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Overheating in Historic Buildings in the UK: An Exploratory Study of Overheating Risks, Building Performance, and Thermal Comfort

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Abstract: A study reviewing overheating in historic buildings in the context of extant climate change. Due to global warming, more research is required when considering summertime thermal comfort in the UK, which is a more significant topic of conversation due to the heatwave in 2022. With a large demographic of the UK population residing in dwellings with historic value, this paper aimed to contribute findings that review their specific traits with respect to overheating. This was achieved by monitoring and analysing internal (and external environmental data) in three case studies in the south-east. Upon examination of the literature, many buildings in the UK are consistently subject to temperatures that exceed overheating. It was found that many properties of historic buildings lend themselves to summertime cooling such as higher thermal mass, better ventilation (without the use of mechanical or active systems), and less insulation. This, however, could come at the cost of winter thermal comfort. In all three case studies, the surveyed buildings passed the CIBRE criteria, but users still commented on being 'too hot'. The high recorded RH levels in all properties, coupled with the inadequate overheating criteria, were deemed the cause. There are new regulations in place to minimise overheating in new buildings but no support for those that are already existing.

Keywords: historic buildings; climate change; thermal comfort; overheating; risk assessment

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1. Introduction

It is widely agreed that urgency is now required in responding to climate change given the accelerated pace at which our planet is heating up, as outlined in the recent 26th United Nations Climate Change Conference (COP26) [1]. As a result, the UK government made a commitment to guarantee that greenhouse gas emissions will be cut by 100% from levels found in 1990 by the year 2050. This target is legally binding, as per the Climate Change Act 2008 Order 2019 [2], which stemmed from a recommendation by the Climate Change Committee (CCC) in 2019 [3]. These radical imperatives have been enacted to arrest climate change due to the severe associated consequences to human health, the environment, and global economy, all of which are already being felt around the UK [4]. According to the Met Office [5], average temperatures in the UK have increased by 0.5 °C in the last decade and are a further 1.1 °C warmer than between 1961 and 1990. There is also an increasing number of extreme weather events, most notably, hotter summers, which, as a result of global warming, are now 30 times more likely to occur. The previous record temperature of 38.7 °C (July 2019) was topped in July 2022 when temperatures in excess of 40 °C were felt for the first time in the UK, as recorded by five weather stations from London to Lincolnshire, with a level 4 heatwave warning being initiated for the first time [6]. It is forecast that under a higher emissions scenario, by the end of the century, temperatures could exceed 40 °C every three years [7]. These extreme changes to our climate are linked to serious health risks and excess mortality rates. According to the Office for National Statistics [8], between 17 and 20 July 2022, 1012 excess deaths were recorded and attributed to the heatwave (253 excess deaths per day, excluding COVID-19). It is forecast that by 2050, 7040 heat-related deaths in the UK could occur per year [9].

With the average adult in the UK spending 87% of their time indoors [10] (a percentage that is likely to have increased since the COVID-19 pandemic), the role buildings play in keeping us cool in an increasingly hotter climate, as well as the associated impact this has on carbon usage, cannot be understated. With the demand for cooling increasing, mechanical means of cooling are being most commonly relied upon in the UK (i.e., fans, HVAC). With new builds accounting for less than 1–2% of the overall building stock each year, most of the demand for cooling is attributed to those residing in existing buildings [11]. Many of these existing buildings in the UK would be categorised as 'historic', as the UK is home to some of the oldest building stock in the world, with 4.3 million buildings being built before 1944 and a further 5.9 million prior to 1919 (20.6%) [12]. Due to the importance of preserving heritage buildings, adaptations utilised by their modern counterparts are not always feasible [13]. However, the pressure to ensure dwellings are environmentally efficient is increasingly important due to the reasons already stated, coupled with the ever-changing government legislation that could leave historic properties behind the curve.

Much of the existing building stock found in the UK has been designed and adapted to manage cold weather by retaining heat [14,15]. Furthermore, tensions have been documented between energy efficiency and historic preservation, leading to extensive research in conservation-compatible retrofit solutions [16]. Given the sudden change prompted by climate change, traditional building design and retrofit measures are now potentially leading to discomfort and health implications for users of heritage buildings amid more frequent heatwaves and hotter summers, as discussed above. Mitigating these changes is far from straightforward due to the accompanying legislative limitations and technical challenges [17].

Understanding thermal comfort and its drivers within the context of historic buildings is an under-researched topic. There is little existing literature that relates specifically to overheating in historic buildings. Moreover, the overheating standards are very simplistic (see Section 1.1.1) and based on historic climatic data and research. This illustrates the need for a more nuanced methodology to understand factors that influence overheating in historic buildings. Most of the present studies focus on winter thermal comfort and retrofitting [18]. The studies that specifically target overheating allude to the fact that modern building design is the main contributing factor behind the overheating crisis [19]. While this narrative is supported by several research papers [14,20], there is little research on how overheating impacts historic fabrics and their users. Aiming to bridge this gap, this study is an initial exploration to achieve a better understanding of the following:

1. how historic buildings' unique properties impact the likelihood of overheating.
2. the historic building's ability to regulate a consistent internal temperature and relative humidity when compared to recorded external conditions.
3. how the occupants/users of historic buildings react and behave in accordance with fluctuating temperatures and relative humidity.

Prior to investigating various cooling methods, it is important to understand the unique properties of historic or traditional buildings that can impact overheating, as well as their ability to accommodate changes. The research has shown that developing an overheating profile for each building should be unique, as there is a large list of contributing factors [21,22]. To this end, we developed an overheating risk assessment for historic buildings based on the literature review. We implement this risk assessment in three historic properties in the UK. We also monitored the properties to evaluate their performance and interviewed the residents/users to assess their comfort levels. Overheating not only concerns users' thermal comfort but also their health and well-being [23,24]. It also could affect the usability of the building. The primary risk that we explored in this paper concerns indoor environmental quality. Other risks associated with overheating in historic buildings include risks to the building fabric and objects. While this is an important area to be investigated, the impact of overheating on heritage buildings and artefacts is beyond the scope of this paper.

The paper is structured in six consecutive parts. Section 2 describes the methodology adopted for this research. Section 4 describes the results. Section 5 discusses the implications of this research. The paper concludes with possibilities for future work.

1.1. Key Concepts

1.1.1. Overheating and Thermal Comfort

We acknowledge that there is no robust and universally accepted definition of overheating [25]. It is largely a subjective term, lacking a formal definition, although it can be loosely described as when an individual experiences discomfort as a result of an increase in internal temperature [26]. In this research, we adopt the Chartered Institution of Building Services Engineers (CIBSE) criteria [27]. Based on these criteria, for residential buildings, the indoor temperature should not exceed 26 °C for bedrooms for 1% of the annual occupied hours. For living rooms, it should not exceed 28 °C for 1% of the annual occupied hours. For schools and office buildings, the indoor temperature should not exceed 28 °C for 1% of the annual occupied hours. While managing indoor microclimate risk in museums is out of scope for this research, the authors refer readers to the book 'Environmental management: guidelines for museums and galleries' [28]. High temperatures can induce 'heat stress', which can prove fatal (when the human core temperature exceeds 37 °C). The American Society of Heating and Air-Conditioning Engineers [29] states that an indoor temperature of above 35 °C is the heat stress 'danger line', with the danger line temperature decreasing by as much as several degrees in higher humidity levels. The authors note that this guidance is not yet specified in building regulations or health and safety guidelines in the UK. Increased humidity affects human health as it is directly related to thermal comfort, as it increases the difficulty the body experiences when removing heat via sweat evaporation [30].

1.1.2. Defining Historic Buildings

Historic buildings are defined by a building's age, special features, or designation in planning regulations. This research adopts the definition by English Heritage, which defines historic or traditionally constructed buildings as "nearly all buildings constructed prior to 1919, as well as a significant proportion of those built before 1945" [31].

2. Materials and Methods

A methodology has been devised that includes three different methods, including

1. developing overheating risk assessment that relates to historic buildings using a literature review
2. case study selection to test and validate risk assessment
3. risk assessment of the case studies based on the model developed
4. collection of environmental data (temperature and humidity) for case studies
5. semi-structured interviews with those who occupy the properties
6. validation of risk assessment using interview data and environmental data

A combination of qualitative and quantitative methods was chosen to address the issues holistically. Combining these methods is expected to neutralise any limitations of either in use alone and also build on both their strengths [32,33].

The details of the three methods are provided in Sections 2.1–2.3.

A total of three historic buildings were assessed for their ability to remain cool in the summer months. The case studies were selected to test and evaluate the methodology to assess overheating and its impact on buildings users. The selected case studies are located in the south-east of the UK as this area will be disproportionately impacted by global warming. In fact, during the 2022 heatwave, southern areas achieved significantly higher temperatures, with London being the worst affected, as mapped by scientists at the National Centre for Earth Observation [34].

One of the three properties is located in a rural area outside of London, and the other two were in central London (zones 1–2, highly urbanised environment). The spread of locations offers further scope for understanding any variables exhibited between the two environments and how this, in turn, impacts overheating. Both areas are home to a large historic building stock, as evidenced by the data from the Office for National Statistics [35]. The details of the case studies are provided in Section 3. Table 1 provides an overview of the data collected.

Table 1. Data Collected.

	Case Study 1	**Case Study 2**	**Case Study 3**
Location	Marden, Kent	Islington, London	The House Mill London
Environmental Data Collection Period	56 days (28 June 2023–24 August 2023)	56 days (28 June 2023–24 August 2023)	415 days (1 June 2022–21 July 2023)
Number of internal data loggers	2	2	1 *
Location of internal data loggers	Living room and bedroom	Living room and bedroom	First floor, close to south-facing window
Number of external data loggers	1	1	1
Interviews	one resident	one resident	one user
Risk Assessment	conducted during July 2023	conducted during July 2023	conducted during July 2023

* A data logger was also located on the ground floor, but the data were corrupted so could not be used for the purposes of this study.

2.1. Risk Assessment

There are a wide variety of factors that contribute to overheating in buildings, such as solar gains transferred through fabric, solar gains transferred through openings/windows, external air temperature, and internal heat gains [22,36]. All these considerations are relevant to historic buildings, however, the areas are broken down within the risk assessment model we developed. The overheating risk assessment models available are not applicable to historic buildings. To this end, the authors developed a risk assessment to be tailored for use in historic buildings, incorporating the findings from the literature review. This will act as a means of cross-referencing the data recorded through the loggers and interviews.

The risk assessment we developed builds upon the Good Homes Alliance tool [37], which is designed to be a 'first filter' risk assessment and assists with establishing a risk category (low, medium, and high) for the likelihood of a dwelling overheating in the UK. The guidance encourages a reduced reliance on mechanical means of cooling, but much of the advice on means of mitigating overheating involves deeper retrofit strategies that do not apply to historic buildings. The Good Home Alliance assessment contains questions that fall into the following categories: regional and local context, site characteristics, occupancy characteristics, key characteristics of the building, solar heat gains and shading, infiltration, ventilation and effectiveness of openings, and energy efficiency characteristics. We followed the same structure of the assessment. We included the same scoring system as it has undergone revisions over the years with the help of case studies [38]. We added factors specific to historic buildings under site characteristics and key characteristics of the building. In key characteristics of the building specifically, we added three factors likely to increase overheating risks, including the floor area of occupied rooms, the condition of the property, and the listed status. We also added a factor likely to mitigate overheating risks, i.e., building construction. In site characteristics, we have added orientation as a factor likely to increase overheating risk. We have expanded the scope of risk assessment tools to include historic public buildings to be able to assess a wider variety of buildings. In this, we have added the number of occupants for public buildings. Furthermore, we have simplified the assessment for non-experts to use easily. In this, we have simplified regional and local context to only refer to the location of the building, i.e., urban or rural context. In this research, we focus on naturally ventilated buildings as they form a large majority of UK's historic buildings, and therefore, we have removed any references to mechanical ventilation from the assessment.

The risk assessment we developed comprises 23 questions and is tailored for assessing historic buildings. Each question has guidance notes to assist the person carrying out the review of the key considerations when scoring, as there are several scoring options for each question. Factors that are likely to increase overheating risk are numbers equal to or higher than zero. In this, the higher the score, the more risk. Factors that are likely to mitigate overheating are numbers less than zero. In this, the lower the score, the lower the risk, which will reduce the total score. When all the scores are entered into the spreadsheet, a total score is calculated, which is categorised into one of the three risk groups; high risk > 32, medium risk 22–31, low risk < 21. The score categories have been calculated through averages of previously worked case studies in a wide variety of dwellings. It is the intention that this will provide the authors with the factors that are most likely to increase the risk of overheating. The list of considerations in the developed assessment is as follows:

Regional and local context. The location of historic buildings is an important factor in assessing the risk of overheating. Areas located in highly urban districts such as central London are dominated by hard surfaces. These surfaces increase the average air temperature as they absorb heat during the day and release it at night [37]. Table 2 illustrates the risk assessment for regional and local context. The buildings located in towns or cities, due to the 'urban heat island effect', where heat is stored in pavements, roads, and buildings, is further compounded by a lack of trees when compared with the countryside [39,40]. The presence of green spaces and large water bodies in the context can help mitigate the effects of overheating [41].

Table 2. Regional and local context.

	Explanation	Options	Score
Where is the building situated?	Heat urban island effect increases the likelihood of overheating	Central/high heat risk London	6
		Towns Cities	4
		Suburban areas	2
		Rural Areas	0
Is there significant blue/green infrastructure in the surrounding area?	How close is the property to green spaces/large water bodies?	Yes: As guidance, score 2 mitigation points for at least 50% of surroundings within a 100 m radius to be blue/green or a site in a coastal area.	−2

Occupancy characteristics Overheating risks are also dependent on the length of occupancy [42]. The more time spent indoors, the warmer the internal environment is likely to be. On the other hand, under-occupied properties pose less risk of overheating. In public buildings, the higher the number of users per day, the warmer the internal environment is likely to be [43]. How the occupants use the buildings could also add to overheating risks [44]; however, we have not considered it in our initial exploration. Table 3 illustrates the risk assessment in relation to occupancy characteristics.

Site characteristics. The characteristics of a site can influence the overheating risks. In this, we consider the orientation of the property and the opening of windows. South-facing buildings receive the most amount of solar gains. Therefore, these buildings are most likely to be subjected to overheating. The surroundings of a historic property also dictate whether the windows can be opened without any risks such as pollution, noise, and security [45]. If such risks exist, the property may be more at risk of overheating due to lack of ventilation. The overheating risks can be mitigated if there are tall trees or buildings that can shade the solar-exposed areas [46]. Moreover, pale or blue/green surroundings can further reduce overheating risks. Please see Table 4.

Table 3. Occupancy characteristics.

	Explanation	Options	Score
Length of occupancy (dwelling)	The more time spent, the warmer the internal environment is likely to be	Long occupancy hours: score 3 per adult at home most of the day (excluding the first adult), e.g., score 0 for 1 adult with long occupancy hours, 3 for 2 adults with long occupancy hours, etc.	3X
		High occupancy density, i.e., more than 2 people per bedroom: count the total number of bedrooms (including the main room in a studio), multiply by 2, and score 3 per occupant over that "2-per-bedroom total"	3X
Number of of occupants (public buildings)	The higher the number of users, the warmer the internal environment is likely to be	More than 100 people	4X
		Between 50–100 people	2X
		less than 50 people	0X
Are the homes under-occupied or likely to be?	"Under occupancy" is taken here as less than 1 person per bedroom, based on the total number of occupants and bedrooms—whether or not occupants share a bedroom, bedrooms are used as offices etc.	Low occupancy density: count the total number of bedrooms (including the main room in a studio), and score 2 per occupant under that total number of bedrooms. e.g., score 0 for 2 occupants in a 2-bed flat; 2 for 1 occupant in a 2-bed flat; 4 for 2 occupants in a 4-bed	−2x

Table 4. Site characteristics.

	Explanation	Options	Score
Orientation	Buildings that are south facing (with the majority of facing windows) receive the most amount of solar gains	South-facing	4
		Other	0
Window Opening	Can windows be opened without risk? Risks could include acoustic risks, poor air quality, e.g., near factory, car park, or very busy road; security risks; adjacent to heat rejection plant	Day time—considerable restrictions on opening windows	16
		Day time—some restrictions on opening windows	8
		Day time—few restrictions on opening windows windows	4
		Night time—considerable restrictions on opening windows windows	16
		Night time—considerable restrictions on opening windows windows	16
		Night time—some restrictions on opening windows	8
		Night time—few restrictions on opening windows	4
Are immediate surrounding surfaces in majority pale in colour, or blue/green?	All surfaces within 10 m of the property	Yes, the large majority of surfaces	−2
		Yes, approximately half of the surfaces	−1
		No	0

Table 4. *Cont.*

	Explanation	Options	Score
Are there existing tall trees or buildings that shade solar-exposed glazed areas?		Yes, to all or a majority of solar-exposed areas	−2
		Yes, but only to some of the solar-exposed areas (only score this when considering individual dwellings: do not score for a whole apartment block if some apartments are shaded but not others, except if scoring specifically these shaded apartments rather than the whole block)	−1

Key characteristics of the building. Table 5 illustrates the risk assessment in relation to key characteristics of the building. Identifying a building's age is key to the process of identifying its innate characteristics and, in turn, the efficiency of its fabric. Despite the challenging nature of identifying a building's age, it is made possible by recognising the major changes to techniques that were used in constructing them. Pre-1919 dwellings range from mass-built solid-wall stock to exemplary individual buildings. In the UK, traditional buildings typically comprise solid load-bearing masonry walls, with pitched rooves and timber framed windows [13]. This building envelope is characterised by its high thermal mass, due to the materials' dense and heavy nature. A building that obtains a high thermal mass (or 'thermal inertia') is associated with being efficient at absorbing external thermal gains while not exhibiting considerable changes to ambient temperature, remaining thermally stable. Heavy materials such as brick or masonry act as a buffer by absorbing energy, which is, in turn, released slowly, hence, why churches are often cool in the summer [47]. Exposed thermal mass refers to thermal mass without appropriate ventilation that gradually releases the heat in occupied rooms and contributes to overheating. High exposed thermal mass can contribute to mitigating overheating when it is combined with night ventilation. A lack of safety and noise have been identified as the main barriers to ventilation. We also acknowledge that occupants' awareness of the importance of night ventilation is a key factor in mitigation.

While we considered high thermal mass in combination with night ventilation a mitigation point, we must acknowledge that with the increased likelihood of 'tropical nights' in the UK, a high thermal mass can be an issue. When the temperature is high throughout the night (rather than historically cool) and materials with a high thermal mass radiate heat rather than absorbing it, the indoor environment is more likely to be impacted [48]. This is further exacerbated for buildings located in towns or cities due to the 'urban heat island effect', where heat is stored in pavements, roads, and buildings and further compounded by a lack of trees when compared with the countryside [39].

A literature review of investigations into the overheating of homes carried out by Departments for Communities and Local Government [49] summarised that the scale of the problem for existing buildings was considerable (as highlighted by several monitoring studies). The studies informed that the areas that were most at risk from large variations in internal temperatures during heatwaves were top floor flats, end terraces, and purpose-built dwellings, with bedrooms being the greatest cause for concern [50,51].

Older buildings that have been left in a state of disrepair can face severe overheating as negative solar gains are absorbed though any openings. which are then, in turn, transferred into the living spaces.

Historic buildings are also protected by law through forms of designation. When applying these restrictions to changes that could be made to historic buildings to better cope with overheating, there is currently a fragmented approach to the approval of retrofit schemes. This is largely down to the associated variety in size, operation mode, and local cultures of the NGO's advising on the designations, as well as the local authorities. This, in turn, leads to the guidance and advice that is provided not always being consistent or compatible [52]. There are several studies that highlight these inconsistencies (See for example, [53–55]).

Table 5. Key characteristics of the buildings.

	Explanation	Options	Score
Are the buildings a higher-risk typology?	Flats and bungalows often combine risk factors such as dwelling size and heat gains from surrounding areas or the roof	Flats	6
		Bungalows	4
		Mid-terrace, end terrace	1
		Detached/semi-detached	0
What is the aspect of the building?	Dual aspect buildings make effective ventilation easier and more likely.	Single aspect	6
		Corner aspect or dual aspect with convoluted air path	3
		Dual aspect	0
Floor Area of occupied rooms	Smaller surface to floor area (SA/FA) increases overheating risk	small	3
		medium	2
		large	1
Condition of the property	Buildings that are poorly maintained have an increased risk	Poorly maintained	6
		Adequately maintained	3
		Well maintained	0
Listed status	Buildings that are listed are less likely to be able to accommodate changes	Listed	4
		unlisted	0
Do buildings have high exposed thermal mass and a means for secure and quiet night ventilation?	Medium and heavyweight construction materials can be effective in reducing overheating risks in combination with night-time ventilation. Relying on night-time ventilation must take account of occupants' awareness and security	Yes	−2
		No	0
Building Construction	Correlation between construction types and overheating	Solid masonry	−2
		Cavity wall	−1
		Timber frame	0

Well-insulated buildings are increasingly likely to experience overheating [25]. The same can be said for windows that have secondary glazing units installed [26]. When considering overheating in historic buildings, there are three main considerations, forming a 'trilema': energy performance, practical usability, and heritage preservation.

The 'heritage preservation' is a uniquely specific factor of the overheating trilemma that applies to the UK. There are two key areas where legislation is directly involved when carrying out any adaptations to an historic building, building regulations and planning consent or approval [56]. The approved documents that specifically apply to historic buildings are Part L-Conservation of Fuel and Power and Part F–Ventilation. Part L aims to achieve the conservation of fuel and power by regulating the efficiencies of mechanical systems (i.e., cooling and heating), as well as by enforcing fabric performance standards [56]. Part F is intrinsically linked to Part L, with both needing to be viewed together when enacting any change on a building. As alluded previously, the difference in imposed standards is far more relaxed when reviewing the existing buildings. Many of the considerations found within the approved documents are generic, so expecting the same standards for both new and old buildings is unrealistic due to the extent of the differences in their make-up and the way they perform [57]. Overheating is directly addressed in building regulations part O [58] but only applies to newly constructed domestic buildings.

Capuano et al. [59] make the case that most conventional methods of passive cooling have design implications (or utilise unsustainable methods), which, in turn, conflict with the heritage preservation philosophy. These methods range from; new windows (reduce glazing areas and g-value, modern draft strips, solar control films), external shading (awnings, shutters, and canopies), urban redesign (increasing green spaces, shade landscaping), altering roof form and introducing vents, solar reflective paint, and external insulation. However, there are methods that can be incorporated by historic buildings without legislative restriction for the most part; cross ventilation (strategic window opening across aspects), internal insulation (pipes, roof spaces, with particular materials as to not exacerbate the issue), modify interior design (lighter, less thick materials), and solar window films [60–62].

Solar heat gains and shading. Considering solar heat gains from glazing exposed to solar radiation is necessary for risk assessment as it increases the likelihood of overheating [63]. The more glazing exposed, the higher the likelihood of overheating [37]. In this, there are five categories to consider, depending on the proportion of exposed glazing. We acknowledge that in historic buildings in the UK, the proportion of higher glazing, i.e., more than 50%, is a highly unlikely scenario. However, this factor is relevant for historic buildings with highly glazed features such as conservatories. While we acknowledge that the type of glazing can also impact overheating risk [63], for our initial exploration, we used only the ratio of glazing to surface criteria. Refer to Table 6.

Table 6. Solar heat gains and shading.

	Explanation	Options	Score
What is the solar-exposed glazing ratio for the buildings?	The more glazing that is exposed increases the likelihood of overheating.	Solar exposed glazing-to-facade > 65%.	20
		Solar exposed glazing-to-facade > 50%.	12
		Solar exposed glazing-to-facade > 35%.	8
		Solar exposed glazing-to-facade < 35%.	4
		Highly glazed feature, e.g., conservatory, enclosed glazed balcony	14

Infiltration, ventilation, and effectiveness of openings. Internal air tightness leads to an increased risk of overheating. High energy standard retrofitted buildings, as well as internally heavyweight structures, have an increased likelihood of severe overheating [25], with buildings in the south of the UK facing the largest risk.A very leaky building is less likely to be at risk of overheating. On the other hand, airtight buildings are more likely to be overheated. Internal airtightness can be mitigated by effective ventilation. Cross ventilation is an effective means of cooling a building. In this, we consider the positioning of windows in historic buildings. Single aspect refers to openable windows on one wall. Dual aspect refers to buildings with openable windows on two or more walls, whereas corner aspect means two sides that are exterior walls. As airtightness regulations refer to new buildings only, in historic buildings, more of a qualitative approach is adopted due to the unique characteristics and different typologies of heritage buildings. In energy efficiency research, airtightness is assessed through hydrothermal simulations and blower door tests. For these risk assessment tools, the level of airtightness is following the criteria: presence or not of window and door draughtproofing, wall insulation, loft insulation, and floor insulation. The main sources of the air leakage points [64,65] that can be detected in historic buildings are

- Fenestration, in the wall joints and the joints in the frame, especially in mobile parts.
- Apertures across the envelope to let ducts or conduits go inside (fresh water, waste water, gas, and/or ventilation)
- Electrical devices (switchboards, plugs, switches, lighting)
- Large cracks caused by ground settlement or cavities in wooden structure.
- Baseboards and in tongue and groove joints of the floor boards.

Refer to Table 7.

Table 7. Infiltration, ventilation, and effectiveness of openings.

	Explanation	Options	Score
Air tightness	As per the Historic England (2021) study, air tightness increases likelihood of overheating	Very leaky building, e.g., at least 3 “high leak features” If test available: >12 $m^3/m^2/h$ at 50 Pa	0
		Average or very airtight building but with suitable background ventilation provision.	1
		Average airtightness, WITHOUT suitable background ventilation provision.	1
		Very airtight building, WITHOUT suitable background ventilation provision.	1
Do windows and openings support effective ventilation?	Cross ventilation is an effective means of cooling a building	Single aspect	−4
		Corner aspect	−5
		Dual aspect	−6

Energy efficiency. Certain measures that are put in place to increase the performance or efficiency of a building could increase the likelihood of overheating risk [66]. In this, we consider the heating systems, roof and loft insulation, and type of window glazing as factors that could increase risks of overheating. The heating systems are divided into two types: (1) communal/district heating and (2) individual heating and hot water systems. For evaluating risks due to heating systems in communal heating, if there is not much information available on the scheme, we suggest taking scoring route 1. Scoring route 2 should be taken if information is available on the scheme. Roof coverings can aid in heat gains. Properties with no or minimal insulation are more likely to be at risk. Lastly, the type of windows should be considered when evaluating risks. Buildings with single-glazed windows are least at risk. We consider the ground-floor insulation as a mitigating factor. Un-insulated suspended floors mitigate the risks to a great extent. Please refer to Table 8.

2.2. Environmental Data

Environmental monitoring is a reliable way to assess historic building performance in a changing climate. In order to have a quantifiable measure of the internal gains of a property, capturing temperature and relative humidity (RH) data in each of the three properties was a necessity. Of the three properties, the authors set up two data loggers in two of the buildings, with the other property having already been capturing the data prior to this study being conducted. Table 1 illustrates the data collection period. Tinytag Ultra 2 Temperature Loggers (TGU-4017) were utilised, as they are most suited to monitor internal environments where there is little moisture. The loggers recorded temperature and RH every hour, 24 h a day. The loggers were placed in two different locations due to the differing overheating thresholds, as per the CIBRE criteria. External environmental data were also collected in the three different locations 24 h a day for the same time periods that the internal loggers were recording.

Table 8. Energy efficiency.

	Explanation	Options	Score
Does the heating system create a risk of high internal heat gains?	Community/district heating can create a risk due to hot pipework operating during the summer, especially if it runs across internal areas (e.g., corridors), leading to heat gains and higher temperatures in these areas and ultimately into adjacent dwellings. Individual heating systems can create a risk too	Communal/district heating: Scoring route 1: not much information on the scheme/early design stage: Score 7 for scheme details unknown or unlikely to be best practice OR Score 2 for best practice, e.g., following CIBSE CP1 2020 "Best Practice", or ambient loop, and no store in apartments. Scoring route 2: information on the scheme is available: Score 2 if long corridors with no or limited ventilation, Score 1 if corridors with effective ventilation to limit overheating, Score 0 if corridors with running pipework are very short or there are no internal corridors, or the communal heating scheme is at low temperature distribution PLUS Score 3 if poorly insulated store inside the dwelling, 1 if well insulated store inside the dwelling, and 0 if no store inside the dwelling PLUS Score 1 if poorly insulated distribution.	Up to 7
		Individual heating and hot water systems: Score 3 for poorly insulated store, 1 for well insulated store, and 0 for no store PLUS Score 1 for poorly insulated/long distribution, 0 for insulated/efficient	Up to 5
Roof and loft insulation	Significant heat gains can be generated from roof coverings	Houses, bungalows, top floor flats: No or minimal (<50 mm) insulation: 2 points	2 or 3
		Houses, bungalows, top floor flats: Some insulation (>100 mm): 1 point PLUS 1 point if roof covering likely to get hot	1 or 2
		Houses, bungalows, top floor flats: New build levels of insulation e.g., new loft roof, exemplar retrofit. All flats except top floor flats	0
Windows	Window U-Value	Single glazed	0
		Existing double glazed or single + secondary	2
		Similar to new build standards	3
Ground floor insulation	Ground temperature is relatively constant throughout the year, and this can provide beneficial cooling in the summer, particularly in the case of suspended floors.	Houses, bungalows, ground floor flats: Un-insulated suspended floor, ventilated	−2
		Un-insulated slab, or minimal insulation	−1
		Insulated slab, or insulated suspended floor. All upper floor flats.	0

The readings were also analysed by working them into the overheating criteria to record whether the buildings were subject to overheating, as per the CIBRE metrics. Where applicable, heatwave and winter data were also reviewed to provide a comparison.

2.3. Interviews

An occupier of each property was interviewed to assess their experience in the property, as well as a discussion regarding other variables that lend themselves to overheating. In other words, the interviews were used to inform the risk assessment, particularly the section on occupancy characteristics. There was a total of 19 questions, which attempted to obtain information that cannot be captured through the data loggers or risk assessment methods. Interviews were also used to validate the results of the risk assessment model according to the thermal comfort perceptions. The topics of conversation were as follows:

1. Occupant characteristics/patterns
2. Defining unique relationship with overheating
3. Satisfaction with the environmental performance of the building and its impacts
4. Understanding areas and features of the building that impact overheating risk
5. User behaviour in hot weather when occupying the building
6. Ability to make alterations/adaptations to improve cooling capacity
7. Awareness of support/incentives to improve building performance/efficiency

All three interviews took place face-to-face at the property in question, along with the risk assessment taking place immediately before or after the interview. Once they were completed, the authors analysed any similarities in the answers given across the various properties.

3. Case Studies

Three case studies were selected to test and evaluate the methodology to assess overheating in historic buildings. The details of the case studies are provided in Table 2. The case studies are selected for their different attributes. They include residential and public historic buildings in rural and urban contexts. The buildings were constructed in different periods and employed different construction techniques and materials, as evident from Table 2. Two out of three cases are listed buildings.

3.1. Marden, Kent

The first property selected is a semi-detached 3-story Farmhouse located in Marden, Kent. The district authority is Maidstone, located within the Collier Street Parish. Marden is a highly rural area, with this property being situated in a farm, ten minutes away from the village, so there are many trees and large bodies of water near the house. This dwelling was originally constructed in 1662, with the western section being constructed later to extend the property There are several grade II listed buildings within the immediate area, although this building does not obtain listed status. This is a 6-bedroom family home that is only regularly occupied by two individuals. The first data logger was set up in the ground floor sitting room, and the second in bedroom 2 on the second floor Both rooms that the loggers were placed in are lightly used, with the windows closed for the vast majority of the duration of this study (Table 9).

Table 9. Case studies.

	Case Study 1	**Case Study 2**	**Case Study 3**
Location	Marden, Kent	Islington, London	Bromley-By-Bow, London
Type	Semi-detached 3 story Farmhouse, 6 Bedroom	Mid-terrace, Georgian Maisonette, 2-bedrooms	Tidal mill
Context	Highly rural area	Highly developed area	Highly developed area, situated on the River Lea
Built in	1662, subsequent retrofits	1828–1829	1776
Listed status	Un-listed	Grade II listed, conservation area	Grade I listed
Construction	Timber framed, weatherboarded	Solid masonry wall, London stock bricks with stucco bands	Solid masonry wall, timber-boarded rear elevation, stock brick front elevation
Windows	Double glazed, hinged	Double glazed sash	Single glazed sash
Orientation	Corner aspect	North-facing	South-facing
Aspect	South-facing	Dual aspect	Dual aspect
Usage	Residential	Residential	Industrial
Occupants	Regularly occupied by two individuals	Lightly occupied by two young professionals who both work away from home	Open to the public on Sundays where tours take place over the course of five hours
EPC	D	C	N/A

3.2. Islington, London

The second property is a grade II listed Georgian Maisonette situated within a conservation area in the London Borough of Islington. The flat is located on the second and third floors of a terraced house, built circa 1828–1829 by William Chadwell Mylne, Surveyor for the New River Estate. Islington is a highly developed area in central London (zone 1), so this property is likely to be significantly affected by the urban heat island effect. The envelope consists of yellow stock brick set in Flemish bond with a banded stucco ground floor and stucco dressings The windows are double glazed timber sashes, with the downstairs windows being very large, spanning most of the height of the room (3 m). The roof is dual-pitched with turnit slates with an asphalt gully running through the center. The property is lightly occupied by two young professionals who both work away from home. The flat is dual aspect, and there is little risk to opening windows as the flat is situated on the upper floors. As with the first property, the loggers were placed on a high shelf in the downstairs living room and second-floor master bedroom by a north-facing window.

3.3. House Mill, Bromley-by-Bow, London

The third property being studied is House Mill in Bromley-By-Bow, London. It is also known as Tide Mill. It is a grade I listed building located in the borough of Newham, constructed in 1776 The building is only open to the public on Sundays, when tours take place over the course of five hours. Bromley-By-Bow is a highly urbanised area and surrounded by River Lea, from the Thames. Internally, much of the exposed timber is painted with a white lime wash, which was intended to reduce internal temperatures. This was carried out so as to limit the chance of fires breaking out. There are many open cavities in the walls and floor A data logger was placed on a beam by a south-facing window on the first floor (the grinding floor). A data logger was also located on the ground floor, but the data were corrupted so could not be used for this study.

4. Results

In this section, we present the results of the overheating risk assessment of three case studies, results of the environmental data monitoring, and interviews.

4.1. Risk Assessment

Table 10 illustrates the results of the risk assessment. House Mill was found to be least at risk, while the properties in Marden and Islington were found to be at medium risk. Regional and local context seemed to be one of the most important factors in the risk assessment. Comparatively, the property in Islington scored the highest in the risk assessment model among the three properties. This is not surprising as the property is in central London and exposed to the 'urban heat island effect'. However, in this, we also see the importance of mitigation measures. Without any mitigation points, the risks due to context are higher in Islington, whereas the presence of mitigation factors in House Mill lowers the risk, as it is also exposed to the 'urban heat island effect'.

Site characteristics such as the ability to open windows and site orientation can also influence overheating risks significantly. South-facing House Mill with restrictions on opening windows during the day as well as night led the property to score higher in risk assessment compared to other case studies. In terms of mitigation, we see that Marden scored higher than the other case studies because of the presence of trees that limit direct solar exposure and the presence of pale/blue-green colours in the immediate surrounding surfaces.

Occupancy characteristics that could add to overheating risks are dependent on how the occupants use the buildings [44]. In our study, the occupants seem to be working actively on mitigating overheating risks with their behaviour. While the occupancy density was low in all three cases, this may not be true for other cases, particularly in London where the housing crisis is a documented problem.

Table 10. Risk Assessment.

Factors	Increase Points	Mitigation Points	Total
Marden, Kent			
Regional and local context	0	2	−2
Site characteristics	12	4	8
Occupancy characteristics	3	6	−3
Key characteristics of the dwelling	9	4	5
Solar heat gains and shading	4	-	4
Infiltration, ventilation, and effectiveness of openings	2	4	−2
Energy efficiency	13	1	12
Total			22 (medium risk)
Islington, London			
Regional and local context	6	0	6
Site characteristics	8	1	7
Occupancy characteristics	0	4	−4
Key characteristics of the dwelling	15	4	11
Solar heat gains and shading	4	-	4
Infiltration, ventilation, and effectiveness of openings	1	6	−5
Energy efficiency	7	0	7
Total			26 (medium risk)
House Mill, London			
Regional and local context	6	2	4
Site characteristics	20	2	18
Occupancy characteristics	0	8	−8
Key characteristics of the dwelling	11	2	9
Solar heat gains and shading	4	-	4
Infiltration, ventilation, and effectiveness of openings	0	6	−6
Energy efficiency	2	2	0
Total			21 (low risk)

Key characteristics of the dwelling also contribute significantly to the overheating risks. The fact that Islington is a list-property (thereby, limiting active adaptation possibilities) and a flat adds significantly to the increase points in this property. All the case studies are constructed in solid wall masonry, thereby mitigating the overheating risk to some extent.

Solar heat gains and shading were the same for all three study cases as a contributing factor. The absence of shading in the historic environment in the UK is already mentioned in the introduction as one factor for overheating in historic buildings.

Infiltration, ventilation, and effectiveness of openings can also influence the overheating risk of a historic building. Low airtightness in House Mill seems to be contributing to low risk in overheating. In Islington, the effectiveness of window openings is an important mitigation factor. Interestingly, in House Mill, even if there is a restriction on opening the windows, the building is very leaky, which lowers the risk for overheating.

Lastly, the energy efficiency seems to be an important parameter influencing risk for overheating, especially regarding the Marden study case. As a house with no loft insulation and existing double glaze windows, there is the possibility that significant heat gains can be generated from roof and window coverings. On the contrary, House Mill, which was found with no floor insulation, contributed to mitigation points. As the ground temperature is relatively constant throughout the year, a beneficial cooling effect can be provided during the summer.

The combination of all the above factors created in each study case a unique overheating risk profile. Even though two of the studied buildings fall into the medium risk band, each building has its own risk points and limitations but also adaptation possibilities to be considered.

4.2. Environmental Data Analysis

In Table 11, we can see the environmental monitoring period in the case studies, the number of days spent monitoring the internal and external environments. In each study case, the internal temperatures and relative humidity are compared with the measured external temperatures, which were monitored as well for the same period. The average temperature is noticed to be relative stable between the different floors for the monitored period. For the first two case study buildings, the indoor temperature is higher in comparison with the external temperature, in the scale of 5 °C. This is not noticed in House Mill, where the indoor average temperature is only 1 °C higher than the external average.

In the Marden building, there is a little difference between the monitored floors (0.15 °C). The average temperature in the ground floor is 22.2 °C and 22.4 °C upstairs. On the contrary, according to the Table 11, there is a rise in the average relative humidity by 3.15% from the ground floor to the bedroom, which can cause a different feeling for the same absolute room temperature.

In the Islington building, there is a slight difference between the average temperature on the living room (on the lower floor) and the master bedroom (0.87 °C). The average relative humidity is also relative stable on the two floors. According to Table 11, both buildings pass the CIBRE criteria for overheating. However, the risk assessment indicated both study cases had medium risk.

Table 11. Environmental data analysis.

Marden, Kent	**Sitting Room, Downstairs CP08**	**Bedroom 2, Upstairs CP05**	**External**
Recording period	28 June 2023–24 August 2023	28 June 2023–24 August 2023	28 June 2023–24 August 2023
No. of days	56 days	56 days	56 days
Average temperature (°C)	22.23	22.38	17.25
Average RH (%)	59.8	62.95	78.21
CIBRE Criteria	PASS, 0% of recorded hours above 28 °C	PASS, 0.024% of recorded hours above 26 °C	N/A
Islington, London	**Living Room, Downstairs CP03**	**Master Bedroom, Upstairs CP04**	**External**
Recording period	28 June 2023–24 August 2023	28 June 2023–24 August 2023	28 June 2023–24 August 2023
No. of days	56 days	56 days	56 days
Average temperature (°C)	22.71	23.58	18.21
Average RH (%)	61.36	62.04	71.21
CIBRE Criteria	PASS, 0% of recorded hours above 28 °C	PASS, 0.024% of recorded hours above 26 °C	N/A
House Mill, London		**1st Floor (Internal)**	**External**
Recording period		1 June 2022–21 July 2023,	1 June 2022–21 July 2023
No. of days		415 days	415 days
Average temperature (°C)		14.13	13.26
Average RH (%)		73.85	73.38
CIBRE Criteria		0.00048% of recorded hours above 28 °C	N/A

Figures 1–3 present the monitoring data from air temperature and relative humidity in each of the study cases for the monitored period. Figure 4 shows the results of monitoring in the House Mill during the heatwave period of 2022.

In Figure 1, we notice that the temperature measured inside the house has lower limits 20 °C and peaks can reach 30 °C. The external temperature is documented with higher fluctuations, the lower external temperature in the documented period is 10 °C and the higher external temperature is 28 °C. In general, the peaks in indoor temperature follow the peaks of external temperature. While there is a higher external temperature, there is a higher temperature indoors. However, there is an instance in the graph where external temperature rose above the indoor (7 July 2023). In the end of the monitored period, 15–24 August, low external temperature spikes seemed to cause higher internal temperatures. Regarding the relative humidity, it is important to point out that indoor relative humidity min level is 45 and the max level is 65%. These fluctuations are inside the human comfort scale for non-air-conditioned buildings.

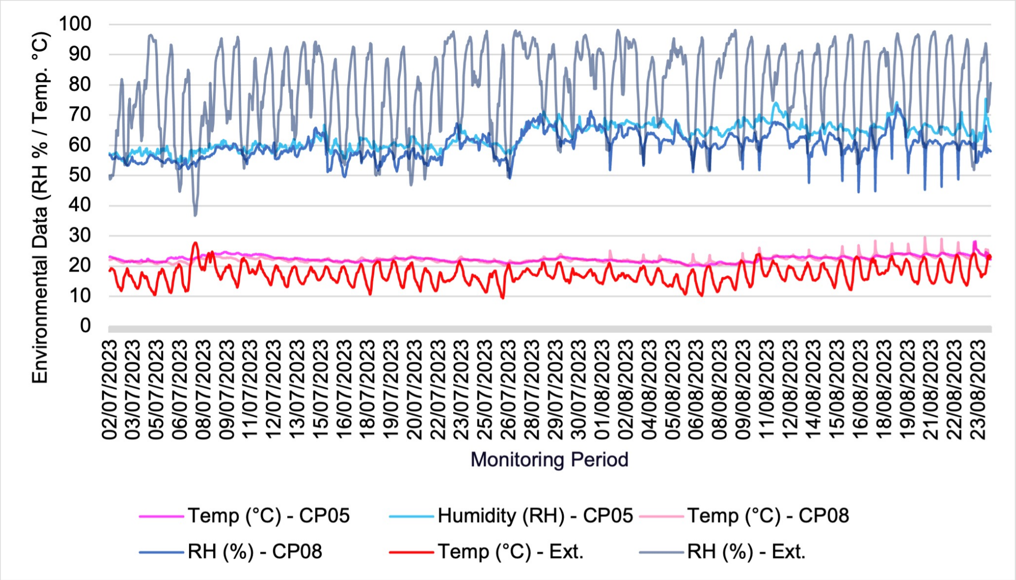

Figure 1. Temperature and relative humidity in Marden, Kent.

In Figure 2, we notice that the temperature measured inside the house has lower limits 20 °C and peaks can reach 28 °C in the beginning of the monitoring period. The external temperature is documented with higher fluctuations, the lower external temperature in the documented period is 10 °C, and the higher external temperature is 30 °C. There are approximately six instances in the graph where external temperature rises above the indoor. Regarding the relative humidity data, it is important to point out that indoor relative humidity min level is 42 and the max level is 73%. Relative humidity is, in a few instances, outside the human comfort levels for non-air-conditioned buildings.

In House Mill, the environmental monitoring devices were placed for over a year. We also have data from the heatwave period of 2022 in which UK was most affected. From Figure 3, we see that the pattern of indoor temperature and relative humidity follows the external conditions. During the coldest period, i.e., December 2022, where the external temperature was below 0 °C, the indoor temperature was above 0 °C. The indoor temperature during the coldest period was approximately 4 degrees higher than the external.

Figure 4 illustrates the results of environmental monitoring during the heatwave period of 2022. We see a trend of the building heating up during the day but cooling off at night. Nevertheless, the building is significantly cooler (about 10 °C) during two days of extreme weather conditions.

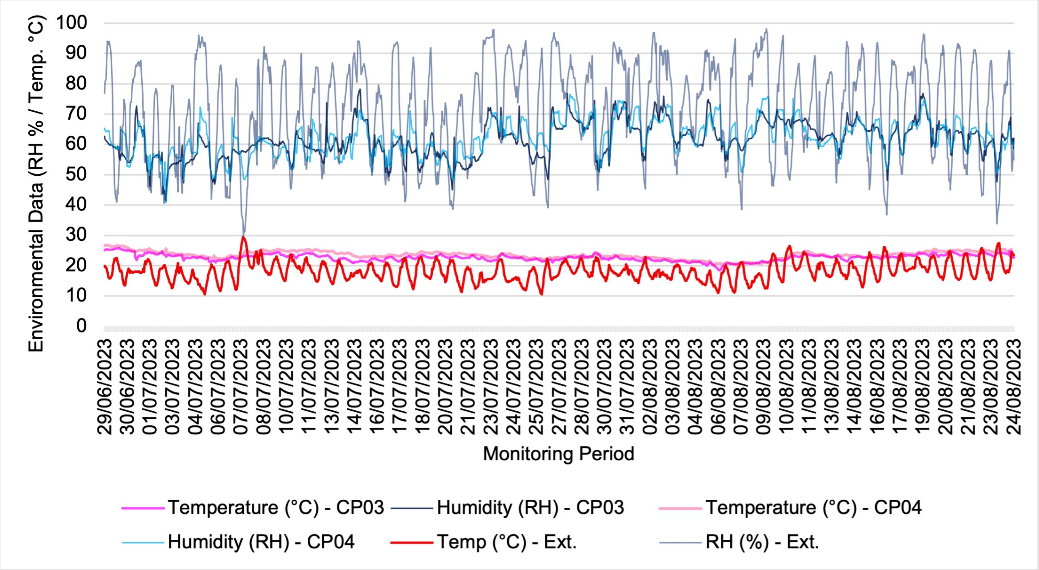

Figure 2. Temperature and relative humidity in Islington, London.

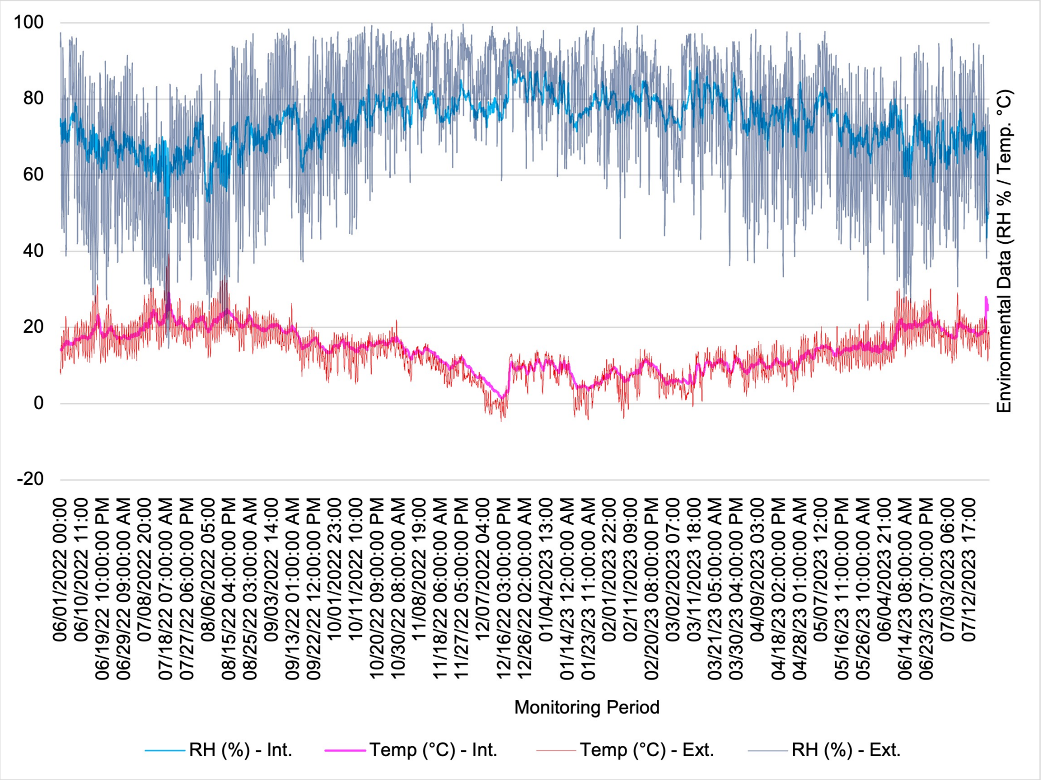

Figure 3. Temperatureand relative humidity in House Mill, London.

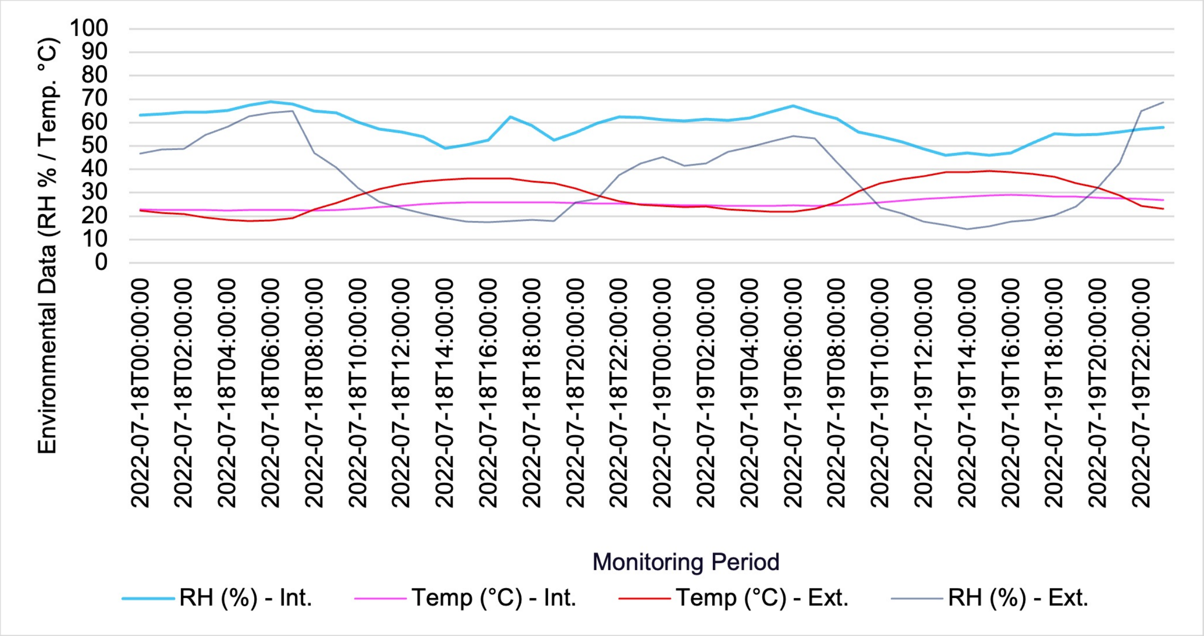

Figure 4. Temperature and relative humidity during heatwave in House Mill.

4.3. Interview

In Marden, an interview was carried out with one of the two occupants of the property. The occupant stated an overall satisfaction with the indoor environmental conditions in their home in all seasons. However, during the summer, there is documented a strong thermal discomfort in parts of the residence. In the summer, the second floor gets 'extremely' hot, as they describe it. We do not have environmental data for the second floor, but on the first floor, the documented temperature rises up to 30 °C, although the lower floors, especially the ground floor, manage to stay cooler. To make themselves more comfortable during the summer, the occupants are aware and already using some common adaptive strategies, such as the use of curtains to keep the direct sunlight out of the room and opening of the windows and doors in the ground floor. They also mention a different use of the house rooms during the summer months, by avoiding the bedrooms on the top floor and sleeping on the lower floors to stay cool. This may be disturbing for the occupants in the long term, but as the rooms are used periodically, this is not a permanent change for the main occupants. Regarding active cooling, they use a fan, as they state, 'but in the absence of an airconditing, they are prepared as best they could' for future heatwaves. It is important to note that despite the overheating experience, the wood and brick construction of the house (wooden Kentish weatherboarding) is recognised as a contributing factor to the ability of the house to stay cool in the summer and to retain the heat in the winter. Regarding winter comfort specifically, the occupant was, in general, satisfied with the indoor conditions; they comment that the building 'isn't too draughty' and has double glazed windows, and additionally, there were no damp/condensation problems either. To make themselves more comfortable in the winter, the occupants use central heating and also log fires. For the energy efficiency of the building, the interviewee was only aware of incentives offered for insulation, as well as for certain heating boilers.

In Islington, the interview was carried out with the individual who was renting the property at the time. During the summer, the occupant is generally satisfied, but in high temperatures, they experience overheating. They also stated that the hot weather is unlikely to directly impact productivity in this case as they work away from home; however, the heat does impact sleep quality, which, in turn, does have an effect on their productivity. In particular, the upstairs, i.e., the bedroom, was described as 'noticeably worse than downstairs'. This causes a different use of the rooms because of thermal discomfort and a disruption of sleep, as the user stated that they need to sleep 'on the sofa downstairs'. To make themselves more comfortable during summer, they use passive adaptive techniques like closing their shutters in the day, keeping their windows open. They already use a fan to stay cool. To prepare for possible future heatwaves, the occupant has bought a new fan, as they have recognised that it helped previously, but still they feel unprepared. Historic characteristics of the building such as high ceilings and large slash windows were recognised as factors that influence the indoor environmental conditions by the interviewee. The occupant was experiencing poor comfort conditions during winter as well. The reasons for poor winter thermal comfort were stated as building characteristics such as high ceilings and an older boiler. These cause the flat to remain cold throughout the season. Regarding energy efficiency, there was no awareness of incentives or initiatives relating to overheating or retrofitting by the interviewee, but there is the feeling that it is going to be more difficult to make adaptations due to the age of the building.

An interesting point raised from both interviews was that the occupants needed to change their everyday routines and use of their rooms during the summer due to overheating and not during winter thermal discomfort. Even though, in one case, they were satisfied with the indoor conditions and the other was not during winter. Both of them were informed about overheating and have already been using a fan. They both are also aware how the historic characteristics of their building (construction technique, high ceilings, small/large windows) influence the indoor environment. Another key takeaway was that both interviewees indicated a lack of knowledge of what could and could not be changed in their property due to its heritage properties or an awareness of any initiatives regarding overheating and regarding retrofitting.

At House Mill, there was no formal interview conducted; rather, a few questions relating to the buildings' thermal comfort were asked during the guided tour. Regarding the indoor environmental conditions during summer, the guide stated that the building remained cool without the need to open windows. The interviewee gave a reason for this: a large body of water surrounding the mill and the open areas of the structure due to age and viewing areas for historic mechanisms. Regarding the winter environmental conditions, they described how cold the building would be. There is no heating system, according to the guide in the building. The interviewee recognised that the factors that attributed to poor thermal conditions in the winter were contributing to the building's ability to keep cool during the summer months.

There is a difference between the three interviews regarding the experiences of overheating, where occupants of Marden and Islington have stated discomfort during summers. The use of the building, as well as the building type and direct external environment, can be possible reasons for this. According to the risk assessment, House Mill is categorised as low risk for overheating. This is confirmed by the interview.

5. Discussion and Conclusions

It is important to discuss the extent of overheating as an issue in the UK. Many perceive the UK to be mild, which is true for the most part of the year. Due to extant climate change, our summers are warmer, and heatwaves are more frequent and longer. This can lead to health concerns, and even deaths are becoming more common [67]. Studies have shown the cognitive impact of heat. In this, researchers claim that global warming trends may be correlated to increasing violent crime rates [68]. Furthermore, hotter temperatures have also been reported to impact productivity. Our research has demonstrated that productivity is related to quality of sleep, which is affected during hot summer days. A study on the impact of hotter temperatures on productivity found that productivity is decreased by 76% when operational temperatures of 40 °C are experienced [69]. Most of these concerns are caused by internal heat. Overheating can cause a disturbance to everyday human activities such as eating, hydration, and sleeping [70,71]. This was also evident in our research in two residential case studies: Marden and Islington. The occupants were forced to change the use of the rooms to comfortably carry out their everyday activity. With 20 to 30% of buildings in the UK obtaining heritage value [72], a significant demographic reside in them.

If the ‘most aggressive’ 4–5 °C temperature rises are realised, many of the homes we occupy would be uninhabitable. Despite this not yet being a reality, temperatures in the UK are on the rise, meaning that more needs to happen to be proactive and not allow historic buildings to be left behind. A reliance on active cooling is not feasible to mitigate this reality due to active cooling systems contributing to the cause, as well as hurdles that limit their installation. Despite it being understandable that the application of building regulations to existing properties is not as feasible, the creation of Buildings Regulations part O [58] is evidence that the government recognise this issue. It does not affect newer buildings in isolation, and therefore, more research needs to be carried out to understand the issues in-depth, devise mitigation strategies, and inform policies.

The second is that the unique properties of historic buildings, for the most part, are better equipped to deal with hotter weather conditions. Due to their design and construction materials, they take longer to heat up and have better ventilation (due to lack of air tightness, a largely unintended benefit). This is often at the cost of winter thermal comfort. In more extreme weather events, e.g., the 2022 heatwave, and with the need to prepare for regular 40 °C plus temperatures in the future, it was found that there are many obstacles that prevent adaptation in older buildings. Low-cost building materials that inherently have lower thermal mass seem to contribute the most towards modern buildings’ poor performance, which is now being mitigated through updates to Building Regulations Part O, with no such regulations applying to existing buildings. Moreover, the tension between energy efficiency and historic preservation has an impact in the way adaptive opportunities can be approached in historic buildings. More research is required to understand whether overheating considerations can further add to or relax the already existing tensions.

When reviewing the data, the first observation would be that all three properties passed the CIBRE criteria when considering the entire recorded period, where each scored well below the 1% threshold for both the upstairs and downstairs criteria. This could largely be due to the weather conditions exhibited in 2023. According to the Met Office [73], summer 2023 was warmer and wetter than average. Even so, despite the CIBRE criteria not being exceeded in any of the properties for the recorded period, interviewees in Islington and Marden claimed that the upper floors of their dwellings were ‘unbearably hot’. Through a detailed analysis of the monitoring data and not only based on the CIBRE criteria, there were documented several instances of higher than 28 °C temperatures indoors in both buildings. There is still an open research question about how often and for how long occupants can tolerate overheating indoor conditions. Nevertheless, the proposed risk assessment indicated that Marden and Islington were under a medium risk for overheating, as was confirmed from the users through interviews. The proposed risk assessment model was also validated in the third study case in House Mill as it indicated the house to be subjected to lower overheating risk, as was confirmed by the interview. Researchers [66] believe that the threshold of 26 °C for bedrooms is outdated and propose a new overheating criterion due to changes in summertime bedding and bedwear that have occurred since the original guidance was published. The World Health Organisation [74] have also qualified in their guidance for thermal comfort that temperatures in excess of 24 °C can lead to discomfort and potential harm for those who are more vulnerable. It is important to recognise that standards are a way to ensure equality and consistency; therefore, the values and even methodologies described in the standards do not ensure prediction of reality. Concurrently, this could also highlight the ambiguity and cultural differences toward the way overheating is interpreted as illustrated by researchers [66]. These definitions are also limited by the fact that there are many variables when determining what temperatures are comfortable or safe for an individual in particular vulnerable populations.

In the academic community, the urban heat island effect has been a prominent discussion point in overheating research. Comparing the cases of Marden and Islington, we see that even though Marden is not subjected to the urban heat island effect, the overall risk profile of the property is the same as Islington, i.e., both of them were found to be in medium risk. We also see that the temperatures in Marden were higher indoors in more occasions than in Islington. This study also highlights the importance of mitigation points in the historic properties that can lower the overheating risks, even if the building is subjected to the urban heat island effect.

The buildings could feel hotter than they are due to the high RH levels. Higher RH levels are linked to overheating as sweat cannot evaporate at the same rate [75]. While the average RH in all case studies are between the recommended range of 60–80% [76], it fluctuates above 80% in all case studies, thereby adding to the discomfort of the occupants. Guidance from the Health and Safety Executive (HSE) [77] differs, saying that a healthy range for relative humidity should be within the range of 40–70%. This is then qualified by the need for the RH to be at the lower end of this range at higher temperatures. Islington was considerably in excess of this threshold, and in the case of House Mill, well above even the HSE maximum of 70%. Relative humidity was found to be excessive in all three properties, which could be further raising the overheating risk. Upper floors were also found to be marginally warmer that ground floor levels, although the perception of heat is greater when we are trying to sleep [14]. The effect of RH is under-studied and we cannot conclude with certainty that elevated RH had a significant effect on thermal comfort perception.

When reviewing the data for House Mill during the heatwave period of summer 2022 (Refer to Figure 4), the building failed the CIBRE assessment, as 12.5% of the recorded temperature data were above the threshold. The highest recorded temperature externally at House Mill during the heatwave was 39.4 °C, where at the same time internally, it was 29.2 °C. Given the unprecedented nature of this weather event, for the building to remain more than 10 °C cooler when no 'active cooling' measures were present would be considered a revelation to most. While this research did not investigate the cause of this, it could be attributed to many factors including context, orientation of the building, construction, and so on.

For the most part, the results are in alignment with the existing research. As mentioned by Historic England [78], increased ventilation, small windows, and larger floor to surface area all increase the likelihood of a building remaining cooler in the summer months. The most noteworthy example of this is House Mill, where all these features are present. The building is lightly occupied and situated above a large body of water, which is also proven to reduce overheating [25,36]. There were also notable differences between the case studies in Islington and Marden, where the property in Islington had a higher average temperature. Despite the Marden property being occupied for less of the time and being south facing, the urban heat island effect and being situated on the top two floors meant the property in Islington performed worse during the monitored period. The very high relative humidity reading for House Mill is likely a result of the building's location near a large water source with many openings in the floor where moisture can permeate.

Despite the CIBRE guidance [27] stating that bedrooms require lower temperatures to achieve thermal comfort, the case studies that had loggers on multiple floors both displayed higher temperature in the bedrooms than in the living rooms. It is well documented that heat rises, so it is expected that this would be the case as bedrooms in both case studies were located upstairs. This could also be likely due to sporadic interactions and behaviors. For example, in Marden, the occupants use the room in which the ground floor logger was placed in the evening and often make use of a log fire during colder spells, including in the summer. It was also noted that the occupier of the Islington property left the upstairs windows open for most of the time to 'air out' the room, even when the home was unoccupied. Such behaviour is not surprising as researchers have demonstrated the buildings we occupy have systems in place to warm a property but less can be done to cool it [79].

5.1. Reflection on the Overheating Risk Assessment

In this research, we developed an overheating risk assessment tailored for historic buildings. The risk-based approach can support current retrofit approaches. Overheating standards at the moment are applied in a way that focuses on temperature limits and occupancy hours. However, this may be outdated, unfitting in historic contexts. The risk-based approach gives the opportunity to create a unique overheating risk profile for each building. The risk assessment includes both factors that are likely to increase overheating and factors that are likely to mitigate overheating risks. When reviewing the results of risk assessment against environmental monitoring and interview data, the results remained consistent with one another. As the hottest building, Islington had the highest average temperature recorded, the highest score on the risk assessment, and the user raised the highest levels of concern regarding overheating factors during the interview. Equally, House Mill had the lowest average temperature and lowest risk assessment score, as well as comments made by the guide highlighting the low internal temperatures. This demonstrates the applicability of risk assessment in historic buildings in the UK.

One must consider that the risk assessment was developed for historic buildings in the UK. The three case studies used to demonstrate the applicability of the risk assessment are located in the south of the UK. More case studies from different regions of the UK should be used to further test and develop the risk assessment. This risk assessment may not be useful for countries in different climatic zones than the UK. However, it can be used as a baseline to develop overheating risk assessments for different climatic zones. The risk assessment we developed gives a generic understanding of how likely it is for a historic property to be overheated. It does not, however, give any specific indication for those who might be more at risk. In other words, the overheating risk assessment is a good tool when used in combination with a good understanding of vulnerabilities. Lastly, the risk assessment is the first iteration that is meant to empower people who are not trained professionals to assess the overheating risks posed by a property in their working or residential environments. For professionals, more details could be added regarding traditional building characteristics.

5.1.1. Limitations

There are a few limitations to this study. The first being the loss of data from the logger on the ground floor of House Mill. This meant that an analysis of the differences in environmental data could not be established. Ideally, a larger sample of buildings would have been assessed, which would have provided a more comprehensive overview of the issue of overheating. It is also important to note that despite the UK summer of 2022, according to the Met Office [73], 'of ten of the warmest summers on record by mean temperature, summer 2023 is the wettest'. It was also stated that July was the 'UK's sixth wettest July on record'. Despite the summer season of 2023 being 0.8 °C warmer than the average, the majority of the 'dry days of warm summer sunshine', brought about by high pressure, occurred in June. Wet and windy conditions then proceeded due to low-pressure systems for much of July and August, i.e., during the period of data collection for this research. These irregular weather conditions are likely to skew the collected data as recording for this study, for two of the three case studies did not begin until 28 June 2023, with all but a few days falling within the overcast second half of the season. This meant that a like for like comparison could not be achieved, although this does not detract from the valuable data that were collected. The overheating risks not only concern their thermal comfort but also their health and well-being when using the building. It also could affect the usability of the building. The primary risks that we explored in this paper are risks concerning indoor environmental quality. There are other risks associated with overheating in historic buildings, including risks to the building fabric and objects. The impact of overheating on heritage buildings and artefacts is beyond the scope of this paper.

5.1.2. Further Research

This study has drawn attention to several areas that require further research. The first is reassessing the overheating criteria. As highlighted, there are numerous overheating criteria, all of which tell a different story. Any temperature that is below the 35 °C threshold for human health is largely based on conjecture. More research is required to flesh out the existing models to account for more variables (e.g., age). Future studies should incorporate a wide pool of buildings with varying typographies, grouped and analysed based on the factors that cause overheating, as discussed.

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