The impact of climate change on the performance of residential buildings from an occupant-centric perspective – A systematic review

The impact of climate change on the performance of residential buildings from an occupant-centric perspective – A systematic review.

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ABSTRACT:

Europe faces the challenge of providing affordable and high-quality housing for growing populations, while reducing its buildings' energy consumption and phasing out fossil fuels. However, in the context of climate change, progressively warmer summers and increasingly frequent heatwave events not only intensify the risks of overheating, but they also impact building energy consumption and indoor environmental quality. To better understand these impacts, there is a need for the development of reliable methods to predict future weather scenarios and building performance that appropriately accounts for occupants. This systematic literature review aims to investigate methodologies and metrics for assessing performance of dwellings under future climate conditions, including health and wellbeing of building occupants. The PRISMA 2020 approach was applied to identify the current literature of case studies of dwellings' performance under future weather scenarios. The Mendeley Reference Manager and the ASReview Lab were used to assist screening the papers, while the selected case studies were chosen based on relevance and quality criteria. The results of this review indicate that methods based on building simulation tools can be used to project building performance in response to Climate Change. While the current literature has been focusing on buildings' thermal and energy performance, indoor air quality (IAQ) is still a topic not much explored. Additionally, despite the complexity and uncertainty on occupant's behaviour, the application of uncertainty/sensitivity analysis associated with the use of computational tools can provide promising results for occupant-centric building performance in changing climate.

KEY WORDS: Climate Change; Residential Buildings; Indoor Environmental Quality; Building Performance; Occupant Behaviour Models.

1 INTRODUCTION

The housing sector in Europe is currently facing many challenges. According to the European Union (EU) Statistics on Income and Living Conditions, around 7% of the European population have difficulties to pay their energy bills [1], while 11.6% are unable to keep their house appropriately warm during cold seasons [2]. In Ireland, both indices are slightly higher than 7% [1, 2]. Approximately 16% of the Irish and the EU population face leaking roofs and dampness in their residences, which are only part of the many issues of poor housing conditions [3, 4]. In addition, there is a growing imbalance between the Irish population growth and the number of new houses built over the last decades [5].

Current national plans propose a considerable number of investments to tackle the challenges of housing. Ireland's Housing for All Plan, for example, has a target of investing over €4 billion into more than 300,000 new homes up to 2030 [5]. While the National Retrofit Plan aims to fund about €8 billion for housing renovations before 2030 [6].

Nonetheless, these much-needed investments in housing construction and renovation should not disregard the future effects of climate change on people and their homes. In the context of future climate, mortality rates are projected to increase, affecting especially the older population, which is more susceptible to different health issues, such as heart diseases and heat strokes [7, 8]. At the same time, demands for space cooling might also grow significantly, putting even more pressure on the existing power grid [9].

Building codes from different countries within the EU, including Belgium, France, Germany, and the Netherlands, account for overheating as a climate-related issue [10]. However, there is an often-reported mismatch between acceptability criteria in building standards and people's thermal comfort expectations [11].

In Ireland, overheating is briefly mentioned in the Domestic Energy Assessment Procedure (DEAP) of the technical guidance for Building Energy Rating (BER) certification [12]. However, it does not provide a clear approach to indoor environmental quality (IEQ) or its implications for the future. In this sense, the new Met Éireann climate data for future extreme climates provides tools for advancing this topic [13]. These are in line with standards from other countries (e.g. UK's CIBSE TM48 standard [14]), but they still have some limitations, as models based on historical datasets do not represent the stochastic nature of future climates [15-17].

Additionally, the new Energy Performance of Building Directives (EPBD) sets new ambitious targets for decarbonisation [18]. The EU building stock should have zero emissions by 2050, while all new buildings must meet the nearly zero-energy building (nZEB) requirements by 2030. The downside is that highly insulated and airtight buildings might reduce people's ability to ventilate their homes, resulting in increased overheating risks and poorer indoor air quality (IAQ) [19, 20].

For all these reasons, a robust scientific background should support decision-making at different levels (from policymakers, building designers and developers, to homeowners and tenants) in designing and operating dwellings for future climatic conditions [11].

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This paper contributes to a research gap not specifically addressed by existing literature. The work focuses on reviewing research on residential buildings' performance in future climates. It reports current approaches to different building performance metrics and assessment methodologies, while advancing the current literature, by investigating how current studies address occupancy profiles, occupant behaviour and other occupant-related topics. To reach this goal, this paper reviews publications to answer the following research questions (RQ):

1. What are the key aspects of the current methodologies used to assess building performance under future weather scenarios?
2. What metrics are currently being used to evaluate building performance in terms of indoor environmental quality (IEQ), energy consumption, and occupants' health and well-being under extreme future climate conditions?
3. What approaches are being used to assess occupancy profiles and occupants' behaviour in building performance models for different future weather scenarios?

2 METHODOLOGY

This paper is a systematic literature review based on the PRISMA 2020 approach [21], with a full methodological approach presented in Fig. 1. The review began with a publications' search undertaken in four databases, i.e. ScienceDirect, WebOfScience, MDPI, and Proquest (Figure 1). Different keyword combinations related to residential buildings, climate change, building performance simulation, occupant behaviour and heatwaves/overheating were used. The published research was filtered based on the publication year (2014 to 2024), subject area, and language (English).

The database search resulted in 785 papers, which were organised in a spreadsheet with title, DOI and publication year (Figure 1). Then, papers not relating to buildings, considering article titles and abstracts, were excluded (n = 232), while the remaining publications were added to Mendeley Reference Manager [22]. The full Mendeley library was exported to an open-source machine-learning tool called ASReview Lab [23]. The tool has been previously used for systematic reviews, as its algorithm can analyse abstracts from a given library of academic papers and rearrange them based on their similarities [24]. An initial list of papers, that were well-fitted for inclusion in this review, was selected and labelled. The criterion for selection was that papers had to include case studies of residential buildings with models of the future climate. The ASReview software used the information provided to rearrange the stack of abstracts from the most to the least relevant.

Next, an individual assessment identified all the papers that would be selected for further analysis, based on the same selection criteria (Figure 1) (n = 64). This process followed the order provided by ASReview until a continuous sequence of 20 papers was labelled as irrelevant. Case studies located outside Europe were discarded (n = 22) and the remaining papers were assessed based on their relevance and quality for the final selection (Figure 1).

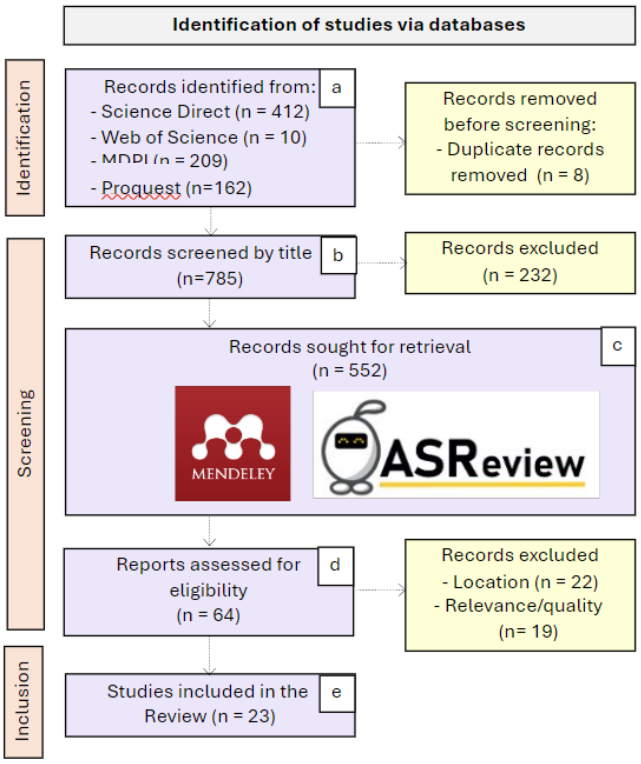

Figure 1. Methodology of the systematic review.

For the relevance assessment, different performance aspects were graded (thermal performance, IAQ, energy, occupants' health and equivalent greenhouse gas emissions). If the paper provided a clear description of the building occupancy profile or occupancy behaviour or provided different scenarios of occupancy, the grade would be increased. Then, the studies were assessed based on their methodological quality. Papers that provided clear evidence of following a comprehensive data analysis and validation process were given a higher grade. Considering maximum grades for relevance (performance and occupants) and methodological quality, a maximum score of eight points represented papers most likely to be relevant to this research scope. Only papers with a score of five or more points were selected for an in-depth text review (n = 23) (Figure 1).

3 RESULTS

This section presents the outcomes from the 23 papers selected for full review. Section 4.1 addresses the methodologies used in the current literature to assess the performance of dwellings under future climates (RQ1). Section 4.2 presents the building performance metrics addressed by the papers reviewed, including their perspective on occupant's health (RQ2). Finally, Section 4.3 illustrates how the selected case studies accounted for occupants in their models, with a focus on occupancy profiles and occupant's behaviour (RQ3).

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3.1 Assessment of building performance in future climates

The methodological approach adopted in the reviewed studies can be generally expressed in two stages (Fig. 2), where a building model is created using data representative of the current conditions (i), and next, this model is used as a baseline for testing conditions that are representative of the future (ii). The comparison of the results between these two stages provides means to estimate the impact of climate change on building performance. Figure 2 presents the general workflow adopted by the case studies reviewed, e.g. [20].

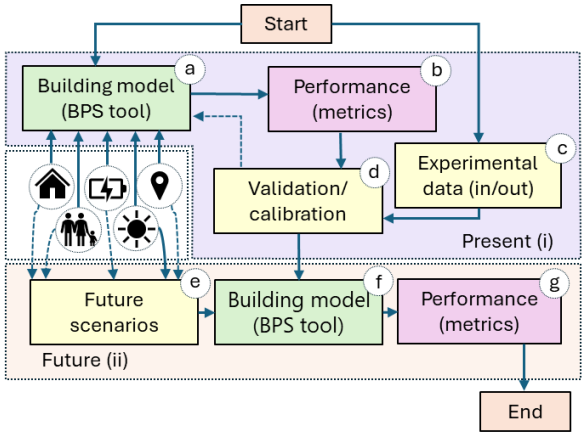

Figure 2. Performance assessment under future scenarios.

Initially, these studies created a prototype in a building performance simulation (BPS) tool (a), allowing to acquire performance metrics of the current conditions (b). The outputs were compared to experimental data (c), as a strategy to validate and calibrate the models (d). Then, the inputs of the model were changed to the considered future weather scenario (e), generating a new model (f) and performance metrics (g).

Individually, the methodology of reviewed papers had some distinctive characteristics depending on the data available. This was implied in different approaches for the experimental data used for validation/calibration (c), and the validation procedure itself (d). Studies used data from measurements of indoor thermal parameters [25], building energy consumption [20, 26, 27], or outdoor environmental parameters [28]. While their statistical methodologies for validation included variance [29], root mean square error (RMSE) [28], and mean bias error (MBE) [25, 28].

When defining the future scenarios (e), the input weather file was changed. The weather files were based on climate projections at a global scale and scaled down (downscaling) to an area representative of the building location [19]. The studies considered climate projections usually based on different greenhouse gas emissions scenarios, as described by the International Panel on Climate Change (IPCC) [30, 31]. While their downscaling approach either relied on dynamic methods (higher resolution) [32-34], statistical (based on historical datasets) [35-41] or hybrid methods [42] (a combination of those two). In some cases, they also applied additional bias-correction procedures depending on the downscaling approach selected.

Furthermore, some studies applied uncertainty and sensitivity analysis approaches to understand the impact of one or more inputs on the overall building performance [26, 32]. In studies applied to a building stock scale, additional considerations and assumptions had to be made due to the uncertain nature of other aspects, such as population growth, and building construction/demolition/retrofit rates [27, 40, 41].

3.2 Building performance metrics

Table 1 summarises the reviewed literature based on building performance metrics. Most of the studies considered building performance associated with energy efficiency or thermal performance. Other metrics included IAQ, equivalent greenhouse gas (GHG) emissions, and temperature-related mortality. Those metrics are discussed in subsections 4.2.1 (thermal performance), 4.2.2 (energy performance) and 4.2.3 (IAQ performance). Indices on mortality are included in the thermal performance section, while indices on GHG emissions are presented in the energy performance section.

3.2.1 Thermal performance

A wide range of metrics associated with building thermal performance in future weather scenarios was identified. A common approach was to consider them under the scope of thermal resilience. Thermal resilience refers to the building's ability to cope with disruptive weather events, while still providing appropriate indoor thermal conditions [19].

The risk of overheating was a major concern; thus, studies restricted their analysis to summer periods [26, 38, 42-44] or extreme heatwave events [20, 28, 32, 35]. In this context, the overheating hours of exceedance (HE) was the metric most frequently used within the selected case studies [29, 32, 36, 37, 44, 45], as an approach relatively easy to apply and adopted by international standards, e.g. CIBSE/TM59 [46].

However, the HE is a criterion that has some limitations. An example is its inability to capture the intensity, frequency and severity of building overheating. The indoor overheating degree (IOD), the ambient warmness degree (AWD), the overheating escalation factor (αIOD) and the Climate Change overheating resistivity (CCOR), were some of the metrics capable of capturing overheating aspects [20, 35, 38]. Previous research compared different metrics to better evaluate building response and recovery from heatwave events, with or without the co-occurrence of other concerning events, such as during a power outage [20], which allowed for a more comprehensive understanding of a building's thermal resilience.

Other papers used metrics that included humidity to evaluate indoor thermal comfort in current conditions [33, 36, 38, 40], including PMV, PPD, Givoni's psychrometric chart, and the humidex. However, a challenge for using these humidity-dependent metrics in future scenarios is the uncertainty regarding people's adaptation to climate change [38].

The effects of indoor overheating on increasing mortality risks were also previously assessed [41, 43, 44]. The reviewed papers used a method that estimated a temperature threshold in which the exceedance was associated with increased mortality risks for given age groups. The method adapted methodologies previously applied to outdoor heat-related mortality.

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Table 1. Performance metrics and future scenarios.

Ref.	Location	Building Type	Performance Metrics		
			Thermal	Energy	Other
[20]	Belgium	TH	IOhD, AWD, CCOR, IDD, HI, TA, IOcD	H/C/Tot	-
[25]	France	HR	%DH(adap), %DH(stat)	H/C/Tot	-
[26]	Belgium	TH	IOhD, IOcD	H/C/Tot	GHG
[27]	Belgium	SD	-	H/C	-
[28]	Portugal	HR	%DH(adap), %DH(stat)	-	-
[29]	UK	HR	HE	H	-
[32]	France	HR	HE		-
[33]	Sweden	SF, LR, MR	PPD	H/C/Tot	GHG
[34]	Italy	LR	HE	H	-
[35]	Belgium	DT	IOhD, AWD, CCOR		-
[36]	Europe	DT, MR	HE, Psy	H/C	-
[37]	Italy	SF, LR, MR	HE	H/C/Tot	-
[38]	Spain	HR	IOhD, AWD, aIOD, HI, H	Tot	-
[39]	Switzerland	SF, MF	-	C	-
[40]	Italy and Luxembourg	LR, MR, HR	PMV	H/C	GHG
[41]	UK	TH, SD, BG, LR, HR, AP	-	H	Mor
[42]	Worldwide	MR	-	C	-
[43]	UK	TH, SD, BG, LR, HR, AP	-	-	Mor
[44]	UK	DT, SD, TH, BG, AP	HE, WCDH	-	Mor
[45]	Finland	MR	HE	H/C	-
[47]	Germany	SF	DI	-	-
[48]	UK	DT	HE	H/C	-
[49]	Finland	MR	HE	C	-

Abbreviations:
Building type: DT – detached house; SD – semi-detached house; TH – terraced house; LR- low-rise apartment building; MR – middle-rise apartment building; HR - high-rise apartment building; SF - single-family house (no additional information provided).
Thermal metrics: HE - Overheating hours of exceedence; IOhD - Indoor Overheating Degree; AWD - Ambient warmness degree; aIOD - Overheating escalation factor; CCOR - Climate Change Overheating Resistivity; IDD - Indoor Discomfort Degree; HI - Heat Index; H - Humidex; TA - Thermal Autonomy; PMV - Predictive Mean Vote; PPD - Percentage of People Dissatisfied; %DH(adap) - Percentage of Discomfort Hours (Adaptive thresholds); %DH(stat) - Percentage of Discomfort Hours (Static thresholds); IOcD - Indoor Overcooling Degree; DI - Discomfort Index; WCDH - Weighted Cooling Degree Hours; Psy - Givoni's Psychrometric chart.
Energy metrics: H - Energy demand for heating or Heating Degree Days; C - Energy demand for cooling or Cooling Degree Days; Tot – Total energy demand or demand for HVAC system.
Other metrics: GHG – equivalent CO_2 emissions; Mor – heat/cold-related mortality.

3.2.2 *Energy performance*

The assessment of energy performance mainly focused on space conditioning in terms of heating and cooling demands [20, 27, 29, 38]. This was mainly expressed in terms of monthly and annual energy consumption for one or more reference years in the future. The calculation of energy demand per building area was a useful metric to compare outputs from different building types [20, 25, 26, 36]. This aspect was also observed for the heating (HDD) and cooling degree days (CDD), which are not direct measures of energy consumption, but are useful measures to compare energy demand from different buildings [26, 37, 41].

Besides estimating energy use for energy performance assessment, some studies calculated the equivalent GHG emissions due to the operation of the HVAC systems [26, 33, 40]. This included a carbon emissions factor to calculate the equivalent CO_2 emissions associated with the amount of energy consumed. It was an effort associated with recent advancements in European policies, that now integrate GHG emissions estimation into the decision-making process [18].

3.2.3 *Indoor Air Quality (IAQ)*

The investigation of IAQ in future scenarios was assessed by only one of the reviewed research articles [47], where authors considered how future climate projections might affect the outdoor concentration of selected pollutants and the emission rates of furniture and building materials. The indoor concentration of temperature-related pollutants was assessed by a mass balance with data input from the building performance simulations. The metrics included indoor and outdoor contaminants concentrations, ventilation rates, deposition factor, and emission rates of indoor sources.

Even though this paper was the only one (of the reviewed research) to address IAQ performance in future scenarios, other papers did not completely disregard IAQ parameters in their analysis. The topic of air quality was still considered in terms of ventilation (natural and mechanical), which affects energy and thermal performance.

Natural ventilation was mostly assessed as a factor of windows opening behaviour. The windows' opening patterns were designed with assumptions based on the indoor and outdoor environmental conditions and were either controlled by automated systems or building occupants [25, 32, 45]. A common goal of the studies was assessing the efficiency of different passive cooling strategies, such as night ventilation, to reduce overheating risk and buildings' cooling energy demand in the warm seasons [33, 42].

The use of mechanical ventilation was an aspect investigated as an additional measure to natural ventilation to provide safe and comfortable indoor environments. There was a preference for simulating mechanical ventilation systems with heat recovery (MVHR) and constant air volume (CAV) supply [20, 26, 48, 49] with an occupancy profile and fixed temperature thresholds. However, when studies compared the effect of fixed supply/operative temperatures to adaptive setpoints, the adaptive setpoints provided better results for thermal comfort [25, 33]

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3.3 *Occupant-centric modelling*

The building occupancy in the reviewed papers was generally characterised by the number of residents, their age, and occupation schedule. While most papers considered dwellings occupied by families of adults and children [20, 26], others considered scenarios with elderly individuals [28, 29, 45].

To characterise the occupancy schedules of the assessed buildings, studies considered the application of surveys and interviews [29], information from previous studies [20], or profiles from standards and guidelines [26]. These approaches, however, might not be representative of future conditions as people's behaviour inside homes might change in future weather conditions. Thus, to deal with this uncertainty regarding occupants' behaviour, some studies applied models based on pre-assigned rules. In these cases, windows' opening and shading devices' operation were dependent on indoor and outdoor temperature thresholds and solar radiation [32, 36, 45]. However, none of the reviewed studies provided a comprehensive exploration of the effects of multiple behaviour scenarios on building performance.

4 DISCUSSION AND CONCLUSIONS

The results point out a presumptive research gap in occupant-centric modelling and IAQ conditions under future climate scenarios. These topics still carry a considerable level of complexity and uncertainty that justifies the gap. However, recent publications addressing numerical models to assess IAQ and employing uncertainty and sensitivity analysis might be extremely useful alternatives for bridging this gap in future works.

The trends of increased overheating risk and energy demand for cooling seem to be the major challenge investigated by the reviewed literature. This was reflected by the wide range of thermal-related metrics identified and the consistent use of well-established energy-related metrics. From these metrics, the IOD, AWD, αIOD and CCOR are the most comprehensive ones to be used in future research due to their characteristic of capturing the intensity, frequency and severity of overheating. Nonetheless, other performance aspects were also assessed, including the GHG emissions, due to the impact of climate change and associated national/international legislation; as well as heat-related mortality resulting from extreme thermal conditions. However, other concerns, such as the effects of poor ventilation especially during the colder seasons, have not been specifically addressed by the reviewed literature. This might be a topic for further investigation.

This paper provides a general overview of the current literature on residential building performance under future climate scenarios. The systematic approach and its focus on occupants under future projections are strengths that set it apart from other reviews. However, some limitations might rely on the initially designed search strings. Even though the search was designed to consider studies assessing future extreme weather conditions, it might neglect papers that would solely focus on conditions in milder winters, for example. Nonetheless, the findings of this review highlight the need for future research with a different perspective on building performance. A perspective that centers the attention on people who occupy the buildings of the future, their health and well-being.

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