%). In sum, the arising considerations confirmed the effectiveness of the analysed sunshades for the southeast-facing position and emphasised the highly efficient performance of the external Venetian blind systems in S2, the configuration with volumetric window opening projection and an integrated shield, as well as the sunshade perpendicular to the facade with horizontal blinds in S5.

5.2. Limitations of the implementation of passive cooling design strategies

The construction industry is undeniably leaning towards a more sustainable environment in which residential buildings characterised by a low energy demand are challenging for the policy implications in retrofitting (Berardi, 2013a; Tozer, 2020; Tootkaboni et al., 2021). Significant resources are being spent researching efficient ways of reducing built asset maintenance energy consumption (Berardi, 2013b; Monzón-Chavarrías et al., 2021). Most of the research already carried out in this field, however, has only focussed on a building's energy performance as a single entity (Shi, 2019; Wei & Skye, 2021). Recently, the concept of the microenvironment related to the thermal efficiency of a building has become more popular, and as a result, researchers have started to embrace a more holistic view the individual spaces while also concentrating on the buildings (Wright et al., 2013; Berardi, 2015, 2016; Wang et al., 2021). In this study, we found that passive design is a conscious design process that takes into account and maximises the potential of the site, including its natural ventilation, sun exposure and other site features (see **Videos A and B**), using them to heat and cool the building at a minimum cost, intended as a benefit to both monetary realities and the natural environment. However, passive design strategies have some restrictions in an urban context, where tight spatial requirements might hinder the process, causing adverse mutual effects between buildings (Mavrigiannaki et al., 2021). The reciprocal effects can, in turn, create microenvironments and influence the energy consumption of the building, as has been proven by Gupta et al. (2019). The UHI effect is the array or complex of every building that, in different ways because of proximity, has an influence on other structures.

The research presented in this paper takes, as a base-case scenario, the mutual shading impact factor made by other prototype innovative housing typologies constructed on the same demonstration project site at the BRE Innovation Park; more precisely, two semi-detached terraced housing typologies presenting similar thermal properties and building codes but different sun exposure. It is important to note that these two buildings are characterised by proximity, which influences the solar gains and internal temperatures of each occupied space differently. The findings indicate that there is a discrepancy between the aggregated energy consumption and the quantification of passive design measures in the base-case scenario, which was discussed in Section 4. This is because the existing thermal properties of a building can have a greater influence on the solar gain of each occupied space and ultimately on overall energy consumption. Therefore, the research presented in this paper was based on the environmental monitoring and simulation of a specific location and time frame. Mutual reflection from the adjacent buildings and passive shading systems, however, have different impacts in different geographical areas of the world, which need to be carefully analysed over a year or similarly extended time frame to obtain a better overall assessment of energy use and occupants' thermal comfort in residential buildings (Caro & Sendra, 2021; Linhares, Hermo & Meire, 2021).

5.3. Limitations of the environmental monitoring and sample size

This section explains the methodology developed and presents some limitations that result from the setups of environmental monitoring, building energy modelling, archetype sampling recruiting procedure and discrepancies detected for overheating risk assessment of passive cooling design strategies. Hence, this study was found to explore a number of questions to be investigated in future research. These include the following:

- **Confidentiality:** Visual information allowed to validate the *in-situ* measurements and confirm or reject the subject respondents' thermal sensation votes. In previous longitudinal field studies, conducting a field survey may be an issue, therefore future research may develop to survey and diagnose with a wireless monitoring device. This would require a more through calibration process.
- **Sample:** Although the main study sample was well distributed within the sample frame, the number of representativeness of European housing stock remains relatively small to detect discrepancies between subject respondents' thermal sensation and actual environment conditions monitored. One of the main barriers remains the thermal properties of the state-of-the-art building technologies implemented at the time of construction of those prototype houses. The development of the automated segmentation process in this study may allow future research to recruit larger number of participants.
- **Season location and setting:** Although the study was carried out by using terraced house typology in the south-easter England where the climate is temperate, future research may apply similar methods to gather information on the innovative multi-family apartment typologies. Additionally, this longitudinal approach may be used to investigate seasonal behavioural adaptation of occupants' thermal comfort.
- **Parametric statistical analysis and regression forecasting:** Methods developed in this study allow the estimation of the degree of overheating risk during frequently occurred long term heatwaves across continental Europe. Future research may predict the probability of occurrence of different building energy simulation approaches.

The variables included in this research are the result of the systematic literature review, environmental monitoring and building energy simulations developed to provide background information on the development of cutting-edge passive cooling design strategies for building's retrofitting. To summarise, the implications and contributions to existing knowledge of this study is threefold. First, theoretically this study introduces a framework to review extant literature on overheating risk, thermal comfort and building energy modelling that incorporates a wider range of retrofitting solutions. Second, methodologically this study demonstrates the efficacy of multi-method parametric analysis for understanding the degree of overheating risk Third, substantially this study highlights the importance of researcher's critical approach when evaluating building performance evaluation of newly built housing stock, as this could differ from the traditional method of designed used to assess energy performance of existing housing stock.

6. Discussions and recommendations

The previous section discussed the importance of environmental conditions that affect indoor air temperature fluctuations and their indications for assessing the overheating risk experienced in summer. More insight into the differences of occupancy patterns in domestic energy use and the representativeness of the total residential building stock provides another perspective on the effect of energy performance evaluation on actual energy consumption by using passive cooling design strategies. The objective of this calibration study was to determine representative occupancy profiles and their significant impact on home energy use in the hot summer month of August 2018. To fulfil the research aim, three research questions were identified. The first was related to the effect of the thermal properties of buildings on actual energy consumption for cooling. The second was related to the effect of environmental parameters and their significant impact on occupants' thermal comfort. The third referred to differences in actual energy consumption and occupancy patterns observed in the state-of-the-art terraced house typology to validate environmental findings in conjunction with concurrently running the dynamic thermal simulations. The following sections present the main research outcomes and recommendations drawn from this exploratory case study conducted in the south-eastern part of England.

6.1. Main research outcomes and their implications

This study sought to explore the impact of passive design strategies on the annual energy consumption of an innovative terraced house. It determined that passive design strategies have an impact on energy-efficient design, which accounts for up to 53% of energy savings. The findings revealed that the most effective design strategy was S2, which included natural ventilation systems through the implementation of the windcatcher system, skylight and operable pinewood external shutters, and window to wall ratio. It was found that S1, a proposed design with the addition of volumetric sun space on the ground floor living room area and the integration of operable pinewood external shutters on opaque window surfaces and BIPV systems on the roof surface of this volumetric space, had less impact. However, S3, which included natural ventilation systems with the integration of window opening projections and overhang window canopy shading systems, can increase the overall energy consumption due to the increased heating demand to offset the reduced solar heat gain of the first-floor large bedroom space. The results highlighted that, in relation to annual energy consumption and thermal performance, there was no significant difference between S3 and S4 (natural ventilation systems) and S5 (floor plan layout configuration). The main reasons were the extreme weather conditions recorded during the long-lasting heatwave in the summer of 2018 in south-eastern England and the available natural ventilation systems and operation schedules that were unable to handle the warming conditions in this innovative housing typology. Figure 29 demonstrates the development stages of building energy simulations.

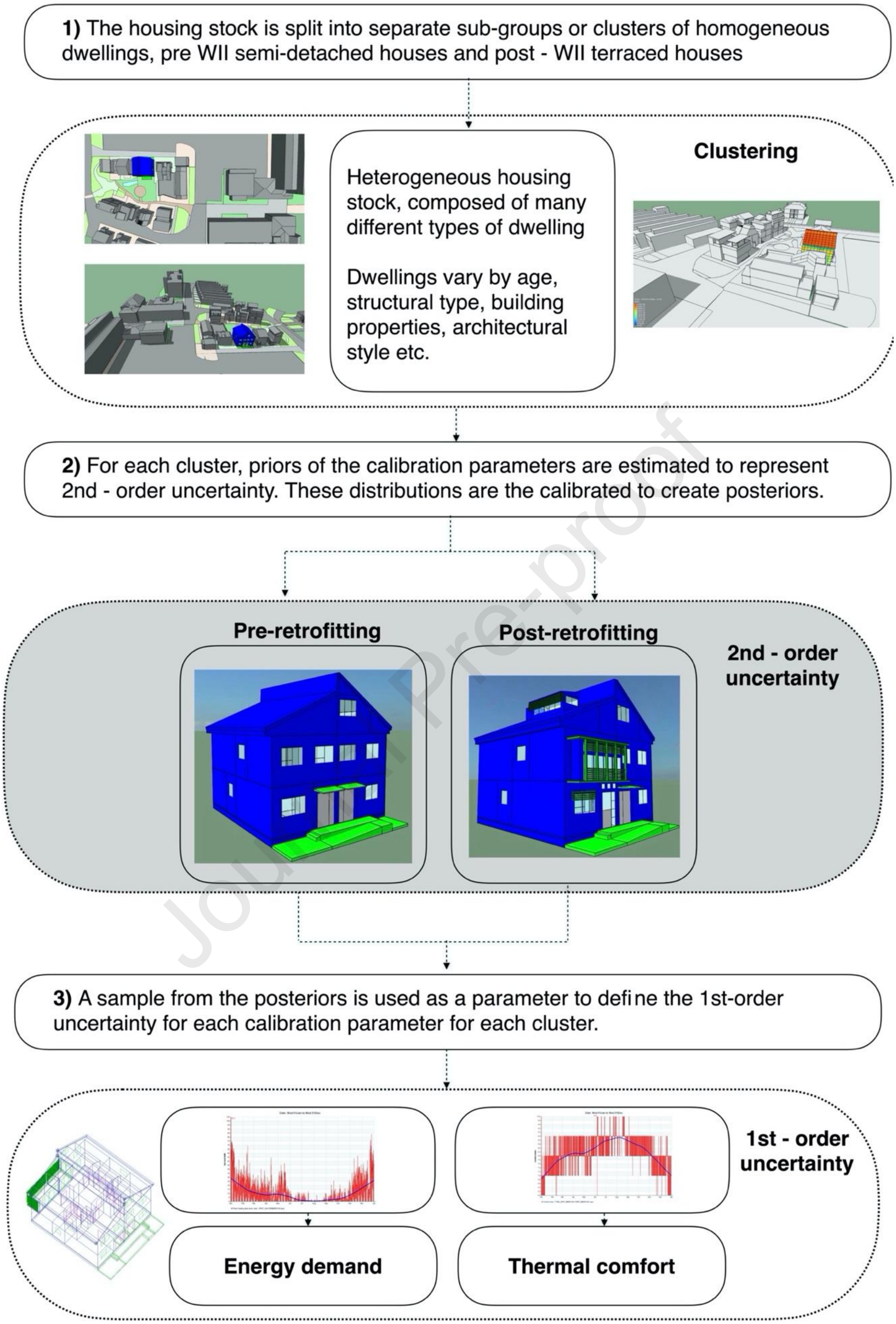


Fig. 29. The selection of national representative housing stock, archetype houses' retrofitting stages and its outcome on domestic energy use and occupants' thermal comfort. ***Image Credits:*** The flow diagram was conceptualised by the author – the 3D rendering model of case study location and prototype house were modelled in IES software suite by using ModelIT application and the dynamic thermal simulation graphs were produced by using the VistaPro application.

For this reason, future studies on the passive design of state-of-the-art residential buildings should be conducted to explore the impact of passive wall systems on energy efficiency and carbon reduction. Furthermore, passive design is not sufficient to deliver nearly zero carbon affordable housing development estates in the UK climate. However, it can bring the annual heating consumption to 17.1 kW/m^2, while reducing the annual cooling requirement to near zero. It delivers a cost-effective solution to integrate other passive design strategies that could be adopted from the revival applicability of vernacular bioclimatic design principles investigated by Tatarestaghi et al. (2018) and renewable energy supply systems to deliver nearly zero-carbon homes in the UK and Europe.

6.2. Lessons learnt from the building performance evaluation and optimisation studies

This section explicitly discusses the findings from the empirical study to evaluate the energy effectiveness of the retrofit interventions and makes suggestions concerning future systemic retrofit schemes to provide guidance in the decision-making process. The key aims and main objectives of implementing passive cooling design strategies for building retrofitting, in general, are outlined in Sections 1 and 4. Of these, two principal aspects are generally recognised as the main aims of residential building retrofitting in practice: increased quality of the indoor air environment and reduced household energy bills through a combination of shading and natural ventilation systems for passive cooling in retrofit interventions. These are addressed individually below and subsequently considered together as a means for upgrading the thermal efficiency of the buildings under investigation.

The subsequent stage analysed the current thermal performance of the prototype house and potential retrofit solutions that could help improve the occupants' thermal comfort, particularly during long-term heatwaves in the summer (Harkouss et al., 2018; Psomas et al., 2016). Six retrofit strategies were selected and applied to the prototype house to explore their impact on the building's performance and thermal comfort. The strategies incorporated into the prototype house design showed that S2 had the greatest impact on overheating risk reduction with a 19% improvement, and that a 53% gain in comfort can be achieved through the use of a correct orientation, shading devices, volumetric sunspace roof additions, overhanging window opening projections and natural ventilation in the development of the existing energy performance of the prototype house, respectively.

From a comfort and performance perspective, retrofitting work completed in the temperate climate characteristics of south-eastern England should, in the future, be designed to include passive natural ventilation strategies, as these proved to be the optimum retrofitting strategy (Baborska et al., 2015; Shrubsole et al., 2014). Passive ventilation systems can be implemented at little cost, given that passive ventilation systems a feature of climate change adaptation in the political climate. As this study has demonstrated, passive design strategies can be both energy-efficient and cost-effective in retrofitting both newly built and existing, semi-detached or detached terraced housing stock in the UK. This is a critical finding that needs further investigation to assess and minimise the risk of overheating and to understand occupants' thermal comfort when enhancing feasible retrofitting scenarios in temperate climates. Figure 30 demonstrates the developed methodological workflow as an outcome of systematic literature review, environmental monitoring and building energy simulations.

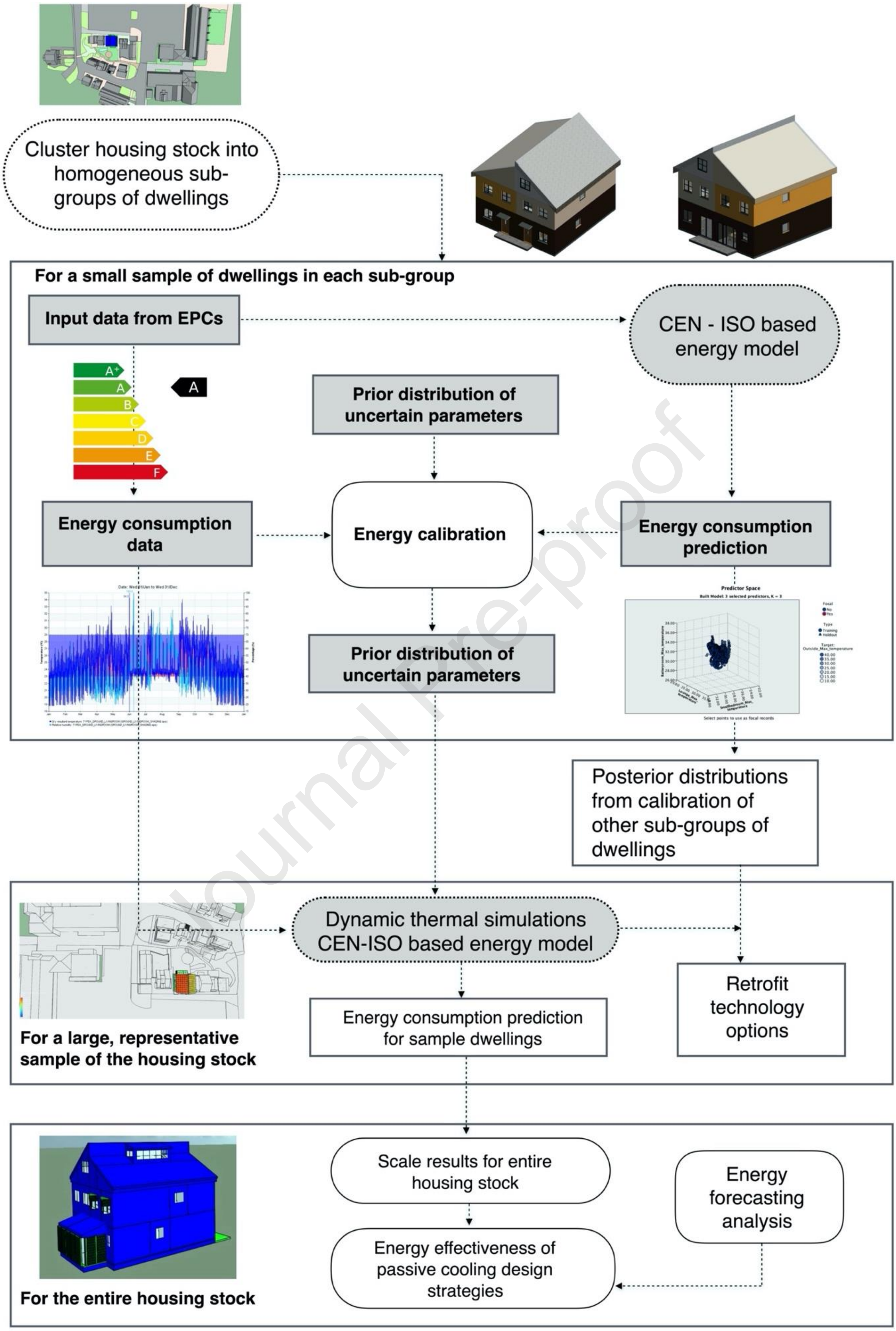


Fig. 30. The evidence-based archetype housing stock analysis developed for this study. ***Image Credits:*** The flow diagram was conceptualised by the author – the 3D rendering model of case study location and prototype house were modelled in IES software suite by using ModelIT application and the dynamic thermal simulation graphs were produced by using the VistaPro application. The case study building was re-modelled by the author using the Autodesk® Revit® software suite.

As noted earlier, very little can be found in the literature on the question of implementing passive cooling design strategies in retrofit interventions. However, findings have emerged about the monitored use of data from each occupied space to diagnose overheating risk problems experienced by occupants (Coleman et al., 2012; Firth & Wright, 2008; Gillott et al., 2010). For this study, a weather station was installed to measure the long-term outdoor air temperature and the RH of the base-case study location. During data processing, the data sets were extracted from the weather station to allow researchers to observe outdoor environmental conditions during August 2018. This shows that it was essential to have a deep understanding of the barriers in which the additional weather data set was embedded to calculate cooling degree days (CDDs) for building energy modelling. In fact, the monitored data were used specifically to investigate indoor air temperature fluctuations and to calibrate domestic energy use in order to provide basic information on identifying various design strategies in retrofit interventions.

6.3. Policymaking decisions on building retrofitting

The extensive monitoring campaign was undertaken in the summer of 2018 in the south-eastern England in the UK located in a large-scale innovation park. It consisted of a variation of terraced house typologies situated around a historically important building with novel construction applications where the climate is temperate (Staszczuk & Kuczyński, 2021). This prototype building had a steel-framed structure, and the walls and roof were insulated with energy-efficient materials to retain the heat. The research design approach involved running DTSs on one prototype state-of-the-art building in the innovation park. The aim of the research on this type of building structure was to assess the feasibility of the construction materials used to design affordable housing units for low-income groups in Europe. Over the course of this research process, the researcher was involved with the architects, developers, stakeholders and material manufacturers to gain an in-depth understanding about this base-case prototype house. This hands-on experience enabled the researcher to gain practical insights into factors ranging from the decision-making process to its planning, construction, thermal performance and policymaking in the residential sector.

The final outcome of this study's results was in agreement with similar research projects undertaken to investigate the exacerbation of climate change and its effects on CO_2 mitigation in both the UK and Europe (Beizaee, Morey & Badiei, 2021; Goncalves, Ogunjimi & Heo, 2021). This project included testing the thermal efficiency of building systems with a wide range of materials that could be applied to improve the thermal performance of existing buildings under different climatic conditions. The research methodology used in this project adopted energy performance development studies when testing different types of materials by employing building modelling simulation. Further, the research findings could be used to demonstrate the necessity of implementing passive cooling design strategies into building retrofitting.

Coupled with the research findings, building physics shows that, while heat transmission losses can be precisely predicted from the thermal properties of building materials, typically derived from quantities of energy consumed, the theoretical significance of home energy performance should be highlighted (Das et al., 2014; Davis & Durbach, 2010; McGill et al., 2017). More recently, other scholarly pilot studies' concerns over calibrating discrepancies between actual and predicted energy use using surrogate energy models have increased (Oladokun & Odesola, 2015; Peacock et al., 2010). Other studies have swayed the policymaking process by arguing that DTS are not accurate in terms of prediction to provide an effective road map for the implementing passive cooling design systems during the decision-making process for policymaking. This has led to estimates of current energy consumption and of the savings potential of retrofitting that do not reflect reality. For this reason, it seemed appropriate for policymakers to review the prominent methodological approach for implementing effective retrofit solutions while taking into account the location and climate of buildings. Due to the technical challenges of implementing any type of holistic retrofit intervention, emphasis should be placed on conducting both longitudinal and transverse surveys with occupants before underestimating the impact of retrofit interventions (Rodrigues & Gillot, 2013).

Nevertheless, it is evident that upgrading the thermal efficiency of existing residential building stock to higher and higher standards has led to basic problems of physics and psychological impacts on occupants concerning thermal comfort. A general trend is that highly efficient insulation materials or building systems have led to increased indoor air temperatures in each occupied space (Verbeeck & Hens, 2005). This could result in uncomfortable temperatures for residents. At first glance, it seems that retrofitting existing residential buildings should require careful planning within the evidence-based socio-technical systems approach adopted as the inherent methodology for policymaking decisions. This indicates an increased uptake in holistic retrofit interventions that are not household-oriented. From these policy implications, it is evident that improving the thermal efficiency of building envelopes to higher and higher standards involves the basic problems of physics and technical procurement during construction phases in the residential sector.

In terms of the issue of high cooling demand, building fabric retrofitting seems to be as cost-effective as other possible retrofit solutions, in that there are no other new building systems such as an appropriate, locally available material for exterior cladding or vacuum insulated panels (VIPs) installed with which occupants can adjust indoor air environments effectively. There is evidence that promoting the installation of new technologies – which have not been directly selected by the occupants during the decision-making process of retrofitting – in social housing, whether in retrofit or new build situations, can lead to increased indoor air temperature due to the selection of inappropriate materials according to the requirements of climate characteristics of the case-study projects. The findings of this study revealed that other scholars and further studies should consider the selection criteria of state-of-the-art building materials and passive cooling design systems when planning building retrofitting.

6.4. Policymakers' knowledge gap in building retrofitting and recommendations

The reliable prediction of domestic energy use is an important determining factor for energy efficiency implementation and for the management and implementation of passive cooling systems. It is possible that there is a knowledge gap among policymakers and their expert advisors that it is technically and economically possible to significantly reduce both the heating and cooling demand through implementing various types of systemic retrofit interventions. To address this critical knowledge gap, this study has suggested a new experimental and analytical approach for effectively providing guidance to researchers and designers in the evaluation of the impact of appropriate retrofit design strategies on the building – improving home energy provision – and on the calculation of energy, environmental and economic indexes in both the decision-making and construction phases of retrofit interventions as follows:

- Cladding Material – This well-insulated, fully airtight, lightweight external wall material is applicable only in cold climate conditions to reduce heating demands in winter. This study found that the use of this type of construction material leads to issues with overheating risks during long-term heatwaves and in temperate regions that are under the threat of climate change. An alternative type of building material could be used to combat exacerbated climate change.

- Vacuum Insulated Panel (VIP) systems – When used on external walls instead of composite cladding systems, VIP systems allow the walls to have micro ventilation by providing a sufficient condensation factor for the wall.

- Ventilated terra cotta panel cladding systems – These systems can be mounted on external wall surfaces. Their ability to indicate the effectiveness of the insulation material is due to their absorption and ability to cool the external surfaces of the building. Additionally. other locally available (i.e., mud brick or limestone), traditional construction materials can be applied as cladding material to lower the building's heat absorption.

- BIPV solar panel systems – This study found that they are efficient in tackling excessive heating demands in winter. However, this type of state-of-the-art technology leads to overheating risks in the summer. It is recommended that an alternative to the solar panel systems be used on the roof surfaces to generate electricity for the prototype houses in this research study; an intensive green roof design allows for the cooling of the first-floor indoor spaces while collecting storm run-off and rainwater and simultaneously storing it for recycling. The solar panel systems could then be placed on the south-facing walls and external window shutters. This recommendation provides optimum indoor thermal comfort and mitigates the UHI effect in densely built cities. This design principle is also correlated with CO_2 emission reduction in urbanised areas.

- Floor plan layout design – This prototype building is representative of a semi-detached type of house in the UK, and it uses the same floor plan design as traditional terraced houses, in which the internal occupied spaces are compact with insufficient daylight and natural ventilation. Since this prototype house is volumetric and modular, it is recommended that the floor plan layout design be changed so that the internal walls are removed and replaced with user-adaptable sliding doors. This would allow for natural ventilation and sufficient daylight.

- Passive design strategies – To reduce the overheating risk for this building, six different possible design strategies were tested to optimise the building's energy performance during the long-term heatwave period. It was found that the most predominantly effective strategies were the fenestration design and shading systems implemented on window surfaces to reduce the impact of solar radiation. These future recommendations are the most cost-effective and energy-efficient, and they also take into account the revival and applicability of traditional building materials and systems to reduce the impact of the external environmental factors of the built environment on this type of prototype house in different climatic locations. In the next phase of the project, flood and fire risks must be considered for large-scale construction designs in the application of this type of prototype house.

The abovementioned recommendations could contribute significantly to bridging the knowledge gap in building performance by considering warming climate change projections in the future. This is the reason why much more research is required in the field of passive cooling, especially in newly-built housing stock alongside poorly insulated, existing residential stock, to protect the health and well-being of occupants, regardless of their socioeconomic condition notwithstanding. This theoretical study found that different measures that contribute to the improvement of residential buildings' energy efficiency are predominantly reliant on heating, which have proven to be energy-conscious measures in the winter but, bearing in mind future global warming scenarios, could lead to increased indoor air temperatures in the summer. For that reason, much more research is needed in order to improve occupants' thermal comfort in heat-vulnerable homes with passive measures that minimise energy or system costs, especially in the collective social housing sector both in the UK and Europe, as both building regulations and climate have shown similar characteristics to the construction of terraced house typology across the continent.

7. Conclusions

The study directly contributes to the EPBD objectives development program, which mandates energy-efficient, climate-resilient housing stock in all 27 EU countries by 2030. Specifically, standards were introduced by European Commission in 2016 that focused on promoting the implementation of energy efficient technologies to reduce CO_2 emissions of existing housing stock.

In light of these requirements, this study adopted the quantitative research approach to assess the risk of overheating and potential ways to overcome this issue through the implementation of energy-efficient state-of-the-art passive design strategies on the newly built terraced house typology in the south-eastern England. The results reveal the necessity of considering passive measures to harness natural ventilation in these condominiums. In the base-case model, the first-floor level rooms were shown to have the worst thermal performance because of the hot air that moved from the low-U value of energy efficient roof insulation material and the BIPV systems installed on the roof surface.

It was found that there was a lack of diurnal temperature variation within the occupied spaces both on the ground and first floors, which suggests that the internal operative temperatures remained relatively high throughout the day and night, ranging from a maximum 26.5–32.5°C; this was not significant enough to induce cooling at night – where the climate is temperate and lack of window control to operate natural ventilation effectively. Furthermore, it was found that the external fabric – composite cladding system without any air gap between the steel frame and the insulation material, and three exposed wall surfaces were a key determinant factor due to the low U-value, the surface area and the level of exposure to solar gains. This resulted in a high heat transmittance into and out of the occupied spaces, which had a significant effect on the operative temperatures during long-term heatwaves in this particular region and climate.

Notably, overheating was more likely to occur large bedroom (bedroom 1) and medium bedroom (bedroom 2) of the first-floor level than in the living-room area located on the ground floor. These results indicate that temperatures rose above 28°C for 7% of the hours each day; the upper limit for BS EN 15251 Category II for calibrated temperatures were evaluated in the living-room areas using the CIBSE standards and the adaptive thermal comfort models. High summer temperatures above the 26°C indicator was experienced for 18% of the hours, and warm discomfort above the BS EN 15251 Category II upper limit was reported in large bedroom and medium bedroom for 15% of the hours.

Finally, the study elucidated the potential applicability of passive cooling design strategies in various retrofitting interventions to optimise occupants' thermal comfort and mitigate with climate change impact on this energy efficient housing typology. Based on this study, the passive design principles were shown to result in significant reductions in energy consumption and optimised thermally comfortable indoor air for the occupants. This was an important finding that needs to be further explored by a robust optimisation study, which will provide a wider domain to assess and optimise the risk of overheating and better understand occupants' thermal comfort when seeking to enhance 'night cooling' effects in an innovative terraced house typology in the southeast England.

One of the significant findings of this study was that cooling energy consumption decreased by 53% after all six passive design strategies were implemented. These conclusions will create the prerequisites and the background information that is needed for the development of a novel methodological framework and a ground-breaking epistemological design approach in the area of development and design, energy policymaking and the drafting of subsidisation schemes and targeted actions to improve the energy efficiency of existing housing stock.

One of the unique results of this study was the provision of a practical solution to off-site modular building design applications in order to reduce the spread of COVID-19 across households during nationwide lockdown measures. In this study, different ventilation strategies provided a series of guidelines that demonstrated how implementing different retrofitting design strategies to the building envelopes of the RTBs improved the indoor ventilation and thereby eliminated the accumulated CO_2.

At the same time, the installed shading systems helped to avoid excessive sun exposure in occupied spaces. This verifies that these strategies, which were developed to improve the indoor air quality with the use of effective fenestration design and the flexibility of the sided window systems, will offer appropriate building optimisation during the decision-making stage.

It should be highlighted that these applications are of the utmost importance at the present time due to the current global health crisis, which has forced families to stay at home for longer durations of time. Implementation of these strategies could result in the development of effective ventilation strategies that will reduce the transmission of COVID-19 if some additional research is conducted. These study findings could provide guidance to householders and stakeholders and help to determine policy initiatives related to effective ventilation strategies in accordance with available recommendations by the *CIBSE COVID-19 Ventilation Guidance, Version 2*, which was updated for buildings on October 23, 2020; these recommended benchmark criteria are currently not feasible for the buildings in locations where the climate is hot and humid. The outcomes of this study could be used by the CIBSE in all 27 EU countries in the following ways:

- To reduce household energy consumption during the lockdown
- To provide effective natural ventilation in occupied spaces, which will in turn help to reduce CO_2 accumulation
- To improve the indoor air quality and the overall health and well-being of the household
- To avoid overheating risks in buildings and make the building stock more resilient to climate changes

- To provide guidelines to avoid transmission of COVID-19 throughout households, especially those with a high number of occupants
- To demonstrate the integration between architectural design and building engineering in order to design energy-efficient, cost-effective retrofitting interventions

The comprehensive methodology that was developed and the resulting field-survey findings can be employed by other EU countries in their attempts at holistic retrofitting approaches and in their decision-making processes related to energy-use policies in the residential sector. The scope for conducting a building energy simulation in this study was limited to input parameters that were obtained from the longitudinal field surveys, the prototype analysis and the results that demonstrated that the differences in energy-use between a retrofitted building and the existing state of the building were correlated with the degree of energy management after cost-effective energy-efficient systems were implemented, which is considered to be a limitation for this study that will provide future opportunities for additional research.

Declaration of Competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

CRediT authorship contribution statement

Bertug Ozarisoy: Writing – original draft, Conceptualisation, Methodology, Investigation, Writing – review & editing. **Bertug Ozarisoy** conducted the field surveys, computational analysis, analysis of the numerical experiments and the designing of retrofit strategies; and **Bertug Ozarisoy** provided sources (e.g. illustrations, tables, datasets and videos), comments, and major edits to the paper. **Bertug Ozarisoy** developed the Methodology and conceptualised the narrative structure of the paper. Bertug Ozarisoy checked the technical merits and accuracy of data interpreted in Data and summery statistics (section 4) and Empirical analysis (section 5). **Bertug Ozarisoy** checked the raw data set and simulation set input parameters of dynamic thermal simulations due to his expertise on the simulation software suite used for the study. **Bertug Ozarisoy** also provided necessary advice and guidance for the architectural design interventions developed as an outcome for the study. **Bertug Ozarisoy** wrote the Conclusions (section 7).

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Graphical Abstract

Graphical abstract to this article can be found online at – The Graphical abstract illustrates the adopted and developed comprehensive methodological design approach for the study.

Supplementary Material

Supplementary data to this article can be found online at – It consists of the inventory form designed to record occupancy patterns, window opening schedules and indoor thermal comfort parameters at the time of conducting both the extensive environmental monitoring campaign and dynamic thermal simulations.

Data Sets

Dataset 1: Readings of CO_2 emissions for each occupied space during the cooling period between May and September

Dataset 2: Readings of humidity for each occupied space during the cooling period between May and September

Dataset3: Readings of humidity of each occupied space at the peak day in August

Dataset 4: Readings of humidity of each occupied space during the peak cooling month of August.

Dataset 5: Readings of indoor air temperatures of each occupied space at the peak day in August.

Dataset 6: Readings of indoor air temperatures of each occupied space during the peak cooling month of August. In order to validate readings through monitoring campaign, the dataset devised in the IBM software SPSS version 25.0.

Dataset 7: It consists of extracted data during the peak cooling period at the time of experiencing long-term heatwaves. This dataset could be exemplar background information for other scholars to conduct more in-depth studies on investigation of occupants' thermal comfort and well-being.

Dataset 8: Analytical energy model of prototype house constructed in IES simulation software platform.

Video

Video A: It demonstrates the natural ventilation-flow frequency of each occupied space.

Video B: It shows the solar exposure analysis of the projects site between January and December.

Video C: Analytical model of prototype house

Video D: Solar shading analysis of baseline prototype house.

Appendix A.

Fig. A1. Monitoring results of the southwest-facing living room between 27 June and 15 October 2018.
Image Credit: Diagram was conceptualised by using specialist environmental monitoring software suite provided by the author.

Fig. A2. Monitoring results of the southeast-facing kitchen between 27 June and 15 October 2018.
Image Credit: Diagram was conceptualised by using specialist environmental monitoring software suite provided by the author.

Appendix A. (Continued)

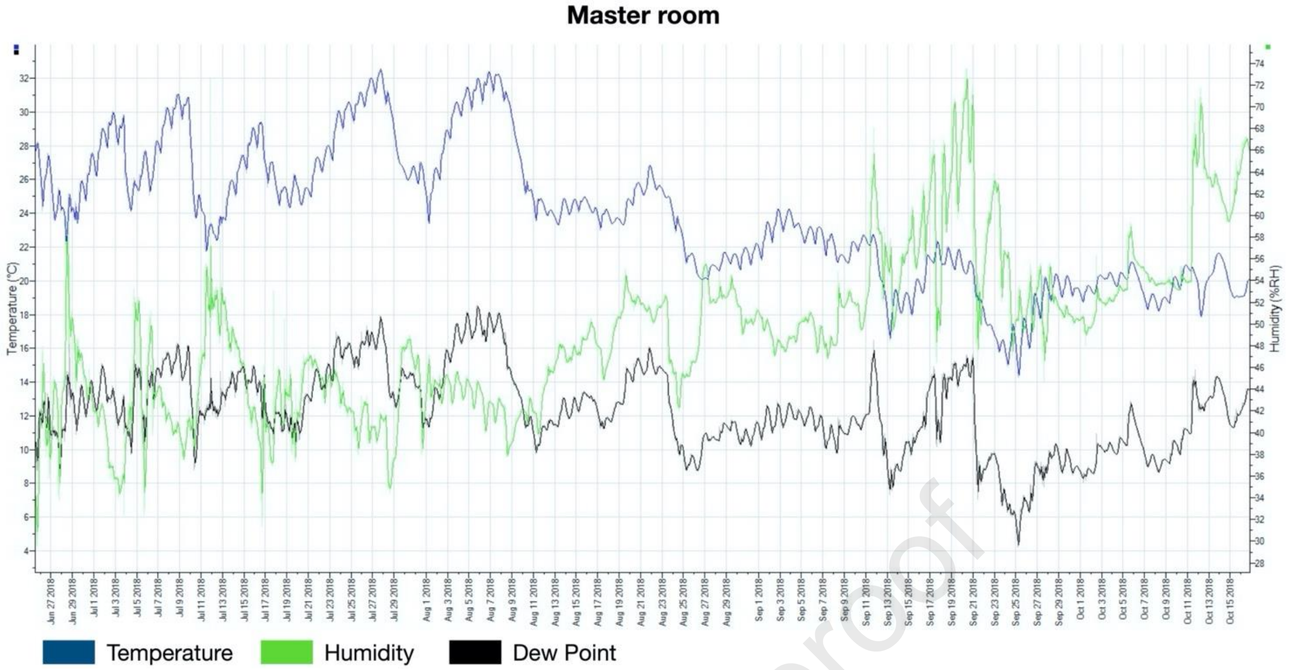


Fig. A3. Monitoring results of the southeast-facing large bedroom between 27 June and 15 October 2018.

Image Credit: Diagram was conceptualised by using specialist environmental monitoring software suite provided by the author.

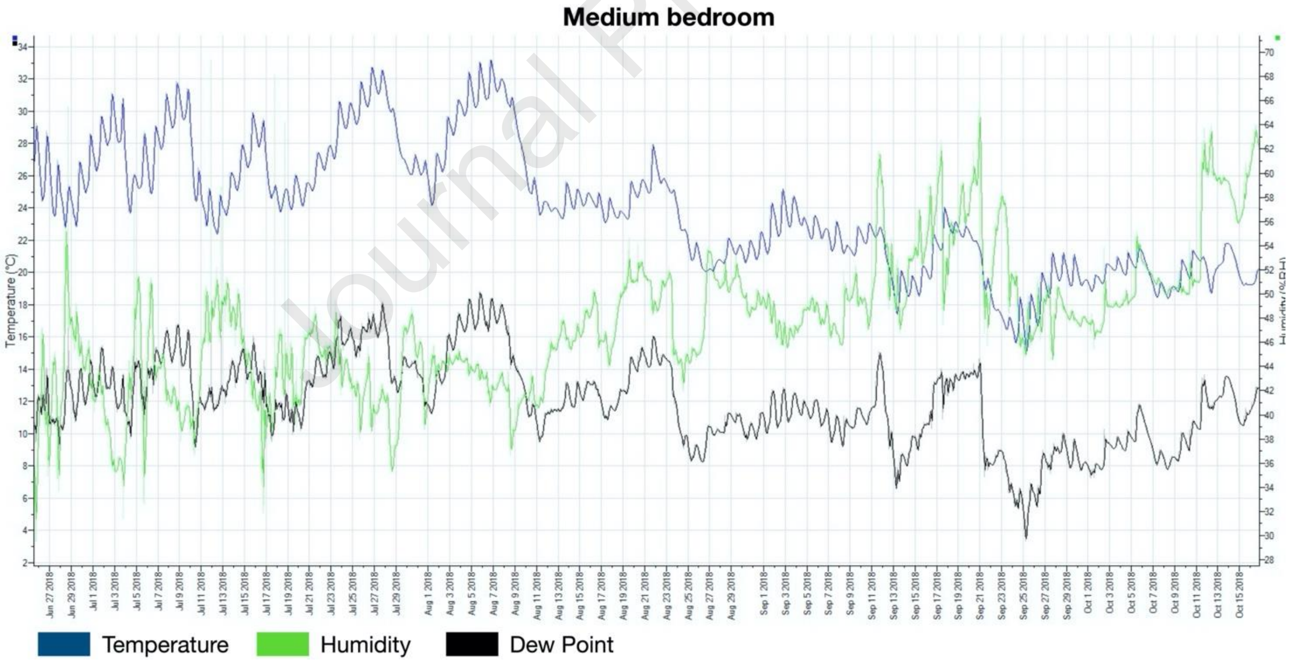
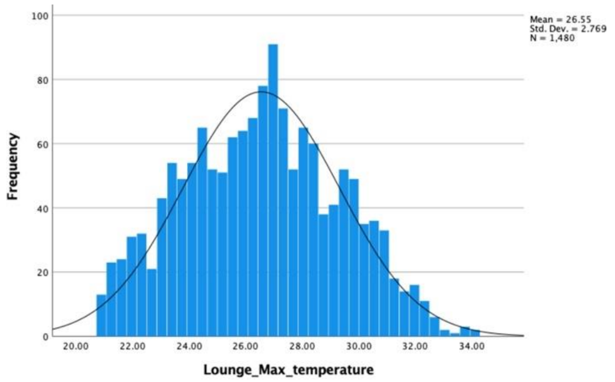


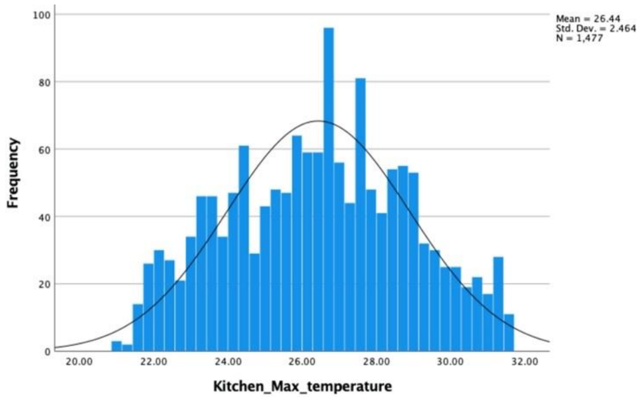
Fig. A4. Monitoring results of the southwest-facing medium bedroom between 27 June and 15 October 2018.

Image Credit: Diagram was conceptualised by using specialist environmental monitoring software suite provided by the author.

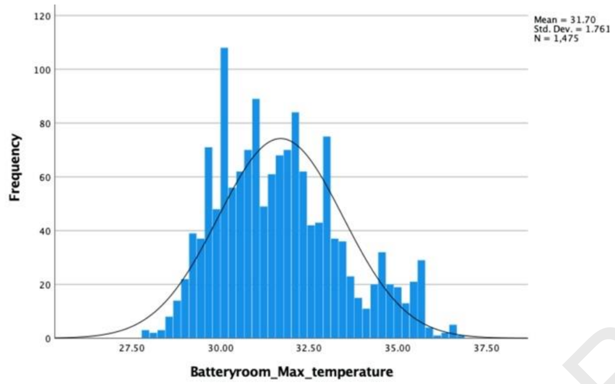
Appendix B.



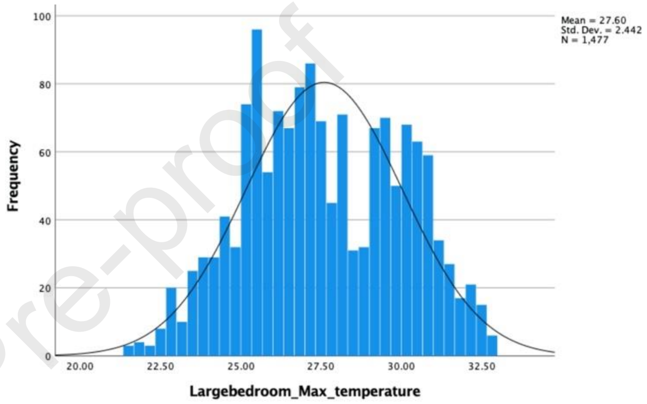
(a)
Lounge/Living room



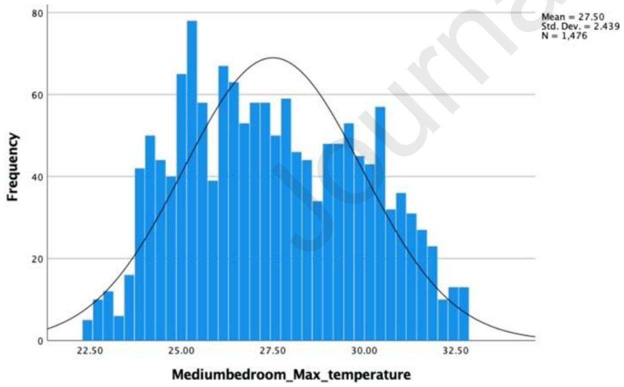
(b)
Kitchen



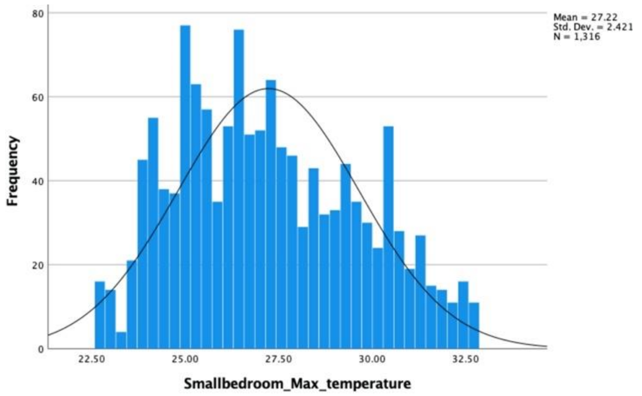
(c)
Battery room



(d)
Large bedroom (Bedroom 1)



(e)
Medium bedroom (Bedroom 2)



(f)
Small bedroom (Bedroom 3)

Fig. B. (a) through (f) Histograms of indoor air temperature relationship between outdoor environmental conditions.

***Image Credits**:* Diagrams were conceptualised by using the SPSS software suite and edited by the author.

Appendix C.

Table C.1

Test of associations between outdoor environmental parameters and indoor air temperature of each occupied space.

		Outdoor	Lounge	Kitchen	Battery room	Large bedroom	Medium bedroom
N	**Valid**	1480	1480	1477	1475	1477	1476
	Missing	8	8	11	13	11	12
Mean		22.9669	26.5468	26.4351	31.6993	27.5965	27.4959
Std. Error of Mean		0.13948	0.07198	0.06410	0.04586	0.06353	.06349
Median		21.6864[a]	26.5975[a]	26.5700[a]	31.5220[a]	27.3680[a]	27.2850[a]
Mode		17.72	27.08[c]	26.75	30.09	25.32	25.36
Std. Deviation		5.36588	2.76899	2.46359	1.76112	2.44157	2.43937
Variance		28.793	7.667	6.069	3.102	5.961	5.951
Skewness		0.680	0.078	-0.014	0.515	0.004	0.159
Std. Error of Skewness		0.064	0.064	0.064	0.064	0.064	0.064
Kurtosis		-0.469	-0.634	-0.761	-0.330	-0.809	-0.943
Std. Error of Kurtosis		0.127	0.127	0.127	0.127	0.127	0.127
Range		22.80	13.20	10.66	8.85	11.43	10.35
Minimum		14.34	20.83	20.90	27.82	21.34	22.49
Maximum		37.14	34.03	31.56	36.67	32.77	32.84
Sum		33990.95	39289.32	39044.69	46756.45	40760.10	40583.95
Percentiles	**10th**	17.0322[b]	22.9400[b]	23.0847[b]	29.6080[b]	24.4790[b]	24.3440[b]
	20th	18.2179	23.9575	24.0940	30.0815	25.4085	25.1713
	25th	18.7512	24.4450	24.4717	30.2810	25.6525	25.4275
	30th	19.2074	24.9150	25.0044	30.5657	26.0880	25.8644
	40th	20.3271	25.8480	25.8866	31.0167	26.7620	26.5536
	50th	21.6864	26.5975	26.5700	31.5220	27.3680	27.2850
	60th	23.2833	27.1867	27.1047	32.0100	28.1768	28.0947
	70th	25.1811	28.0550	27.7740	32.4671	29.2770	29.0748
	75th	26.5440	28.4960	28.2983	32.8488	29.6120	29.5183

a. Calculated from grouped data.
b. Percentiles are calculated from grouped data.
c. Multiple modes exist. The smallest value is shown.

Appendix D.

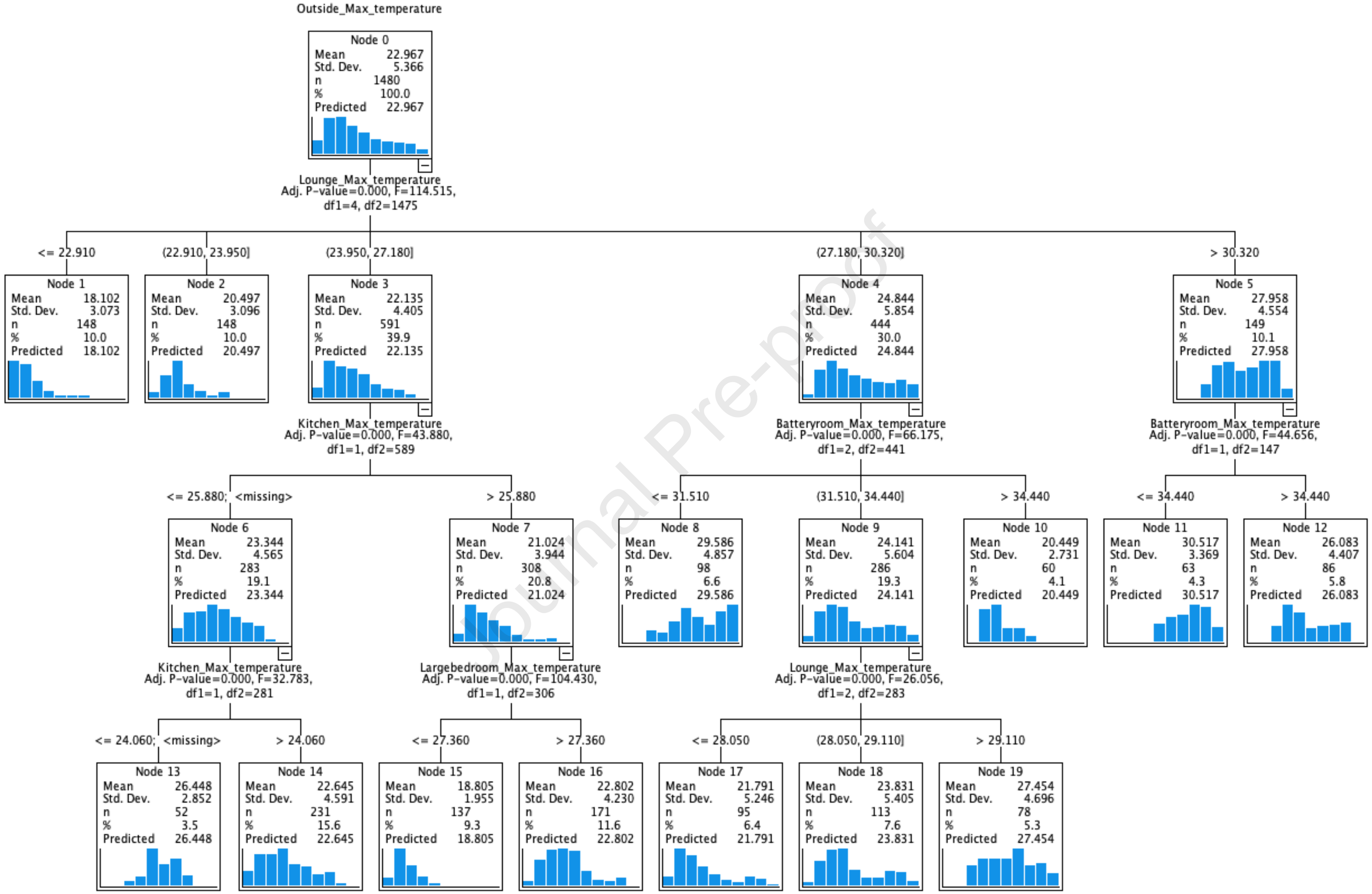


Fig. D. Hierarchy map between outdoor environmental conditions and indoor air temperature of each occupied space.
Image Credits*:* Diagrams were conceptualised by using the SPSS software suite and edited by the author.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

To the readers' information:

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