

Summer thermal adaptation in residential buildings for heating-dominated temperate climates

Assessment and perspectives on low-energy single-family houses in Wallonia

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To the stars and those who are watching them.

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Foreword

This thesis is the result of research conducted over a period of twelve years. It was carried out as part of a part-time position as a teaching and research assistant in the Faculty of Architecture, Architectural Engineering and Urban Planning of Université catholique de Louvain.

Twelve years is a long time during which many things change – world, society, and one’s personal life, all of which can reshape daily priorities and certainties.

In terms of technological research, such a timespan represents a real challenge, confronting the slow and meticulous process of data collection and analysis with the ever-faster evolution of knowledge.

Nevertheless, it is also a period that affords the opportunity to reflect upon the multiple dimensions and conditions of Architecture to engage with them through professional practice and to apprehend them more profoundly through teaching.

This work bears the mark of all these experiences.

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Summary

Rising temperatures and more frequent heatwaves increasingly challenge our built environment. Understanding how buildings and occupants can adapt to these changing conditions has become a critical research and policy priority, particularly in contexts where such adaptation has not historically been culturally embedded. This thesis critically examines how design practices can evolve to more effectively support summer thermal adaptation through passive strategies in residential buildings in a heating-dominated temperate climate, using complementary multidisciplinary perspectives.

Focusing on low-energy single-family houses in Wallonia, the research shows that, despite the introduction of an overheating indicator in the Energy Performance of Buildings (EPB) regulation, design practices remain predominantly centred on reducing heating demand and often underestimate overheating risks.

Drawing on monitoring data, field surveys, and whole-building energy simulations, the research highlights the extent of summer thermal discomfort currently experienced and its expected intensification under climate change. It also identifies the sociotechnical dimensions that shape current practices through surveys and interviews conducted with occupants, building professionals, and public policymakers.

The thesis shows that summer thermal adaptation in buildings cannot be addressed as a purely technical challenge, but must also be understood as part of evolving social practices. It therefore advocates for paradigm shifts grounded in transdisciplinary perspectives, linking building engineering with the social, climate, and health sciences, and calls for new design approaches that better support adaptation processes, with the aim of fostering more effective and socially embedded practices.

Résumé (FR)

Face à l'augmentation des températures et à la multiplication des vagues de chaleur, adapter notre environnement bâti devient un enjeu sociétal majeur, en particulier dans les régions où ces pratiques ne sont pas culturellement ancrées. Mobilisant des perspectives disciplinaires complémentaires mêlant ingénierie et approche sociotechnique, cette thèse interroge les pratiques actuelles de conception et la manière dont elles peuvent évoluer afin de mieux soutenir l'adaptation thermique estivale au moyen de stratégies passives dans les bâtiments résidentiels situés en climat tempéré.

Se concentrant sur des maisons unifamiliales récemment construites en Wallonie, le travail montre que, malgré l'introduction d'un indicateur de surchauffe dans la réglementation sur la Performance Énergétique des Bâtiments (PEB), les pratiques restent majoritairement centrées sur la réduction des besoins de chauffage et sous-estiment fréquemment les risques de surchauffe.

À partir de données de monitoring, d'enquêtes de terrain et de simulations énergétiques dynamiques, le travail met d'une part en évidence l'étendue des situations d'inconfort thermique estival actuellement rencontrées et appelées à s'intensifier sous l'effet du changement climatique. D'autre part, il identifie les dimensions sociotechniques qui façonnent les pratiques actuelles, en s'appuyant sur des enquêtes et des entretiens menés auprès d'occupants, de professionnels de la construction et de décideurs publics.

La thèse montre que l'adaptation thermique estivale des bâtiments ne peut être abordée sous un angle purement technique, mais doit être comprise comme faisant partie de pratiques sociales en évolution. Elle plaide pour des changements paradigmatiques fondés sur des perspectives transdisciplinaires reliant l'ingénierie du bâtiment aux sciences sociales, du climat et de la santé, et soutient de nouvelles approches de conception basées sur les processus d'adaptation, de manière à évoluer vers des pratiques plus efficaces et socialement ancrées.

I.1. Background

I.1.1. Climate change and the growing need for adaptation

I.1.1.1 From observation to projection

Climate change –which refers to long-term shifts in average climatic conditions, including temperature and precipitation patterns [1]– is now a tangible reality.

Global Warming Levels (GWLs) are defined using the global mean surface temperature, compared with a specified reference period (typically the pre-industrial era, 1850–1900, or 1991–2020, which is already +0.85 °C warmer [2], in order to harmonise measurements between the periods being compared). Figure I.1 presents these temperature anomalies since 1940 and shows that the past eleven years (2015–2025) rank among the eleven warmest on record [3]. For the first time in the instrumental record, the global mean temperature over the past three years (2023–2025) exceeded 1.5 °C above pre-industrial levels. Although 2025 itself remained below the Paris Agreement threshold [4], current trajectories indicate that the 1.5 °C limit could be reached on a sustained basis before the end of this decade. This would mark a transition towards rapidly escalating and increasingly irreversible climate impacts, characterised by a sharp increase in extreme heat events and compounded risks to ecosystems and societies [2].

Since the 1990s, Europe has been warming at more than twice the global average rate, at approximately 0.5 °C per decade, compared with around 0.2 °C per decade globally [5]. The Belgian and Walloon climates are not exempt from this trend, with average temperatures rising significantly above the long-term global mean over recent decades [6]. Consequently, there is a clear upward trend in the frequency and intensity of warm days in Europe, as well as in the occurrence of heatwaves and extreme precipitation events [7]. Southern Europe is also experiencing an increase in agricultural and ecological droughts [7].

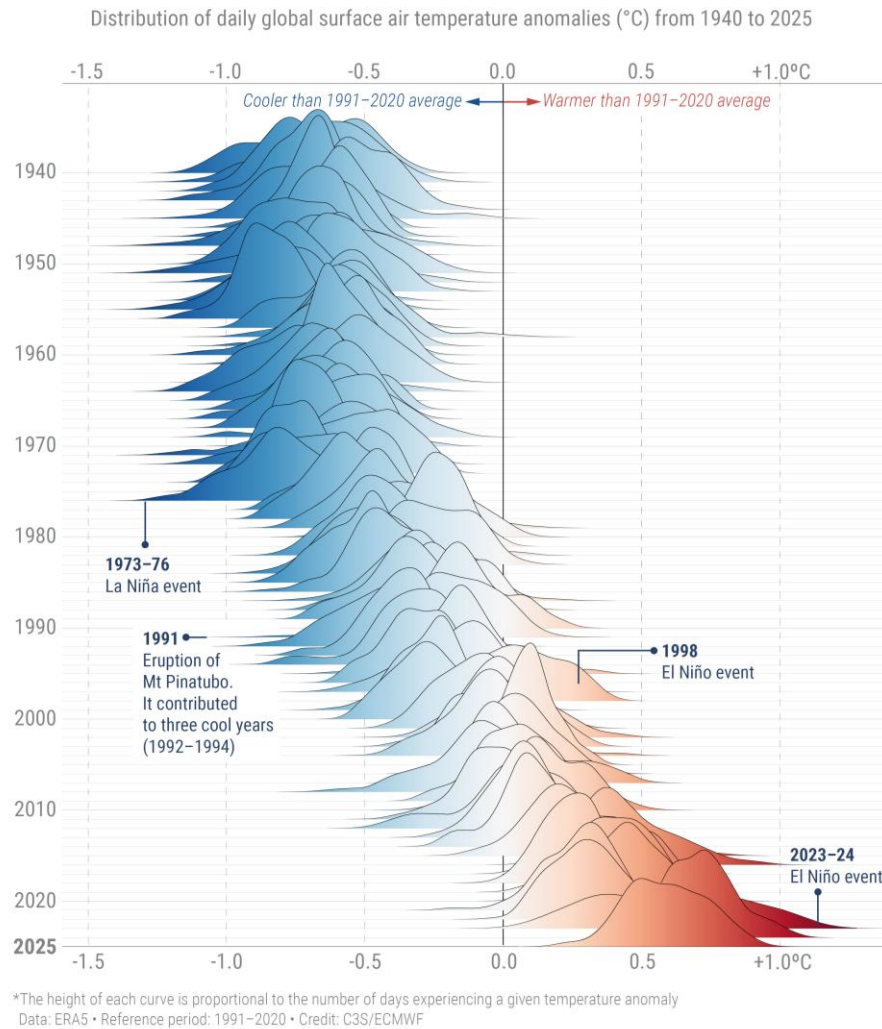


Figure I.1. Distribution of daily global surface air temperature anomalies (°C) from 1940 to 2025. Source: Copernicus Climate Change Service (C3S), *Global Climate Highlights 2025* [3].

During the summer of 2019, Central and Western Europe experienced multiple extreme heatwaves [8]. In Belgium, the most intense heatwave ever recorded was measured that summer [3]. Across Europe, numerous national temperature records were broken, with maximum temperatures exceeding 40 °C in several countries [8]. The summer of 2026 appears to be on course to become one of the hottest summers ever recorded in Europe. By the end of June, several regional and national temperature records had already been broken, and Western Europe had experienced its hottest June on record [9].

The increasing frequency and severity of climate extremes are already having measurable impacts on health and well-being [7, 10]. Numerous studies have reported a strong association between elevated outdoor temperatures and increased mortality rates [11, 12]. Although more recent heatwaves have reached unprecedented temperatures, the summer of 2003 remains a major reference for assessing the health and economic consequences of extreme heat in Europe:

- It caused over 30,000 deaths [13], with some estimates exceeding 70 000 [14]. For comparison, the first wave of the COVID-19 pandemic resulted in 165 000 excess deaths, and the second wave in 339 600 [15].
- It resulted in more than €13 billion in economic losses [16].

These events demonstrate Europe's high vulnerability to extreme heat, with significant consequences for public health, infrastructure, and the economy [16].

The main driver of climate change is the Greenhouse effect due to natural or anthropogenic activities [2]. The Intergovernmental Panel on Climate Change (IPCC) estimates future global warming based on greenhouse gas (GHG) emission scenarios.

Projections are simulated using coupled Earth System Models (ESMs), which numerically represent interactions among the atmosphere, oceans, land surface, cryosphere, and biogeochemical cycles. These models are driven by externally prescribed forcings, such as greenhouse gases, aerosols, solar variability, and land-use change. Future temperature trajectories emerge from multi-model ensemble simulations driven by internally consistent radiative forcing and socioeconomic development scenarios within coordinated initiatives such as the Coupled Model Intercomparison Project Phase 6 (CMIP6) [17]. The definition of these alternative scenario has evolved from the Special Report on Emissions Scenarios (SRES), in the Fourth Assessment Report (AR4) of the IPCC, to Representative Concentration Pathways (RCPs), in the Fifth Assessment Report (AR5) [18], which focused primarily on greenhouse gas concentration trajectories, to the Shared Socioeconomic Pathways (SSPs) in the Sixth Assessment Report (AR6) [2]. These pathways represent alternative trajectories of global socioeconomic development, including population growth, economic development, energy use, and mitigation efforts. Table I.1 presents these scenarios with their associated radiative forcing levels (i.e. 1.9, 2.6, 4.5, 7.0, and 8.5 W/m²), and corresponding projected increases in global mean temperature.

Regional climate models (RCMs) allow climate projections to be refined at the local scale [19]. They rely on downscaling techniques derived from global climate models (GCMs), ensuring consistency between global and regional projections. For Belgium, four RCMs are generally used : ALARO [20], COSMO [19], REMO [21] and MAR [22].

Table I.1. The five core Shared Socioeconomic Pathways (SSPs) used in global climate modelling and their corresponding Global Warming Level (GWL) estimates (reference period: 1850–1900). Source: IPCC AR6 [2].

SSP	Scenario	Global Warming Level (GWL) [°C]			
		2041–2060		2081–2100	
		Best estimate	Very likely range	Best estimate	Very likely range
SSP1-1.9	Sustainability Taking the Green Road	1.6	1.2–2.0	1.4	1.0–1.8
SSP1-2.6	Sustainability	1.7	1.3–2.2	1.8	1.3–2.4
SSP2-4.5	Middle of the Road	2	1.6–2.5	2.7	2.1–3.5
SSP3-7.0	Regional Rivalry A Rocky Road	2.1	1.7–2.6	3.6	2.8–4.6
SSP5-8.5	Fossil-fuelled Development Taking the Highway	2.4	1.9–3.0	4.4	3.3–5.7

Figure I.2 presents the projected changes in mean annual air temperature across Europe between the reference period 1981–2010 and 2081–2100 under the SSP1-2.6 and SSP5-8.5 forcing scenarios (right), together with the historical evolution of temperature for the period 1960–2024 based on ERA5-Land reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The figure shows that mean annual temperatures are expected to increase across the whole of Europe, with more pronounced warming at northern latitudes and in the southernmost regions. By the end of the century, the SSP1-2.6 and SSP5-8.5 scenarios project warming of up to approximately 2–3 °C and 5–6 °C, respectively, in these regions.

Beck et al. [23] presented a comparative map of projected changes in global climate trends using the Köppen-Geiger classification [24]. It shows that Western European countries (such as France, the Netherlands, and Belgium) could shift from Cfb (temperate climate (C) with no dry season (f) and a warm summer (b)) to Cfa (with a hot summer (a)) or Csa (with a dry season (s)) classifications.

The IPCC Sixth Assessment Report (AR6) [25] does not assign formal probabilities or likelihoods to individual SSP scenarios; instead, it treats them as a set of plausible futures. A study by Carvalho et al. [26], which

examined the relative plausibility of these scenarios in light of current emission trends, identified SSP5-8.5 as highly unlikely, SSP3-7.0 as unlikely, and SSP2-4.5 as likely. *Sustainably scenarios* (see Table I.1) avoiding a Global Warming Level (GWL) of +1.5 °C appears also very unlikely. Without a strengthening of climate policies, a warming of +3.2 °C [2.2–3.5 °C] by 2100 is considered probable (medium confidence). Nevertheless, a trajectory limited to +3 °C remains avoidable [27].

Global warming leads to a series of direct effects affecting the climate system itself, including the intensification of temperature extremes, amplification of the hydrological cycle, decline of the cryosphere, continued sea-level rise, ocean warming, ocean acidification, and changes in atmospheric circulation. It will affect the frequency and intensity of extreme events and induce long-term or irreversible changes in the climate system [25].

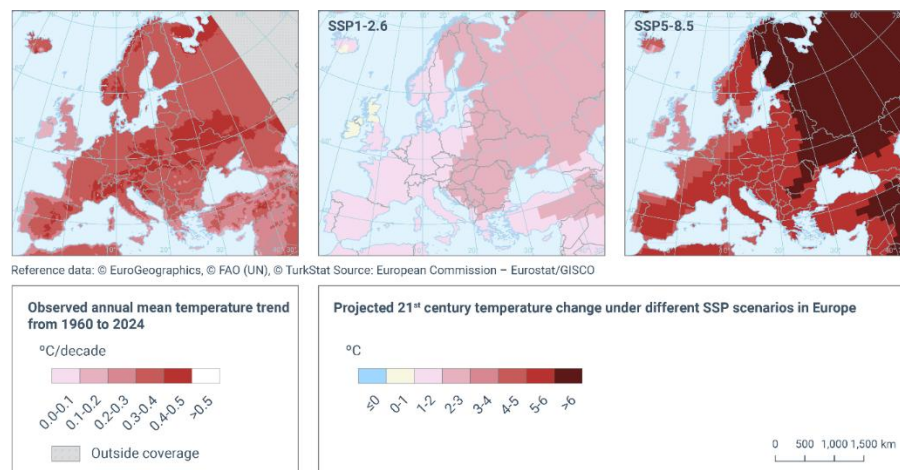


Figure I.2. Observed annual mean temperature trend from 1960 to 2024 and projected 21st-century temperature change in Europe under SSP1-2.6 and SSP5-8.5 scenarios. The projected changes compare 2081–2100 with the 1981–2010 WMO reference period. Source: European Environment Agency (EEA), based on CMIP6/WCRP data and European Commission – Eurostat/GISCO; reference data: EuroGeographics, FAO (UN), and TurkStat [28]. Reproduced under CC BY 4.0.

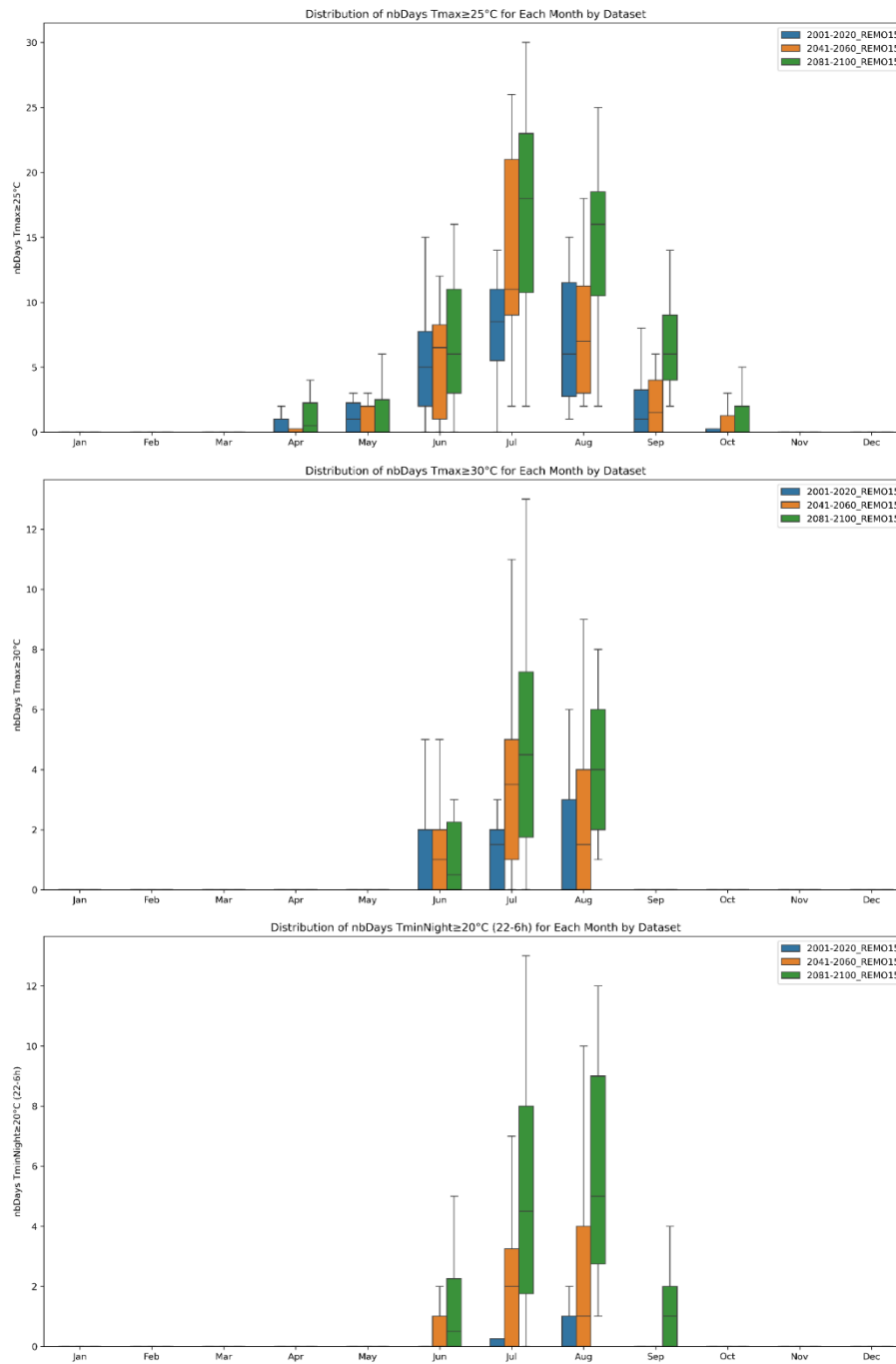


Figure I.3. Evolution of the Belgian summer climate (Uccle) according to the bias-corrected projections of the REMO15 model under the RCP8.5 high-emission scenario. Analysis by the author. (Outliers not represented).

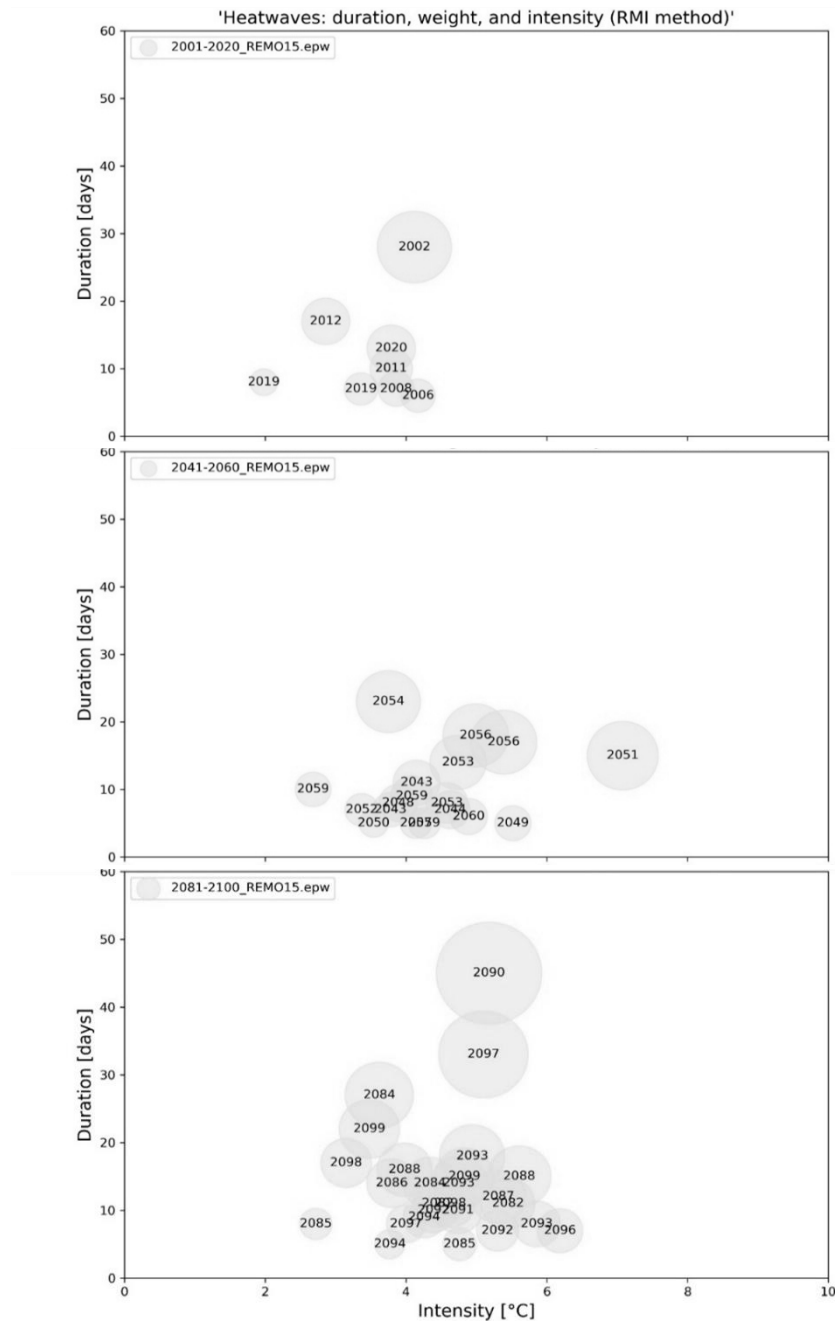


Figure I.4. Evolution of heatwave duration (y-axis), intensity (x-axis), and weight (bubble size, expressed as degree-days above a reference daily mean temperature of 20°C) in Uccle, based on bias-corrected projections from the REMO15 model under the high-emissions RCP8.5 scenario. Modelled years; analysis by the author using the RMI heatwave definition.

Figure I.3 and Figure I.4 present an analysis of the evolution of the Belgian summer climate according to the bias-corrected projections of the REMO15 model [21] under the RCP8.5 high emission scenario (AR5) [18]. As illustrated by Figure I.3, these projections indicate a marked and progressive increase in exposure to high outdoor temperatures.

The mean annual number of summer days (maximum temperature above 25°C [29]) increases by approximately 26% by mid-century and 94% by the end of the century, reaching 51.3 days per year compared with 26.45 days during the historical period. The increase is even more pronounced for very hot days (maximum temperature above 30°C [29]), whose mean annual frequency rises from 4.6 days during the historical period to 8.05 days by mid-century (+75%) and 11.85 days by the end of the century (+158%). These results suggest that hot conditions may become increasingly common during future summers rather than remaining confined to exceptional years.

The largest relative change concerns tropical nights (minimum temperature above 20°C [29]). Although they are absent in many historical years, their mean annual frequency increases from 1.6 nights during 2001–2020 to 5.3 nights by mid-century (+231%) and 14.3 nights during 2081–2100 (+794%). This evolution is particularly critical for buildings and occupants, as elevated night-time temperatures reduce the potential for ventilative cooling, promote the accumulation of heat indoors, and limit physiological recovery during sleep (see following Section I.1.1.5).

Climate change is also expected to increase the frequency, intensity, and duration of heatwaves [30]. In Belgium, according to the Royal Meteorological Institute of Belgium, a heatwave is defined as a period of at least five consecutive days with maximum temperatures of 25 °C or higher, including at least three days reaching 30 °C or more [29]. As illustrated by Figure I.4 the projected evolution could be non-linear according to the REMO15 model. At mid-century, the main change lies in the increasing frequency of heatwaves, while their average duration, severity, and weight remain broadly comparable to those observed during the historical period. By the end of the century, however, heatwaves become simultaneously more frequent, longer, more severe, and heavier. Compared with 2001–2020, their mean duration and

severity increase by approximately 19%, while their mean weight increases by more than 50%. The evolution is even more pronounced for the most extreme events, with maximum duration increasing from 28 to 45 days, maximum severity from 29.7 to 44.5, and maximum weight more than doubling from 115 to 233. These results suggest that climate change may lead not only to a greater number of heatwaves but also to the emergence of exceptionally long and severe events.

These data corroborate that record-breaking heatwaves observed in Europe in recent decades are projected to become the “average” summer conditions. According to the European Commission (EC), under a global warming scenario of +3 °C, an “intense” heatwave currently expected once every 50 years may occur almost every year in southern Europe and every 3 to 5 years in other parts of Europe [31].

Global warming is also expected to induce indirect effects arising from the interaction between direct changes in the climate system and natural and human systems, leading to escalating impacts on ecosystems, health, infrastructure, and socio-economic conditions [25].

I.1.1.2 From mitigation to adaptation

The direct and indirect consequences of climate change, together with their variability and associated uncertainties, call not only for mitigation measures –through the reduction of greenhouse gas emissions– but also for adaptation to these ongoing impacts. This requires the assessment of potential effects and the identification of vulnerabilities. Figure I.5, reproduced from the work of Smit [32], illustrates the role of these necessary responses within the broader framework of climate change.

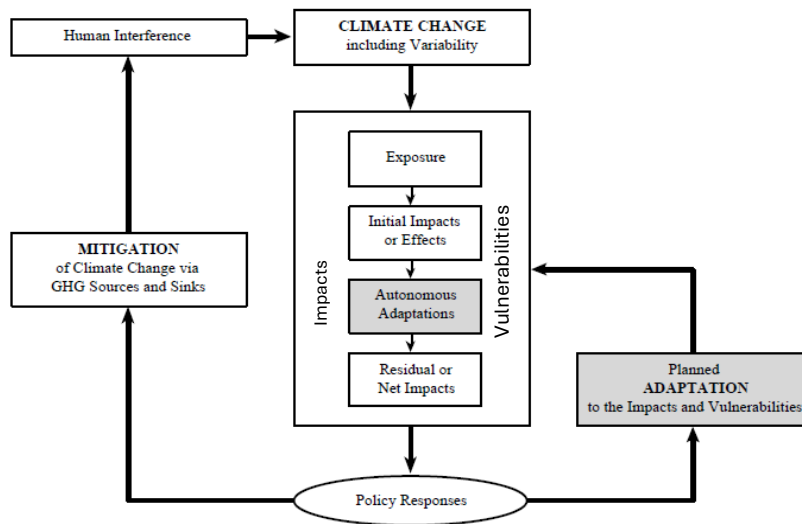


Figure I.5. Responses to climate change and the role of adaptation. Reproduced from IPCC (2001) [33], Figure 18-1, based on Smit and Pilifosova (2001) [32].

In Europe, the reduction of greenhouse gas (GHG) emissions has accelerated over recent decades, and a structural transition towards a low-carbon economy is underway. While final energy demand has decreased, renewable energy sources now account for approximately one quarter of energy production [34]. As a result, the European Union has reduced its GHG emissions by more than one third compared with 1990 levels [35].

Maintaining this pace is, however, essential to meet the EU's 2030 climate target and to place the Union on a pathway towards climate

neutrality by 2050 (see Table I.2). Provided that existing and planned measures are implemented rapidly and effectively, projections submitted by Member States in 2025 indicate a net emission reduction of 54% by 2030 [36], bringing the EU close to its intermediate 55% target [37].

Table I.2. Evolution of EU greenhouse gas (GHG) emission reduction targets.

Target year	Goal (compared with 1990 levels)
2000	Stabilization of CO ₂ emissions
2008–2012	8% reduction of GHG emissions
2020	20% reduction of GHG emissions
2030	40% reduction of GHG emissions
2030	55% reduction of GHG emissions (updated target, including carbon removal possibilities)
2040	90% reduction of GHG emissions (proposed target, to be adopted)
2050	Climate neutrality

At the same time, progress has slowed in several sectors and Member States [36]. Globally, preliminary data indicate that worldwide greenhouse gas emissions continued to increase in 2025 [3], while climate impacts have intensified. The year 2024 was the warmest ever recorded in Europe, marked by severe heatwaves, droughts, wildfires, and floods affecting populations, ecosystems, and economies.

These increasingly frequent and intense extreme events underscore both the urgency of sustained climate action and the growing costs of inaction.

As early as 1996, Burton [38] outlined six compelling reasons for initiating climate change adaptation, which remain highly relevant in the present context:

1. Climate change cannot be entirely avoided.
2. Anticipatory and precautionary adaptation is more effective and less costly than reactive, last-minute emergency adaptation or retrofitting.
3. Climate change may be more rapid and more pronounced than current estimates suggest; unexpected events are possible.
4. Immediate benefits can be gained from improved adaptation to climate variability and extreme atmospheric events.
5. Immediate benefits can also result from removing maladaptive policies and practices.
6. Climate change presents opportunities as well as threats; future benefits may arise under certain conditions.

Adaptation can therefore significantly reduce the negative impacts of climate change and enhance certain beneficial effects, although not without substantial costs and efforts. Alongside mitigation, it thus constitutes a major and necessary response to the consequences of climate change.

I.1.1.3 Adapting buildings to heat

Climate change and the increasing frequency of extreme weather events call for greater consideration of summer thermal adaptation of the built environment. These evolving conditions affect several fundamental aspects of building physics, including indoor comfort and environmental quality, construction strategies and technical solutions, system sizing, and overall energy consumption.

I.1.1.4 Forms of adaptation in the built environment

Adaptation is defined, in human systems, as “the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities” [2].

The term adaptation is often associated with Resilience. However, resilience focuses on the response (and sometimes on breakdown) triggered by the most extreme (or disruptive) events [39], or by the combination of several such events [40], whether or not their uncertainty is considered. Within the framework of the present work, adaptation is considered a necessary condition for this form of resilience.

Smit et al. [32], whose work forms an integral part of the IPCC’s research on adaptation [7], comprehensively discuss the characteristics of possible forms of adaptation.

They differentiate these forms according to:

- The climate stimulus addressed (*adaptation to what?*)
- The system concerned (*who or what adapts?*)
- The process and expected outcomes of adaptation (*how does adaptation occur?*)

As summarised in Table I.3, different adaptation processes [41] [42] may occur depending on:

- The *type of process*: *Autonomous* adaptation corresponds to the intrinsic capacity of individuals to adjust physiologically, behaviourally, and psychologically to their environment and constitutes the primary form of adaptation to thermal stress. The evolution of adaptive thermal comfort [43] is based on these considerations. By contrast, *planned adaptation* relies on proactive measures implemented by private actors and public or governmental institutions to mitigate anticipated impacts.
- The *timing of actions*: measures may be *reactive* (in response to discomfort), *concurrent* (e.g. public awareness programmes such as Heat-Health Warning Systems (HHWS) [44]) or *anticipatory*. Planning regulations, building design standards and system requirements, or subsidies for the installation of specific systems (e.g. solar shading) are all part of this anticipatory category.
- The temporal and spatial scales: measures may be *short- or long-term*, and *localised or widespread*.
- The *scale of change*: adaptation measures may be *incremental* (aimed at preserving the integrity of the system) or *transformational*, involving a *fundamental modification* of system characteristics (new materials, geometry, etc.).
- The *type of intervention*: adaptation measures may be classified as either *hard (structural)*, involving physical modifications to buildings, or *soft (non-structural)*. Soft measures generally require little or no physical modification and may be implemented at limited direct financial cost. Ventilative cooling through window opening belongs to this latter category.

Table I.3. Types of adaptation process encountered in the built-environment and their possible characteristics. Summary by the author based on previous works of [32, 38, 42].

Type of process	Autonomous <i>E.g. unmanaged natural systems</i>		Planned <i>E.g. managed, assisted by public agencies</i>
Timing of action	Reactive <i>From observed modification</i>	Concurrent <i>During modification</i>	Anticipatory <i>Prior modification</i>
Temporal scope	Short Term <i>Adjustments, instantaneous, autonomous</i>		Long Term <i>Adaptation, cumulative, policy</i>
Spatial scope	Localized		Widespread
Scale of change	Incremental		Transformational
Type of intervention	Non-structural/soft		Structural /hard

In the built environment, adaptation operates at different levels: the (urban) environment, the building, and the occupant. It involves technological, structural/institutional, and cultural/behavioural dimensions [42]. Table I.4 summarizes the main adaptation strategies together with their corresponding type of mechanisms encountered in the built environment.

Strengthening the adaptive capacity of a system, region, or community constitutes a concrete means of coping with climate variability and extreme events by reducing vulnerability and promoting sustainable development [32].

Adaptive capacity also depends strongly on cultural and socio-economic factors. Authors have therefore highlighted the importance of verification processes to ensure the effective implementation of adaptation measures [45].

Table I.4. Main strategies for adaptation to heat encountered in the built environment, together with their corresponding underlying mechanisms. Author's synthesis based on [32, 38, 42].

Level of adaptation	Adaptation strategies	Type of adaptation mechanism
Occupant	Physiological (thermoregulation)	Autonomous <i>Reactive</i>
	Psychological	Autonomous or Planned <i>Anticipatory (concurrent)</i>
	Behavioural (changes in activities, clothing, location, uses of Personal Comfort Systems, etc.)	Autonomous or Planned/Assisted <i>Reactive (or anticipatory)</i>
Buildings	Change in building construction, geometry and orientation	Planned <i>Anticipatory/Transformational/Hard</i>
	Change in building envelope characteristics	Planned <i>Anticipatory/Transformational/Hard</i>
	Passive control integration	Passive or planned <i>Anticipatory or Reactive</i> <i>Transformational/Hard or Incremental/Soft</i>
	Active system integration	Planned <i>Anticipatory (or reactive)</i> <i>Transformational/Hard (or Incremental/Soft)</i>
	Smart and automated control integration	Planned <i>Anticipatory (or reactive)</i> <i>Incremental/Soft</i>
Urban Environnement (or building clusters)	Increased access to vegetation and water (blue and green paths)	Planned <i>Anticipatory</i> <i>Transformational/Hard</i>
	Usage of cool/reflective materials	Planned <i>Anticipatory</i> <i>Transformational/Hard or Incremental/Soft</i>

I.1.1.5 Heat impacts on indoor environmental quality

In industrialised countries, people spend most of their time indoors, typically around 85–90% [46].

Indoor Environmental Quality (IEQ) results from the interaction between outdoor conditions, buildings and systems, and occupants' behaviour. It affects comfort, health, and well-being [47]. At the building level, climate change not only increases the risk of structural damage (storms, flooding, snow loads, etc.) but also has significant impacts on the quality of indoor environments. Recent research has extensively reviewed the effects of climate change on the indoor environment [48]. Figure I.6, reproduced from Fisk [49], illustrates the different pathways through which climate change affects indoor environment quality.

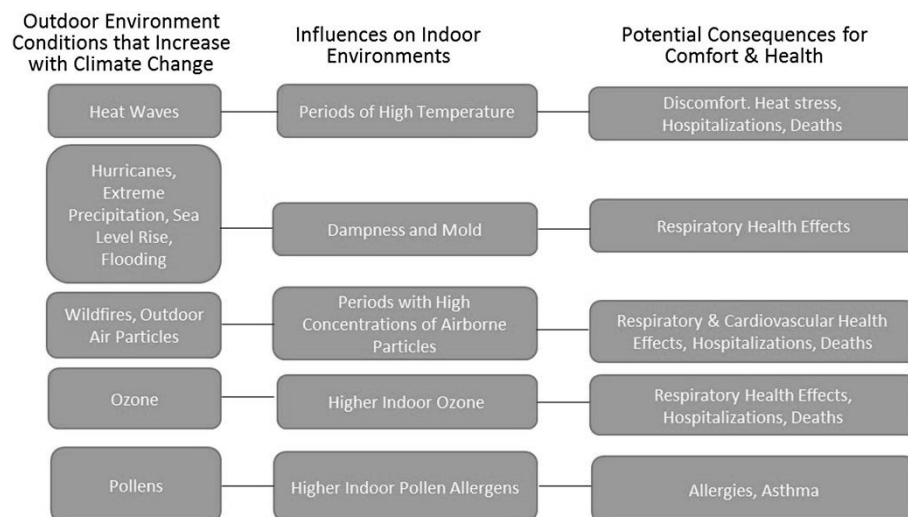


Figure I.6. Climate change impacts on IEQ. Reproduced from Fisk (2015) [49], with permission from Elsevier (Licence 6296441030287). Originally adapted from National Academies of Sciences, Engineering, and Medicine (2011) [50], used with permission from the National Academy of Sciences, courtesy of National Academies Press (Ref. 0831202601).

Increasing temperatures and heatwaves are recognised as the most immediate and measurable climate signals affecting indoor environments. Vardoulakis et al. [51] explicitly place overheating and thermal comfort as the first category of climate-change impacts on the indoor environment, as they have recognised effects on:

- *Thermal comfort*: resulting in occupants' subjective dissatisfaction with their Indoor Environmental Quality (IEQ), manifested as feeling too hot rather than as direct health risks [52].
- *Sleep disruption*: High indoor temperatures negatively affect sleep quality. Temperatures above 24 °C reduce sleep efficiency [53], increase sleep fragmentation, and prolong sleep onset [54]. Poor sleep can lead to reduced daytime productivity and health issues.
- *Work productivity*: Overheating impairs cognitive performance, including perception, memory, and attention. Productivity losses of 10% or more have been reported during overheating events, being increasingly relevant in residential buildings due to the rise in home working [52, 55, 56].
- *Health and mortality*: Prolonged exposure to high temperatures exacerbates major causes of mortality, including respiratory and cardiovascular diseases, diabetes, and renal disease, as reported by the WHO [13]. This constitutes a significant risk factor for vulnerable groups, notably the elderly [56].
- *Energy use*: Increased reliance on air conditioning may strain cooling systems and electricity grids. Heatwaves and future climate conditions could increase cooling demand by 25–50% across Europe by the 2050s [57], raise peak electricity demand by up to 9.5% [58] in temperate regions, and increase the risk of system failures and power outages [59]. In Belgium, residential cooling demand is projected to increase by 123% by the 2090s under SSP5-8.5, relative to the 2010s [60].

However, what elevates heat to a major trend is not only its direct effects but also its interaction with other IEQ components. Heat, for example, can degrade Indoor Air Quality by increasing indoor pollutant concentrations (e.g., increased chemical reaction rates), intensifying ozone ingress, and potentially encouraging occupant behaviours (e.g. reduced window opening during heat stress peak, air conditioning use) that alter ventilation patterns [49].

I.1.1.6 Design evaluation methods

While simple climate data analysis – e.g. through bioclimatic chart analysis – can already provide valuable insights [61, 62], adaptation assessments typically rely on dynamic Whole-Building Energy Model (BEM), as hourly (or sub-hourly) simulations is required to fully capture the dynamics of heat stress impacts on indoor environments.

Research has increasingly provided analyses of climate change impacts on indoor thermal conditions and/or energy use across different climatic contexts. Table I.5 (p.42) presents an overview of identified studies with a detailed analysis of their adopted methods.

Mainly, these studies differ in terms of:

- The *type of buildings* analysed: dwellings, commercial, educational, etc.
- The *number of buildings* analysed: from 1 to 252.
- The *modelled buildings*: existing buildings or theoretical reference cases.
- The *calibration process*: whether or not the model was calibrated.
- The *type of data* used as climate input, resulting from different methods of data selection or generation:
 - *Historical heat stress*;
 - *Morphing*: modifies historical hourly weather data using projected monthly or seasonal climate change signals (e.g. Δ temperature, Δ radiation), preserving the original temporal structure while adjusting mean conditions to represent future climates [63]. Dedicated tools include CCWorldWeatherGen [64], UKCIP02 [65], and WeatherShift [66];
 - *Probabilistic methods*: use of *Stochastic* weather generators to create synthetic future climate time series based on statistical properties derived from climate model projections, allowing multiple realisations and uncertainty representation [67]. Common tools include

the UKCP09/UKCP18 Weather Generator [68] and LARS-WG [69];

- *Dynamical downscaling*: employs Regional Climate Models to simulate future atmospheric processes at higher spatial and temporal resolution, producing more physically consistent projections of extremes and variability [70], including WRF (Weather Research and Forecasting Model) [67] and CORDEX RCM outputs [20].
- The *reference period* considered: historical or current.
- The *evaluation period* considered: e.g. 2030–2100.
- The *emission scenarios* considered: low to high scenarios from AR4 (SRES), AR5 (RCPs), or AR6 (SSPs).
- The *type of assessment* conducted: Typical Year (TY), Multi-year (MY), Extreme Events (E), or Extreme Years (EY). These may be selected from long-term datasets, constructed using dedicated methods (e.g. ISO 15927-4 (TRY) [71], Sandia Method (TMY) [72]), or statistically (morphing) or stochastically generated.
- The *simulation tool* used: EnergyPlus [73], IES-VE [74], TRNSYS [75], etc.
- The *type of analysis* conducted: comfort, energy demand, heat stress, environmental impacts, etc.
- The thermal comfort model used: static or adaptive.
- The *evaluation metrics* used: percentage of hours above a threshold temperature, degree-hours, maximum values, weighted indicators, etc. (cf. Table I.8).

Research has progressively shifted from static comfort analyses towards more adaptive assessment frameworks recognising that adaptive capacity of occupants allows a wider thermal tolerance in free running buildings [38]. In this case, comfort temperature is defined in function of a running mean temperature, which is linked to the evolution of outdoor temperatures. In Europe, the adaptive thermal comfort model is embedded in the EN 16798-1 standard (previously EN15251) [30]. This standard defines different adaptive comfort categories as a function of the deviation between the operative temperature and the adaptive comfort temperature, reflecting different levels of occupant acceptability and building occupancy type.

Table I.5. Overview of studies addressing climate change impacts and building adaptation

Year	Authors	Country	Köppen-Geiger classification	Type of buildings	Nb of buildings	Case study Type	Calibrated Model	Type of climate input data	Periods Covered	Type of emissions scenarios	Emissions Scenarios	Typical (TY) or Multi Year (MY) Assessment	Focus on	Thermal Comfort Model	Tool Used	Source
2016	Rastogi et al.	Various	Cfb, Dfa, Cwa	Dwellings, Commercial	49	Reference	Yes	Stochastic	1981–2013 to 2100	RCPs (AR5)	Medium and High	TY	Energy	Static	EnergyPlus	[74]
2020	Rodrigues et al.	Various	Cfa, Csa, BSh	Dwellings	1	Reference	No	Morphing	Current and 2050	SRES (AR4)	Medium-High	TY	Comfort and Energy	Static	EnergyPlus	[75]
2021	Yang et al.	Various	Cfb, Dfb, Bsk, Csa	Dwellings	252	Reference	No	Downscaling	2010–2039, 2040–2069, 2070–2099	RCPs (AR5)	Low to High	MY	Comfort and Energy	Static	IDA-ICE	[56]
2022	D'Agostino et al.	Various	Cfb, Dfb, Csa	Dwellings	1	Reference	No	Morphing	2018, 2050	RCPs (AR5)	High	TY	Energy	Static	EnergyPlus	[76]
2022	Rahif et al.	Various	BWh, Cfa, Cfb, Dfa	Commercial	1	Reference	No	Stochastic generation	2010s, 2050s, 2090s	RCPs (AR5)	High	TY	Comfort	Static and Adaptive	EnergyPlus	[77]
2017	Shen et al.	USA	Cfa, Dfa, BWh	Dwellings, Commercial	2	Reference	No	Morphing	2040–2069	SRES (AR4)	Medium and High	TY	Energy	Static	EnergyPlus	[78]
2022	Rajput et al.	USA	BWh	Dwellings	5	Reference	No	Downscaling	Current, mid- and late 21st century	Not mentioned	High	EE	Comfort + Heat Stress	Static	Matlab (FE)	[54]
2010	Peacock et al.	UK	Cfb	Dwellings	3	Reference	No	Morphing	2010–2040	SRES (AR4)	Medium-high	TY	Comfort	Static	ESP-r	[79]
2012	Gupta et al.	UK	Cfb	Dwellings	4	Reference	No	Stochastic	2030s, 2050s, 2080s	SRES (AR4)	High	TY	Comfort and Energy	Static	IES-VE	[80]
2013	McLeod et al.	UK	Cfb	Dwellings	4	Reference	No	Stochastic	Historical (1961–1990) to 2080s	SRES (AR4)	High	TY, EY	Comfort and Energy	Static	IES-VE	[81]
2014	Ji et al.	UK	Cfb	Dwellings	1	Existing	Yes	Morphing	2020s, 2030, 2050, 2080	SRES (AR4)	Medium and High	TY, EY	Comfort	Static and Adaptive	IES-VE	[82]
2015	Liu et al.	UK	Cfb	Dwellings	1	Reference	No	Stochastic	Current, 2050s, 2080s	SRES (AR4)	High	EY	Comfort	Static	EnergyPlus	[83]
2017	Parker et al.	UK	Cfb	Dwellings	1	Existing	Yes	Stochastic	2020s, 2050s, 2080s	SRES (AR4)	Medium and High	TY, EY	Comfort	Static and Adaptive	IES-VE	[84]
2018	Gupta et al.	UK	Cfb	Dwellings	2	Existing	No	Stochastic	2030s, 2050s, 2080s	SRES (AR4)	High	TY, EY	Comfort and Energy	Adaptive	IES-VE	[85]
2014	Dodoo et al.	Sweden	Dfb	Dwellings	1	Reference	No	Morphing	1996–2005, 2050, 2100	RCPs (AR5)	Medium and High	TY	Energy	Static	ViP+	[86]
2016	Dodoo et al.	Sweden	Dfb	Dwellings	3	Reference	No	Morphing	1961–1990, 1996–2005, 2050s, 2090s	RCPs (AR5)	Medium and High	TY	Comfort and Energy	Static	ViP+	[87]
2018	Monge-Barrio et al.	Spain	Cfb	Dwellings	33	Existing	Yes	Morphing	Current and 2050	SRES (AR4)	Medium	TY	Energy	Static	EnergyPlus	[88]
2018	Pérez-Andreu et al.	Spain	Csa	Dwellings	1	Reference	No	Morphing	2048–2052, 2096–2100	RCPs (AR5)	Medium and High	TY	Energy	Static	TRNsys	[89]

2014 Taleghani et al.	Netherlands	Cfb	Dwellings	3	Reference	No	Morphing	Current and 2050	Adapted SRES (AR4)	Low and High	TY	Comfort and Energy	Adaptive EnergyPlus	[90]
2015 Hamdy et al.	Netherlands	Cfb	Dwellings	3	Reference	No	Morphing	Historical and 2100	Adapted SRES (AR4)	Medium and High	TY, EY	Comfort	Static and Adaptive	[91]
2017 Hamdy et al.	Netherlands	Cfb	Dwellings	8	Reference	No	Morphing	Historical and 2100	SRES (AR4)	Low to High	EY	Comfort	Static and Adaptive	[92]
2022 Asciatore et al.	Italy	Gsa	Dwellings	1	Existing	Yes	Morphing	2016–2020, 2050s	RCPs (AR5)	Medium and High	TY	Energy	Static EnergyPlus	[93]
2023 Thapa et al.	India	Cwb	Dwellings	1	Existing	Yes	Morphing	Current TMY, 2050, 2080	SRES (AR4)	Medium	TY, EY	Comfort and Energy	Adaptive EnergyPlus	[94]
2020 Lou et al.	Hong Kong	Owa	Commercial	1	Reference	No	Historical Evolution	Not Applicable	Not Applicable	Not	MY	Energy	Static EnergyPlus	[95]
2024 Velasquez et al.	Finland	Dfb	Dwellings	6	Reference	No	Historical Evolution+Morphing	2020, 2050, 2080	RCP (AR5)	High	EY	Comfort	Static IDA-ICE	[96]
2022 Bugenings et al.	Denmark	Cfb	Dwellings	8	Reference	No	Downscaling	2013, 2050, 2090	RCPs (AR5)	High	TY	Comfort and Energy	Static and Adaptive IDA-ICE	[97]
2018 Heracleous et al.	Cyprus	Gsa	Educational	114	Existing	No	Downscaling	Current, 2050s, 2090s	SRES (AR4)	Medium	TY	Comfort	Adaptive IES-VE	[98]
2024 Liu et al.	China	Cfa	Dwellings	3	Reference	No	Historical Evolution	Not Applicable	Not Applicable	Not	TY, EY	Comfort	Adaptive DeST	[99]
2023 Baba et al.	Canada	Dfb	Educational	1	Existing	Yes	Downscaling	2001–2020, 2041–2060, 2081–2090	RCPs (AR5)	High	TY, EY	Comfort	Adaptive EnergyPlus	[100]
2025 Pigot-Navarrete et al.	Canada	Dfb	Dwellings	1	Reference	No	Morphing	2020, 2050, 2080	RCP (AR5)	High	TY	Energy	Static EnergyPlus	[101]
2016 Invidiata et al.	Brazil	At, Cfb, Cwa, Cwb	Dwellings	1	Reference	No	Morphing	2020s, 2050s, 2080s	SRES (AR4)	Medium and High	TY	Comfort and Energy	Static and Adaptive EnergyPlus	[102]
2020 Attia et al.	Belgium	Cfb	Dwellings	1	Existing	Yes	Downscaling	1976–2005, 2050, 2100	RCPs (AR5)	Medium to High	TY	Comfort and Energy	Static and Adaptive EnergyPlus	[103]
2022 De Pauw et al.	Belgium	Cfb	Dwellings, Commercial	7	Reference	No	Historical	Not Applicable	Not Applicable	Not	EE	Comfort and Energy	TRNsys	[104]
2023 Anaripadath et al.	Belgium	Cfb	Commercial	1	Existing	Yes	Downscaling	2010s, 2050s, 2090s	SSPs (AR6)	Medium to High	TY	Comfort and Energy	Static EnergyPlus	[105]
2023 Anaripadath et al.	Belgium	Cfb	Commercial	1	Existing	Yes	Historical	Not Applicable	Not Applicable	Not	EE	Comfort, Heat Stress and Energy	Static and Adaptive EnergyPlus	[106]
2023 Rahif et al.	Belgium	Cfb	Dwellings	1	Existing	Yes	Downscaling	2001–2020, 2041–2060, 2081–2100	SSPs (AR6)	Medium	TY, EE	Comfort, Heat Stress and Energy	Static EnergyPlus	[107]
2023 Ramon et al.	Belgium	Cfb	Commercial	1	Existing	No	Downscaling	1975–2005, 2069–2099	RCPs (AR5)	High	TY	Environmental impact, cost	Static EnergyPlus	[108]
2024 Anaripadath et al.	Belgium	Cfb	Dwellings	1	Existing	Yes	Downscaling	2010s, 2050s, 2090s	SSPs (AR6)	Medium to High	TY, EY	Comfort and Heat Stress	Static and Adaptive EnergyPlus	[36]

Although defined primarily for office buildings, the adaptive model has been also applied in other types of buildings. Studies have postulated that residential contexts might effectively entail more adaptive opportunities than offices [40,41] – for example, linked to the possibility of choosing clothes, opening windows or adjusting solar shading devices. Adaptive thermal comfort approaches are therefore usually applied in residential contexts [17,39] and dedicated, multi-criteria, metrics for overheating analysis have been developed in such basis (see for example CIBSE TM52 [110]).

More recently, in the frame of IEA Annex 80 works, new overheating and thermal resilience metrics were introduced [111]. The Indoor Overheating Discomfort Degree (IODD), which integrates temperature exceedance across time and space, enables multi-zonal model analyses. The Indoor Climate Change Overheating Resistivity (CCOR) metric was parallelly introduced to quantify the relationship between indoor overheating escalation and increasing outdoor thermal severity across future scenarios [111].

Dynamic Downscaling experiments have also progressively produced more detailed future climate projections by nesting processes of Regional Climate Models (RCMs) within Global Climate Models (GCMs) [19]. Compared with other methods such as Morphing and Stochastic weather generators, these data are particularly valuable as they offer high temporal and spatial resolutions (i.e possibly accounting for Urban Heat Island effect), allowing for localised long-term assessment based on stronger physical basis [70]. They allow for average and extreme conditions analysis as well as multi-year assessments.

In recent years, dedicated research has also focused on harmonising protocols, improving future climate data generation and use, and embedding resilience metrics to support more robust and reproducible evaluation of building performance under both current and future summer climate conditions [112].

Figure I.7 presents such a methodological framework developed within the framework of IEA EBC Annex 80 [112, 113]. These frameworks primarily aim to identify, during the design stage, the most effective strategies to implement as anticipatory adaptation measures, in order to prevent overheating risks, improve comfort, or limit energy use based on performance-driven criteria.

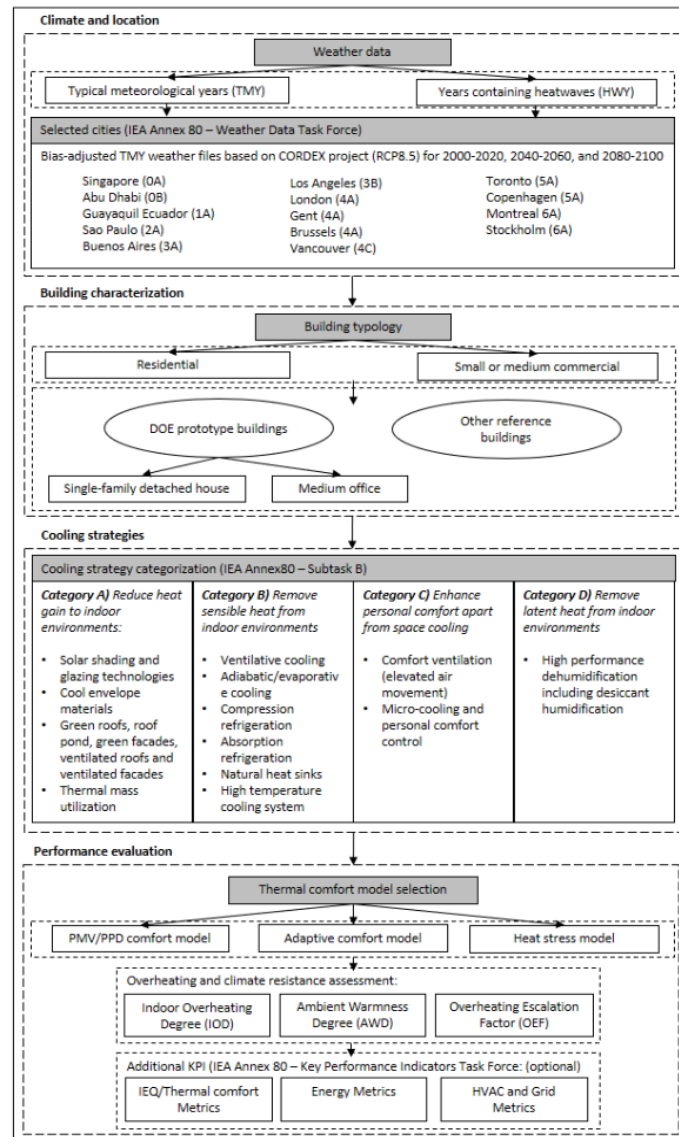


Figure I.7. Dynamic simulation guideline for the performance testing of cooling strategies. Reproduced from [112] with permission from the authors.

I.1.1.7 Strategies for heat adaptation at the building level

Strategies overview

Alongside optimising envelope design, geometry, and orientation, dedicated strategies are required to prevent overheating and improve thermal comfort in buildings. These strategies are often classified according to the traditional passive/active distinction [114].

On the one hand, passive strategies rely on natural processes to maintain indoor thermal comfort without (or with minimal) mechanical energy use [114]. They exploit ambient cooling sinks such as air, water, soil, and the night sky to counteract ambient, solar, and internal heat gains [115]. Because they consume little to no energy, passive strategies are generally more sustainable and cost-effective than active cooling systems [105]. However, their effectiveness may be limited or insufficient in extremely hot climates or in buildings with high internal heat gains.

Passive cooling approaches can be grouped into three main categories: heat protection, heat modulation, and heat dissipation [115]. Figure I.8 illustrates the possible strategies associated with this classification.

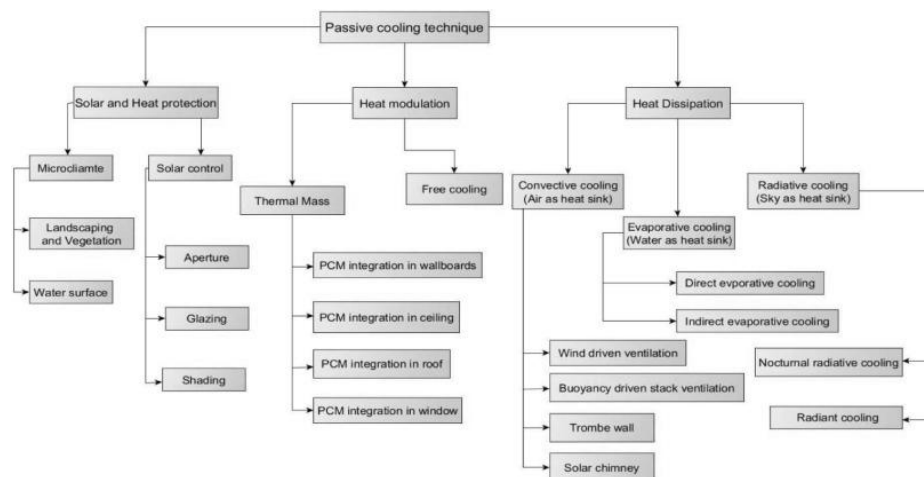


Figure I.8. Classification of passive cooling techniques. Reproduced from Bhamare et al. (2019), *Energy and Buildings*, 198, Fig. 1, with permission from Elsevier. Licence number: 6327530001293 [115].

On the other hand, active strategies rely on mechanical systems to enhance heat transfer and reduce indoor air temperatures. Unlike passive approaches, they require an external power source and are typically driven by electricity, natural gas, heat, or solar energy [116]. These systems can be highly effective in maintaining thermal conditions, even in extremely hot climates or in buildings with high internal heat gains. However, they are energy-intensive and often costly to operate. According to the International Energy Agency (IEA), air conditioners and electric fans account for approximately 20% of total global building electricity consumption [117]. This significant share highlights both their effectiveness and their impact on energy demand and greenhouse gas emissions, as well as broader environmental impacts [[118], including contributions to the urban heat island (UHI) effect and noise pollution. As illustrated by Figure I.9, active cooling systems, also referred as air-conditioning units, can be classified according to their energy source into two categories: electricity-driven or thermal energy-driven [116].

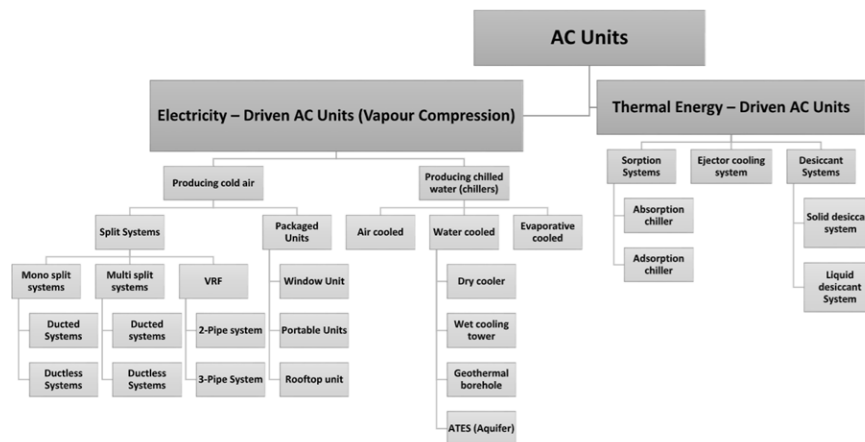


Figure I.9. Classification of active cooling systems. Reproduced from Elnagar et al. (2023), *Renewable and Sustainable Energy Reviews*, 175, Article 113179, with permission from Elsevier. Licence number: 6327530211640 [116].

More interestingly, these systems can also be classified according to their temperature regime and corresponding cooling capacity. High cooling-power systems, often referred to conventional air-conditioning systems, use electric compressors and standard refrigerants to deliver

substantial cooling capacities, typically ranging from 50 W/m² to 150 W/m² [105]. These systems are valued for their ability to ensure high levels of thermal comfort and to provide latent cooling (dehumidification). However, they are characterised by relatively high energy consumption and by the use of refrigerants that are currently being phased out under environmental regulations [119].

In contrast, high-temperature cooling systems – such as evaporative cooling or free geo-cooling combined with floor or ceiling emitters – are more energy-efficient and often use little to no refrigerant. As they are generally less perceptible to occupants, they may still allow for a degree of human thermal adaptation. As such, they are often considered more sustainable cooling systems [105]. They, however, offer lower specific cooling capacities (20–30 W/m²) and carry a risk of condensation, necessitating strict dew point control. They also often need to be combined with passive strategies, such as solar shading and ventilative cooling.

Climate change can negatively affect both active and passive cooling strategies, as their design, sizing, and efficiency are strongly dependent on outdoor environmental conditions [120]. Active cooling systems are particularly sensitive to increases in outdoor temperature. As ambient temperatures rise, the temperature difference between the condenser and the outdoor air decreases, reducing heat rejection efficiency. This results in increased cooling demand, greater electricity consumption, higher operating costs, and reduced overall system efficiency [121]. In addition, elevated temperatures can accelerate the degradation of system components such as pumps, compressors, and condensers. This may result in reduced equipment lifespan, increased maintenance requirements, and a higher risk of system malfunction or failure during extreme heat events—precisely when cooling is most critical [122].

Passive cooling strategies are also affected by climate change. Many passive techniques rely on a sufficient gradient between indoor–outdoor temperatures to remove heat from the building. As outdoor temperatures increase, this temperature difference decreases, limiting the potential of heat dissipation strategies.

Consequently, buildings designed for historical climate conditions may no longer achieve the expected levels of thermal comfort under future climate scenarios. This highlights the need to reassess and adapt both passive and active cooling strategies to ensure long-term resilience.

Moving beyond the traditional passive/active distinction, work conducted within the framework of IEA Annex 80 [123] has recently proposed a four-category classification based on approaches to cooling either occupants or the indoor environment. Table I.6 lists all available cooling strategies according to this classification.

Table I.6. Classification of cooling strategies based on their approach to cooling people or the indoor environment. Adapted from Zhang et al. (2021) [124].

A. Reduce heat load in indoor environments and for occupants
• Advanced solar shading and advanced glazing technologies • Cool envelope materials • Green roofs, roof ponds, green façades, ventilated roofs, and ventilated façades • Thermal mass utilisation, including phase change materials (PCM) and off-peak ice storage
B. Remove sensible heat from indoor environments
• Ventilative cooling • Adiabatic/evaporative cooling • Compression refrigeration • Absorption refrigeration, including desiccant cooling • Natural heat sinks, such as groundwater, borehole heat exchangers, ground labyrinths, earth tubes, and sky radiative cooling • High-temperature cooling systems: radiant cooling, chilled beams • District cooling
C. Enhance personal comfort independently of space cooling
• Comfort ventilation (elevated air movement) • Micro-cooling and personal comfort control
D. Remove latent heat from indoor environments
• High-performance dehumidification, including desiccant dehumidification.

Strategies for residential buildings in temperate climates

Temperate regions (C classification according to Köppen–Geiger) are characterised by moderate mean annual temperatures and marked by seasonal variability [24]. They typically experience four distinct seasons and significant temperature differences between summer and winter. Traditionally, building design in these regions has focused on heat conservation during winter [125]. Summer thermal adaptation of dwellings, if addressed, often relies exclusively on passive strategies such as ventilative cooling and the use of solar shading [126–128].

Heat transmitted through the glazing (driven by its solar factor) is a major cause of overheating in buildings, resulting in uncomfortable conditions for the occupants [129, 130]. In residential buildings, these solar gains are frequently exceeding 60% of the peak cooling load depending on glazing ratio, environmental shading and climate [131]. By absorbing or reflecting solar radiation, *solar shading* devices limit the portion of radiation that reaches interior spaces [132], causing a greenhouse effect. These devices present a high Technology Readiness Level (TRL) (9 according to Zhang et al. [132]). Different types exist on the market: interior or exterior, fixed or mobile, automated or manual. They can be made of textile, wood, metal or even plants, and take different shapes. The choice of a particular solar shading device depends on the orientation, the shading opportunities offered by the external environment (e.g., vegetation, other buildings, etc.), technical aspects, aesthetics, the view to the outside and the level of natural light transmission when the system is deployed.

In general, external solar protection is considered as one of the most effective means to prevent overheating [126, 128, 133], and its usefulness is recognized in many climates [132, 134, 135]. Less expensive, internal solar shading is less efficient because a part of the heat transmitted through the glazing remains unavoidably trapped inside the room. However, the use of very light colours or reflective materials can improve its efficiency by increasing the reflection of solar radiation towards the outside (yet, without reaching the performance of an external protection). In the Belgian temperate climate, it has been shown that cooling needs could be reduced by 37 % using internal light-

coloured solar shading devices and by 70% by external solar shading with low openness factor [136]. Other than preventing overheating, solar shading can also have other roles, such as limiting glare, ensuring privacy, darkening a room, improving the insulation level of the window, contributing to a particular facade aesthetic, etc.

Ventilative cooling is also considered as a very efficient passive strategy [94, 126, 133]. Aiming to remove sensible heat from the inside [132], ventilative cooling is generally achieved naturally in residential buildings by opening windows when external temperature is lower than inside. It does not really require any special additional technology (TRL 9 according to Zhang et al. [132]). The purpose of this strategy is to generate a significant renewal of the indoor air (from 2 to 6 air changes per hour (ACH) [137]) in order to evacuate the heat accumulated inside the building (intensive ventilation). Its role is, therefore, different from the hygienic ventilation necessary to ensure indoor air quality, which generally involves much lower air flow rates (often less than 1 air change per hour) and often relies on a mechanical system with heat recovery in energy efficient buildings. Ventilative cooling is also able to increase the velocity of the air helping the human body to evacuate its heat by convection, thus improving thermal comfort [138].

Generating effective ventilative cooling requires the opening of adequately located windows. It is generally recommended to open windows on different facades to generate cross ventilation or to take advantage of the stack effect by opening windows on different floors. The effectiveness of the technique will depend on the position, size and characteristics of the openings, the presence of wind, but also the difference in temperature between the interior and exterior [137]. The lower the outside temperature compared to the inside, the more efficient the ventilative cooling. Nighttime is, therefore, often ideal for this type of ventilation, and recommended in the literature [99, 139].

In addition to the evacuation of accumulated heat, intensive ventilation is also useful to remove pollutants or odours in case of exceptional use (painting, excessive occupation, etc.). It is, therefore, complementary to the hygienic ventilation strategy [140].

The *thermal mass* (concrete, masonry, stone, etc.) of the building and its accessibility (contact with the indoor environment) can also influence indoor summer thermal conditions [133, 141]. When in contact with the indoor environment, thermal mass can absorb, store, and release thermal energy to regulate the indoor temperature on a cyclical basis [132]. It has been shown that accessible thermal mass does not lower indoor daily mean temperature compared to lightweight buildings but has the capacity to limit indoor temperature extremes in summer [142]. In consequence, many authors recommend the use of high thermal mass in residential buildings [143, 144]. It is recognized that its contribution to mitigate overheating risk is greater when combined with a preventive ventilative strategy, such as night cooling [145-148] which helps to dissipate the accumulated heat. However, the efficiency of this strategy depends on many other factors: climatic conditions, exposure to heat sources, characteristics of the envelope, time when it is desirable to limit the interior temperatures (depending on the presence of the occupants), ventilation schedule, etc. [83, 126].

These strategies are also widely recognised as supporting human adaptive capacity, both behaviourally and physiologically, by enabling actions that reduce thermal stress, and psychologically, by fostering a sense of control among occupants [149]. On such basis, many authors have shown, based on simulation [126, 150, 151] and/or monitoring studies [130, 147, 152], that it is often possible to reach acceptable indoor summer thermal conditions by the use of passive strategies only, without any active cooling system, especially in residential contexts.

For future climate scenarios, however, the debate is still open, with some authors warning that these measures could indeed be insufficient [89, 153]. In any case, it is well ascertained that the implementation of passive techniques may limit the environmental impacts related to the use of air-conditioning by reducing buildings' cooling needs [62] and facilitating the adoption of more sustainable, high-temperature, cooling systems [105].

I.1.2. The evolving role of (building) policies

Policies constitute a key tool to support proactive measures aiming at both mitigating and adapting to climate change [154].

Since the 1990s, the European Union has engaged in a comprehensive strategy to tackle the expected impacts of climate change, progressively framing the objective of becoming climate-neutral (cf. Table I.2 p. 32) and supporting anticipatory measures of adaptation. This strategy encompasses a range of measures, including policy frameworks, binding regulations, recovery funds, support for citizen initiatives, and dedicated research, design, and policy programmes. Table I.7 summarises the historical development of the main mitigation and adaptation measures undertaken at the European level.

Initially, these measures primarily focused on mitigation, progressively strengthening greenhouse gas (GHG) emission reduction targets. In 2021, the entry into force of the European Climate Law [155] made legally binding the reduction of at least 55% of GHG emissions by 2030 and the achievement of climate neutrality by 2050. To reach this objective, the EU introduced the “Fit for 55” legislative package [37], aimed at revising and updating existing legislation, notably targeting the energy performance of buildings.

In parallel, measures have also been taken to support adaptation actions (cf. Table I.7). The EU Adaptation Strategy [156] was introduced in 2021. Since then, political and legal frameworks have supported adaptation efforts through co-financed programmes. Implementation mechanisms, such as the launch of the Mission on Adaptation to Climate Change Portal in 2023 [157], have been established to facilitate the large-scale deployment of actions. There is also growing recognition that all levels of governance play a crucial role in implementing these measures (e.g., through mayoral initiatives). EU-level action thus guides initiatives undertaken within Member States at national, regional, and local levels, with strengthened coordination across governance tiers.

Buildings are the largest energy consumers in Europe. According to European Commission [158]:

- Around 40% of the energy consumed in the EU is used in buildings;
- Around 50% of the EU's gas consumption is attributable to buildings;
- Approximately 80% of the energy used in European homes relates to heating, cooling, and domestic hot water.

Moreover, approximately 85% of EU buildings were constructed before 2000, and 75% exhibit poor energy performance, making the renovation of the existing building stock essential [158, 159].

The successive revisions and recasts of the Energy Performance of Buildings Directive [160] constitutes the central pillar of European policies dedicated to buildings (cf. Table I.7). They progressively aim to transform the European building stock into zero-emission buildings (ZEB) by 2050. The 2024 recast [160] seek to strengthen the previous objective of nearly Zero-Energy Buildings (nZEB) and to accelerate the renovation rate in the EU (from 1% to 2-3%) [161], prioritising the worst-performing buildings in each Member State. It is structured around four main priorities: renovation, decarbonisation, modernisation and digitalisation, financing and technical assistance.

Compared with the 2018 version [159], five structural developments characterise the EPBD 2024 [160], as it introduces:

- Harmonised Energy Performance Certificates;
- Minimum Energy Performance Standards (MEPS);
- The creation of national databases;
- National building renovation plans;
- The definition and strengthening of financial initiatives.

EPBD implementation varies across EU countries. In Belgium, EPBD implementation is managed at the regional level: Brussels, Flanders, and Wallonia. The European Commission monitors Member State (MS) progress and provides guidance and support. According to the Buildings Performance Institute Europe (BPIE), all MS have established nZEB requirements since 2021, except Bulgaria, Hungary, and Greece [64].

While each MS defines its own requirements, a common framework considers energy use, renewable energy production, and environmental impact.

nZEBs are characterised by very high energy performance, with most or all of their energy demand covered by renewable energy sources [162]. In a region such as Belgium, characterised by a temperate oceanic climate with predominantly heating-related energy use (more than 70% of the energy used in residential buildings [163]), nZEB performance requirements primarily aim to drastically reduce heating energy needs. In practice, increased insulation and airtightness of the thermal envelope, mechanical hygienic ventilation with heat recovery, and optimised building orientation have become essential design strategies in Wallonia. These measures undoubtedly improve winter comfort conditions while reducing energy costs [164].

While primarily designed as a decarbonisation instrument, the EPBD 2024 [160] increasingly incorporates adaptation-related provisions, particularly concerning overheating risk, indoor environmental quality, and building resilience. Building codes are indeed recognised as playing an important role in protecting occupants from overheating [165]. A lack of coordination between countries regarding thermal comfort criteria has however resulted in the absence of a standardised European approach to overheating evaluation. Attia et al. classified existing methods according to eight parameters [166]:

- Thermal comfort-based vs. heat balance-based;
- Time-integrated vs. punctual;
- Multi-zone vs. single-zone;
- Static vs. adaptive thermal comfort model;
- Normalisation to occupied hours;
- Short-term vs. long-term criteria;
- Occupant representation: stochastic vs. deterministic fixed models.

In Belgium, EPBD regulations for residential buildings include a simplified overheating assessment based on a quasi-steady-state heat balance approach using a time-integrated overheating index, I_{overh} [Kh],

which sums the normalised monthly excess heat gains relative to an indoor set-point temperature [167]. Although based on a similar calculation method, the Brussels-Capital Region links the results to the Belgian Passive House criteria, defining overheating as the percentage of occupied hours above 25 °C, which must not exceed 5% annually [168].

Work conducted within the framework of IEA Annex 62 [169] highlighted the role of such EPBD calculation methods based on monthly energy balance calculation [170] which may contribute to underestimating the need to properly implement dedicated strategies. Also, as highlighted by Rahif et al., current European building codes do not adequately account for climate evolution in overheating assessments [166], posing critical risks to occupant comfort, health, and well-being.

More generally, climate change context calls for improved consideration of climate change impacts and adaptation within building codes. In line with the IEA Annex 80 work [123], the trend is therefore shifting towards new general frameworks [112] and performance-driven criteria [111] aimed at preventing overheating risks, improving comfort, and limiting energy use.

Table I.7. Evolution of European policy and initiatives relevant to mitigation and adaptation and their impact on the building sector. Author's synthesis.

Year	International Frameworks & Agreements	EU initiatives and policies for Mitigation	EU initiatives and policies for Adaptation	EU Building Policies	Impacts for the building sector
1997	Kyoto Protocol	EU commits to binding GHG reductions	–	–	<i>Energy efficiency policies begin strengthening</i>
2001	IPCC AR3	–	–	–	–
2002	–	–	–	EPBD 2002/91/EC	<i>EPCs & minimum requirements; Inspection of systems</i>
2003	–	EU Emissions Trading Directive adopted	–	–	<i>Carbon pricing legal framework established</i>
2005	Kyoto enters into force	EU Emissions Trading System launched	–	–	<i>Carbon pricing affects energy supply</i>
2007	IPCC AR4	Climate & Energy Package (20-20-20 targets)	–	–	<i>Strengthened building efficiency requirements</i>
2008	–	Covenant of Mayors for Climate and Energy launched	–	–	<i>Local retrofits</i>
2009	–	First Renewable Energy Directive 2009/28/EC Ecodesign Directive 2009/125/EC	–	–	<i>HVAC & product efficiency standards strengthened</i>
2010	–	–	–	EPBD 2010/31/EU (Recast)	<i>nZEB standard introduced</i>
2012	–	Energy Efficiency Directive 2012/27/EU	–	–	<i>Public building renovation obligation</i>
2013	IPCC AR5	–	EU Adaptation Strategy; EU Green Infrastructure Strategy	–	<i>Urban resilience planning integrating climate risk</i>
2014	–	Horizon 2020 (research program); 2030 Climate & Energy Framework (– 40% GHG)	Adaptation integrated into EU funding, Mayors Adapt	–	<i>Long-term renovation strategies prepared</i>
2015	Paris Agreement	Alignment toward deep decarbonisation	Global Adaptation Goal recognised	–	<i>Buildings recognised as key decarbonisation sector</i>
2016	UN- New Urban Agenda	–	EU Urban Agenda	–	<i>Global framework for sustainable urban development, inclusive cities,</i>

					<i>better urban governance</i>
2017	–	–	–	Level(s) launched	<i>Embodied carbon & life-cycle assessment introduced</i>
2018	IPCC 1.5°C Report	Effort Sharing Regulation (ESR); Clean Energy Package; Renewable Energy Directive 2018/2001	Evaluation of Adaptation Strategy; Regulation on the Governance of the Energy Union and Climate Action	EPBD (EU) 2018/844 (Amendment)	<i>Long-Term Renovation Strategies, Smart Readiness Indicator</i>
2019	–	European Green Deal – Climate neutrality 2050	Adaptation mainstreamed in Green Deal	–	–
2020	–	Renovation Wave Strategy ; EU Taxonomy Regulation NextGenerationEU European Climate Pact	Biodiversity Strategy 2030; New Leipzig Charter (Urban policy)	–	<i>Double renovation rate; Sustainable finance reshapes renovation investment</i>
2021	IPCC AR6	European Climate Law 2050 neutrality legally binding; Fit for 55 package (–55% by 2030) Horizon Europe New European Bauhaus	New EU Adaptation Strategy	–	<i>EPBD, EED revision proposals</i>
2022	Sustainable Urban Resilience for the Next Generation (SURGe) Initiative	REPowerEU ; ETS2 (buildings & transport carbon pricing)	EU Mission on Adaptation; Climate-Neutral & Smart Cities Mission; 8th Environment Action Programme; Renewed commitment to EU Urban Agenda	–	<i>Carbon pricing signal applied to building heating fuels</i>
2023	1st Global Stocktake under the Paris Agreement	Revised ETS & LULUCF strengthen to –55%; Renewable Energy Directive 2023/2413 (RED III); Energy Efficiency Directive 2023/1791; Social Climate Fund	1st Climate Law Progress Assessment	–	<i>Social compensation for ETS2; Stronger efficiency targets</i>
2024	–	– EU Nature Restoration Law	Continued adaptation governance; EU Climate Risk Assessment (EUCRA)	EPBD (EU) 2024/1275 (Recast)	<i>Zero-Emission Buildings; Whole-life carbon reporting; Minimum Energy Performance Standards (MEPS); Fossil boiler phase-out.</i>
2025	–	Clean Industrial Deal (proposal)	–	–	–

I.1.3. Overheating in newly built dwellings: a growing concern in temperate climates

Over the past decade, growing concerns have emerged regarding summer thermal comfort and overheating in newly built residential buildings in temperate climates.

Studies conducted across various international contexts –though predominantly in the UK– have focused on indoor summer thermal quality and occupant satisfaction (see Table I.10 p.64). Post-occupancy evaluations (POEs) have primarily been carried out through survey campaigns, using self-developed structured or semi-structured questionnaires with a focus on satisfaction and comfort. Only a limited number of studies have employed standardised instruments, such as the Building Use Studies (BUS) [171] survey and the Swedish MM/Örebro questionnaire [172]. These studies provide either longitudinal (multiple wave) or cross-sectional (retrospective) assessments based on past experiences. They frequently use satisfaction or thermal sensation scales (e.g. ASHRAE [173]) [174] [175].

Studies focusing on low-energy buildings have often reported significant levels of perceived discomfort among occupants:

- 81% of the 52 interviewed occupants of low-energy prefabricated timber houses in UK reported feeling “warm” or “hot” during the summer period, despite overall high satisfaction rates [174].
- 50% of respondents reported finding summer temperatures “too high”, either “usually” (12.5%) or “sometimes” (37.5%), in a study conducted in Belgium (Flanders) on 16 passive houses [176].
- 12% of respondents (4 out of 34) stated that they were “often bothered by overheating” during the summer in a study conducted in Norway on high-performance residential buildings [177].
- 68% of student respondents rated their rooms as “warm” (38%) or “hot” (30%) even before the peak of summer months, opening windows specifically because it was “too warm”, in a study conducted in Ireland on 50 nZEB residential units [178].

Measurement campaigns, sometimes combined with surveys, have also been conducted to assess actual indoor physical conditions, occasionally in response to a high number of occupant complaints [179]. These measurements typically rely on indoor air temperature monitoring in main dwelling spaces (living rooms and principal bedrooms), across samples ranging from single case studies [180, 181] to several hundred buildings (building stock studies [182]). In a limited number of cases, radiant temperature was also measured [179].

Most studies cover monitoring periods ranging from nine days (when focusing on heatwave events) to several years, generally concentrating on specific months (July, August) or summer periods. In some cases, conditions during spring or autumn were analysed to focus on free-running conditions in buildings equipped with air-conditioning systems [147, 183].

Measurement results are primarily analysed using dedicated benchmarks based on thermal comfort models (Table I.8), with a progressive shift from static to adaptive comfort models, sometimes incorporating occupant vulnerability considerations [181]. However, several studies have questioned the applicability of the adaptive thermal comfort model in domestic settings. This model was developed largely from data collected in office environments and may be less suitable for bedrooms, given the specific physiological and behavioural requirements of sleep. Due to these concerns, contemporary methodologies often adopt a combined approach, using adaptive models for living spaces and static criteria for sleeping environments [53].

Table I.8. Summary of main existing criteria for long-term summer thermal comfort analysis

Type	Thresholds	Overheating criterion	Source
Hours of exceedance	25°C	10% of annual occupied hours over temperature of 25 °C 5% of annual occupied hours over temperature of 25 °C	PHI PHP
Hours of exceedance	28°C living areas 26°C bedrooms	1% of annual occupied hours over operative temperature of 2006 28 °C (living areas) or 26°C (bedrooms)	Guide A, CIBSE 2006 TM59, CIBSE 2017 (bedrooms only)
Hours of exceedance	$(T_{op} - T_{max})^* > 1K$ $T_{op} - (EN15251 \text{ Cat II upp. limit}^{**}) > 1K$ $T_{op} - (0.33 T_{im} + 21.8^\circ C) > 1K$	3% of occupied hours during the non-heating period (May to September included) when T_{op} exceeds EN15251 Cat II upper limit by 1K ^{**}	TM52, CIBSE 2013 Guide A, CIBSE 2015 TM59, CIBSE 2017
Daily weighted exceedance	$We = \sum(h_e) \times WF$ with $WF = \min(0; T_{op} - T_{max})$ and h_e : corresponding time [h]	Max 6 in any one day during occupied hours ^{***}	TM52, CIBSE 2013
Upper limit temperature	$T_{upp} = T_{max} + 4K$	Absolute maximum value during occupied hours ^{***}	TM52, CIBSE 2013

*Rounded to the nearest unit

** For spaces that are occupied by very sensitive and fragile persons upper limit of Category I is recommended.

*** May fail to be met in dwellings (TM59, CIBSE 2017).

Most of the reviewed studies note that actual indoor temperatures often deviate from theoretical design predictions or recommended benchmarks:

- 72% of 25 monitored social housing flats built to the Passivhaus standard in UK failed to meet their design criteria, according to a study conducted in 2015 by Tabatabaei et al. [152].
- The two monitored low-energy houses exceeded recommended summertime comfort temperatures of 25°C in living rooms and 24°C in bedrooms in a study conducted in the UK by Jones in 2016 [184].
- One in four analysed passive and low-energy homes in Norway exceeded the upper adaptive thermal comfort limit for more than 5% of the time during the warmest summer period [177].

- The Passive House investigated by Fokaides in Cyprus (2016) recorded living room temperatures exceeding 28°C for an average of 27% of hours [180].
- The Passive House analysed by Fletcher in the UK (2017) failed to comply with CIBSE, PHPP, and EN 15251 thermal comfort criteria [181].
- Three of the four low-energy homes investigated by Toledo et al. (2024) failed the standard overheating assessments (CIBSE Guide A and TM59) [185].

In some studies, comparisons were made with “reference buildings” characterised by lower levels of thermal insulation and airtightness. These comparisons often highlighted a greater overheating risk in highly insulated buildings, originally designed to retain heat during winter [133, 147, 174, 181, 186]. For example, in 2017, Pathan showed that dwellings built since 1996, likely constructed to higher energy efficiency standards, tended to experience significantly higher indoor temperatures for longer durations than older properties [175]. Nevertheless, studies also clearly demonstrated that overheating is not limited to newer buildings [187, 188].

Several studies also examined the causes of observed overheating, identifying factors related to building design, fabric, and services. Table I.9 presents a summary of the factors identified in the literature. Multiple studies further emphasise the decisive role of occupant behaviour, such as window operation and ventilation practices, in managing summer thermal conditions [129]. In 2019, Sharifi showed, for example, that houses with the same energy-efficiency rating could exhibit significant differences in summer thermal performance [189].

Taken together, these studies provide strong evidence of the widespread occurrence of summer thermal discomfort in low-energy dwellings, clearly diverging from the findings of the foundational CEPHEUS Passive House demonstration project [190], and call for further investigation.

Table I.9. Reported causes of overheating in low-energy dwellings linked to building design and occupant behaviour.

Category	Identified Causes	Supporting sources
Building design and fabrics	High window-to-wall ratios and a lack of external solar shading.	[133], [152], [174], [177], [129], [129], [179], [186], [189], [178]
	Low thermal mass in lightweight construction (e.g., timber frame).	[133], [187], [174], [180], [181], [186], [191]
	Specific typologies such as top-floor, single-orientation, or west-facing flats.	[182], [152], [177], [192], [129], [175], [186], [189], [191], [178]
Building Services	High internal heat density from occupants and high-energy appliances in smaller living spaces.	[193], [152], [186]
	MVHR systems lacking a summer bypass or being ineffective for cooling.	[193], [152], [177], [129], [179], [186], [185]
	Heat "leakage" from uninsulated or poorly commissioned communal heating pipes.	[179], [186]
Occupant Behaviour	Knowledge gaps or misunderstandings regarding how to operate complex home systems.	[133], [194], [152], [177], [181], [186], [178]
	Restrictions on adaptive actions (opening windows) due to noise, pollution, or security concerns.	[181], [179], [186], [147], [191], [178]
	Counter-productive actions like keeping windows open when outdoor air is hotter than indoor air or using heating in summer.	[182], [194], [177], [186]
	Vulnerable groups (elderly, neurological conditions) having a reduced perception of heat or higher sensitivity.	[182], [152], [186], [178], [185]

Table I.10. Studies exploring summer thermal conditions through surveys and monitoring in existing (low-energy) dwellings in temperate climates.

Year	Authors	Country	Köppen-Geiger climate classification	Nb of dwellings	Method of Analysis	Survey Type	Standardised Questionnaire	Monitoring duration	Monitoring period	Measurement's location	Focus on	Comfort model used	Source
2013	Bezsee et al.	UK	Cfb	427 (207 monitored)	Survey and Monitoring	Retrospective	No	9 months (focus on 4 days)	July 2007-March 2008	Living rooms and main bedrooms	Comfort and Energy	Static and Adaptive	[175]
2013	Lomas et al.	UK	Cfb	268	Survey and Monitoring	Longitudinal	No	8 months	July-August 2009	Living rooms and bedrooms	Comfort	Static and Adaptive	[180]
2015	Tabatabaee Sameni et al.	UK	Cfb	25	Monitoring	Retrospective	No	From 34 to 122 days	3 cooling seasons: 2011-2013	Living rooms	Comfort	Static and Adaptive	[145]
2016	Adekunle et al.	UK	Cfb	52 (17 monitored rooms)	Survey and Monitoring	Longitudinal	No	2 weeks	June-July 2012	Living rooms and bedrooms	Comfort	Static and Adaptive	[167]
2016	Jones et al.	UK	Cfb	3	Survey and Monitoring	Retrospective	No	2 months	July-August 2013	Living rooms and main bedrooms	Comfort	Static and Adaptive	[177]
2016	Symonds et al.	UK	Cfb	823	Monitoring	Retrospective	Yes English Housing Survey (EHS)	5 months	May-September 2011	Living rooms, bedrooms, and hallways	Comfort and Energy	Static	[185]
2016	Toledo et al.	UK	Cfb	4	Survey and Monitoring	Longitudinal	No	6 weeks	June-August 2015	All occupied rooms	Comfort	Static	[122]
2016	Wright et al.	UK	Cfb	9	Monitoring	Not	No	9-12 days	August 2003 heatwave	Living room, bedrooms, and kitchen	Comfort	Static and Adaptive	[188]
2017	Fletcher et al.	UK	Cfb	1	Survey and Monitoring	Longitudinal	No	21 months	April 2013 to December 2014	Living rooms and main bedrooms	Comfort and Energy	Static and Adaptive	[174]
2017	Kermecie et al.	UK	Cfb	9	Survey and Monitoring	Longitudinal	No	3x2 weeks	3 seasons (winter, spring, summer) 2014-2015	Living rooms and main bedrooms	Comfort and Energy	Static	[189]
2017	McLeod et al.	UK	Cfb	3	Monitoring	Retrospective	No	1 month	Oct-15	Living room, bedrooms, kitchens and corridors	Comfort	Static and Adaptive	[172]
2017	Pathan et al.	UK	Cfb	122	Survey and Monitoring	Retrospective	No	2X2 months	2009 and 2010	Living rooms and bedrooms	Comfort and Energy	Static and Adaptive	[168]
2018	Tink et al.	UK	Cfb	2	Monitoring	Not Applicable	No	Four weeks (+3 with mitigation measures)	Summer 2015	Living room, dining room, kitchen, bedrooms, and bathroom	Comfort	Static and Adaptive	[123]
2019	Ozarsoy et al.	UK	Cfb	1	Monitoring		No	+/- 1 month	25 June to 20 July 2018	Living room, kitchen, bedrooms and hallways	Comfort and Energy	Static and Adaptive	[179]
2020	Yannas et al.	UK	Cfb	16	Survey and Monitoring	Retrospective	No	1 week	October/November 2010-2016	Living rooms and bedrooms	Comfort and Energy	Adaptive	[140]

2021	Lomas et al.	UK	Cfb	750	Survey and Monitoring	Retrospective	Yes (Energy Follow-Up Survey EFUS2017)	12 months	2018	Living rooms and bedrooms (+ 1-3 rooms)	Comfort and Energy	Static and Adaptive	[190]
2024	Toledo et al.	UK	Cfb	4	Survey and Monitoring	Longitudinal	No	11 months	Summer 2015 to Spring 2016	All occupied rooms	Comfort and Energy	Static and Adaptive	[178]
2011	Mrakar et al.	Slovenia	Cfb	1	Monitoring	Not Applicable	No	48 months	2007-2010	Staircases	Comfort and Energy	Static	[126]
2016	Berge et al.	Norway	Cfb	34 (4 monitored)	Survey and Monitoring	Retrospective	Yes (MM questionnaire / Örebro model)	6 or 12 months	May 2013–April 2014	Living room, bedrooms, and bathrooms	Comfort and Energy	Static and Adaptive	[170]
2008	Hasselaar et al.	Netherlands	Cfb	500 (2 monitored)	Survey and Monitoring	Retrospective	No	Not specified	Not specified	Living rooms, bedrooms and bathrooms	Comfort	Static	[186]
2012	Miecnik et al.	Netherlands	Cfb	90	Survey	Retrospective	No	Not Applicable	Not Applicable	Living rooms and bedrooms	Comfort and Energy	Static	[191]
2020	Ascioms et al.	Italy	Csa	1	Monitoring	Not Applicable	No	2.5 (spring) and 1 month (october)	Spring and october 2019	Living rooms and bedrooms	Comfort and Energy	Static	[176]
2024	Colclough et al.	Ireland	Cfb	55 (50 monitored)	Survey and Monitoring	Retrospective	Yes (Building User Survey (BUS))	12 months	2019-2020	Living room, kitchen, and bedrooms	Comfort and Energy	Static and Adaptive	[171]
2006	Schmieders et al.	Germany, Austria, Switzerland, Sweden, France	Cfb	221 (>100 monitored)	Survey and Monitoring	Longitudinal	No	30 months	Spring 2000 to Autumn 2002	All occupied rooms	Comfort and Energy	Static	[183]
2016	Fokades et al.	Cyprus	Csa	1	Monitoring	Not Applicable	No	23 months	March 2014 to January 2016	Living rooms and bedrooms	Comfort and Energy	Static and Adaptive	[173]
2013	Miecnik et al.	Belgium (Flanders)	Cfb	16 (2 monitored)	Survey and Monitoring	Longitudinal	No	2 weeks	June 2010	Living rooms, kitchens, and bedrooms	Comfort	Static	[169]
2013	Strapels et al.	Belgium (Flanders)	Cfb	70	Monitoring	Longitudinal	No	2 weeks	Summer 2012	Living rooms, main bedrooms and bathrooms	Comfort and Energy	Static	[135]
2019	Shariff et al.	Australia	Csa	8	Monitoring	Not Applicable	No	(4 to 8 summers	2011–2018	Living room, master bedroom, other bedrooms, and studio	Comfort and Energy	Static and Adaptive	[182]

I.2. Problem statement and research gaps

Climate change calls for a dedicated adaptation of our built environment. More frequent and intense heatwaves will inevitably lead to recurrent heat stress, causing critical comfort and health issues. There is therefore a growing need for the building sector to consider how summer thermal adaptation is addressed.

At the building level, summer thermal adaptation is often understood as the integration – during the design and construction stages – of dedicated strategies aimed at improving summer thermal comfort under current and/or future climatic conditions. In recent years, methods have been developed to assess the relevance and the necessity of these strategies (see Section I.1.1.6). These methods primarily aim to guide the design of new buildings to prevent thermal discomfort and limit energy consumption based on technical and performance-based evaluations. Overheating indicators have also been introduced into EPBD regulations [166]. These methods notably support the implementation of passive control measures –such as solar shading and ventilative cooling. These strategies are widely recognised as supporting human adaptive capacity [149]. In temperate climates, they have consistently been identified as effective approaches to mitigating overheating risks, supporting free-running residential buildings, and limiting reliance on active cooling systems.

At the same time, evidence from countries such as the United Kingdom (UK), where the study of summer indoor thermal conditions has developed into a well-established research tradition over the past decade (cf. Table I.10), has shown that achieving summer thermal comfort in residential buildings is already challenging in temperate climates. This evidence invites a critical reassessment of current practices and an evaluation of how summer thermal adaptation is occurring in contexts where it is not culturally embedded. On this basis, and in line with developments in other domains [45], such an understanding could support an iterative and cyclical evaluation process aimed at making summer thermal adaptation a tangible and effective reality [199].

Building practices are inherently context-dependent, varying according to climate, building type, and socio-cultural values [200]. In Belgium, an overheating indicator has been introduced within the EPBD for newly built dwellings [201], but no large-scale study has yet examined how summer thermal adaptation is implemented in practice in low-energy dwellings (cf. Table I.10). Furthermore, the assessment of the impacts of climate change on the built environment remains in its infancy in the Belgian context.

The present research addresses these gaps by first examining current and future indoor summer thermal conditions in dwellings (Part A of this thesis) and, second, by exploring practices related to the implementation and use of passive controls (Part B of this thesis). As such, this research provides a first assessment of current summer thermal adaptation practices within the broader context of evolving climate-oriented policies (see Figure I.10).

The primary aim of this research is therefore to raise awareness on the gap between design intent and real-world outcomes.

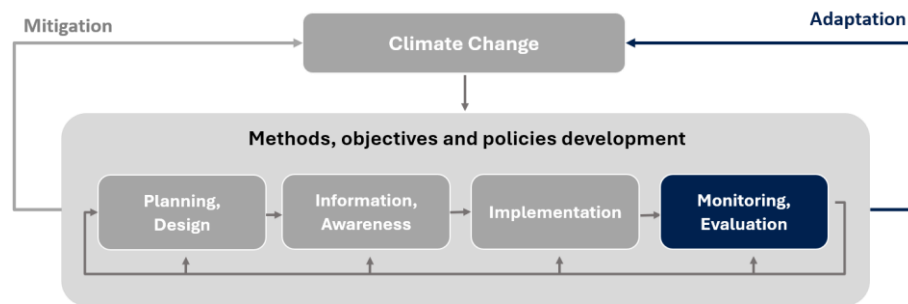


Figure I.10. Research positioning framework, adapted by the author from IPCC (2001) [33], Figure 18-6, based on Klein et al. (1999) [45].

In doing so, this work also seeks to address methodological gaps frequently identified in the literature (see, for example [202]) by:

- Combining physical measurements with surveys to avoid relying solely on subjective metrics [203] ;
- Controlling for independent variables such as building characteristics, occupancy patterns, passive control use, and socio-economic factors [204, 205];
- Ensuring adequate statistical power through large-scale and long-term studies supported by dedicated statistical analyses [206, 207];
- Adopting a socio-technical, interdisciplinary perspective that moves beyond the conventional siloed understanding of summer thermal adaptation in building science [202, 208].

Finally, this research aims to contribute to the ongoing debate on how to assess summer thermal conditions and overheating in residential contexts by questioning the applicability of current static and adaptive benchmarks [175].

In doing so, this thesis contributes to three of the United Nations (UN) Sustainable Development Goals (SDGs) [209]: SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

I.3. Research questions and objectives

This thesis critically examines how summer thermal adaptation currently occurs in newly built, low-energy houses in Wallonia and questions how it could be improved. The main research question addressed can be formulated as follows:

*How can design practices evolve
to more effectively support summer thermal adaptation
through passive strategies in low-energy residential buildings?*

In this study, the term *passive* is used in a broad sense, in line with the prevailing contextual understanding in summer thermal adaptation research, to denote non-mechanical means of regulating the indoor environment [114]. These include fixed and adaptive envelope-based strategies, such as solar shading and ventilative cooling. In this context, the term differs from its stricter use in control theory, as defined in ISO 52016-3 [210].

On the one hand, questioning the possible evolution of practices regarding summer thermal adaptation in buildings requires the assessment of the resulting quality of the indoor environment (IEQ), both physical and perceived, current and future. On the other hand, it also involves understanding current practices regarding the integration and use of passive controls in dwellings.

Following this consideration, the research was divided into two separate parts: Part A and Part B.

Part A focuses on the assessment of current and future indoor summer thermal conditions in low-energy houses and addresses the following research sub-questions:

RQ1. What are the current summer thermal conditions experienced in low-energy houses?

RQ2. How might climate change affect indoor summer thermal conditions?

Part B focuses on current practices regarding the integration and use of passive controls in newly built dwellings and addresses the following research questions:

RQ3. How are passive controls currently integrated into newly built dwellings?

RQ4. What factors shape the effectiveness of passive control use?

To address these research questions, corresponding research objectives were defined. Figure I.11 presents the research objectives associated with each research question.

Research subquestions and related research objectives**PART A. ON CURRENT AND FUTURE
INDOOR SUMMER THERMAL CONDITIONS****RQ1. What are the current summer thermal conditions experienced in low-energy houses?**

- ↳ RO1. To assess occupants' perceptions of indoor summer thermal conditions.
- ↳ RO2. To assess physical indoor summer thermal conditions.
- ↳ RO3. To compare perceived and physical indoor summer thermal conditions.

RQ2. How might climate change affect indoor summer thermal conditions?

- ↳ RO4. To evaluate potential future indoor summer thermal conditions.

PART B. ON THE INTEGRATION AND USE OF PASSIVE CONTROLS**RQ3. How are passive controls currently integrated into newly built dwellings?**

- ↳ RO5. To assess current practices in the integration of passive controls.
- ↳ RO6. To identify the factors that shape current practices in the integration of passive controls.

RQ4. What factors shape the effectiveness of passive control use?

- ↳ RO7. To assess the practical effectiveness of passive control use.
- ↳ RO8. To identify the factors that shape the use of passive controls.

Figure I.11. Research sub-questions with their corresponding research objectives.

I.4. Structure of the thesis

This thesis comprises five core chapters (Chapters III–VII), each written in the form of a journal article or conference paper and addressing one or more of the research objectives (see Figure I.11 and Table I.11). Most of these chapters have already been published in peer-reviewed journals or conference proceedings; further information is provided at the beginning of each chapter.

Chapter III to Chapter V, which constitute Part A, examine current and future indoor summer thermal conditions. They contribute to Research Objectives RO1 to RO4 and address the first two research questions (RQ1 and RQ2). Chapter VI and Chapter VII, which constitute Part B, address the remaining two research questions (RQ3 and RQ4) by examining current practices related to the integration and use of passive controls, thereby addressing Research Objectives RO5 to RO8.

Table I.11. Research questions and objectives addressed in each core chapter of the thesis.

Chapter ID and related paper title	Research Questions and Objectives							
	RQ1		RQ2	RQ3		RQ4		
	RO1	RO2	RO3	RO4	RO5	RO6	RO7	RO8
Part A. On current and future indoor summer thermal conditions								
Chapter III. Occupants’ Satisfaction in High Energy Performance Residential Buildings.	•							
Chapter IV. Long-term evaluation of residential summer thermal comfort: Measured vs. perceived thermal conditions in nZEB houses in Wallonia.	•	•	•					
Chapter V. Indoor Summer Thermal Comfort in a Changing Climate: The Case of a nearly Zero Energy House in Wallonia.				•				
Part B. On the integration and use of passive controls								
Chapter VI. On the effectiveness of passive controls for summer thermal comfort in highly insulated dwellings.					•		•	
Chapter VII. On the practical implementation of passive controls.						•		•

Figure I.12 provides a broader overview of how these chapters are integrated into the overall framework of the manuscript. It shows how they converge in a general discussion of current practices in Chapter VIII, ultimately leading to an answer to the main research question and a presentation of the research implications in Chapter IX.

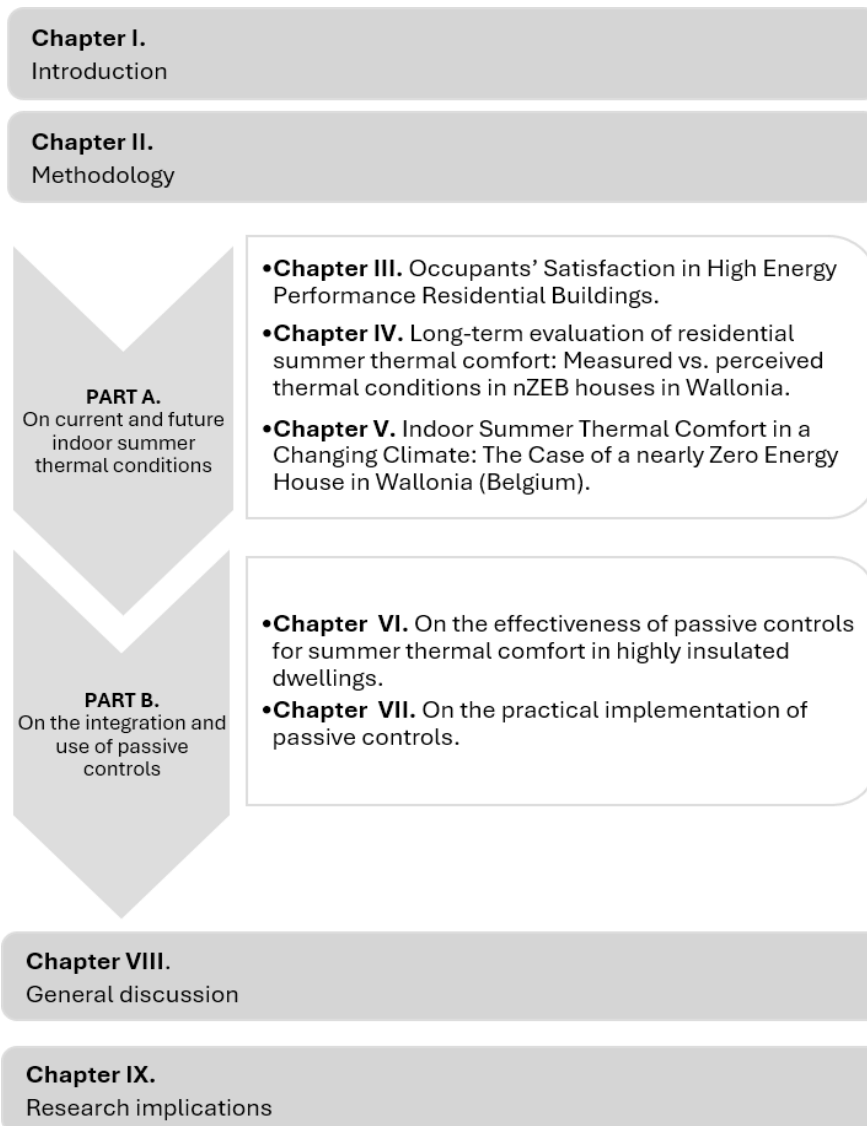


Figure I.12. Structure of the thesis

II.1. Research framework

Addressing the defined research objectives required establishing a collaborative research framework that provided access to representative samples of case studies reflecting current practices, as well as collaboration with the various professional stakeholders involved in the design, construction, and operation of residential buildings. These conditions were facilitated through the development of, and participation in, two collaborative research projects: MEASURE [211] and SOFTSummer [212].

The MEASURE project aimed to assess the energy performance of high-energy-performance residential buildings while evaluating occupants' satisfaction with their indoor environmental conditions. The SOFTSummer project focused on improving summer thermal comfort management in residential buildings through smarter and more sustainable technical solutions, including the deployment of digital technologies.

The associated data-collection activities were conducted primarily in collaboration with Buildwise (formerly the Belgian Building Research Institute), while CETIC, *Centre d'excellence en technologies de l'information et de la communication*, was also a partner in the SOFTSummer project. Both projects received financial support from the Walloon Region. They were accompanied by the public administrations responsible for research and for implementing building energy performance policies in Wallonia, as well as by several professional organisations, including the Union Wallonne des Architectes, Cap Construction, and the Fédération de la Construction (Embuild). Together, these organisations formed the projects' steering committees, providing practical support and helping to disseminate key information about the projects, notably by distributing the surveys.

Embedding this research within these collaborative projects provided access to a broad range of high-quality data and enabled direct engagement with key stakeholders from the building sector. It also helped ensure that the investigated practices reflected real professional

contexts and were sufficiently representative of current practice, while maximising the practical relevance and potential impact of the research findings.

Table II.1 provides a more detailed account of the author's contributions to these projects. Most of the data analyses presented in this manuscript were, however, conducted independently by the author, outside the formal project periods, to address the specific objectives of the present research (see also Figure II.1).

Table II.1 Role of the thesis author according to the CRediT taxonomy [213], to the two research projects supporting data collection.

Contribution Type	MEASURE	SOFTSummer (Task 2)
Conceptualization	✓	✓
Data curation	✓ ^{1,4}	✓ ²
Formal analysis	✓ ^{1,4}	✓ ²
Funding acquisition	✓ ³	✓ ³
Investigation	✓ ¹	✓ ²
Methodology	✓ ³	✓
Project administration	✓	✓
Resources	✓ ^{1,4}	✓ ²
Software	✓ ¹ (Survey)	✓ ² (Survey)
Validation	✓	✓
Visualization	✓ ¹	✓ ²
Writing – original draft (project report)	✓ ³	✓ ²
Writing – review & editing (project report)	✓ ³	✓ ²

1: In collaboration with Sophie Obyn (Research Assistant - UCLouvain).

2: In collaboration with Julie Castreman (Research Assistant - UCLouvain).

3: In collaboration with Buildwise (formerly Belgian Building Research Institute).

4: In collaboration with Véronique Vanwelde (Research Engineer - Buildwise) for IEQ Measurements.

Figure II.1. Timeline and main methodological steps of the research

Figure II.1. Timeline and main methodological steps of the research

II.2. Methodological approach

As presented by Figure II.1 in p.79 presenting the detailed timeline of the main methodological steps, this research began in 2014 and extended over a period of twelve years.

This period can be divided into two main phases, broadly corresponding to the two main parts of the present manuscript. The first phase extended over approximately eight years and focused on the analysis of perceived, measured, and simulated indoor summer thermal conditions. The related findings are mainly presented in Part A of this manuscript. The second phase, conducted over the following four years, focused on the practical implementation and use of passive controls and is mainly addressed in Part B.

Each phase comprised a period of dedicated data collection, followed by data analysis, interpretation, and the formulation of conclusions, ultimately leading to the writing of the corresponding chapters presented in this manuscript.

For the first phase of this research, focusing on experienced indoor conditions, a multilevel analytical framework was specifically developed to support the needed evidence-based data collection methodology (see Figure II.2). This approach, based on the data collected during the MEASURE project, consists of successive levels focusing on progressively smaller, more deeply analysed subsamples. The size of each subsample (i.e. number of buildings analysed) was defined to enable comprehensive and detailed application of the selected methods keeping control of independent variables and trying to ensure adequate statistical power through large-scale and long-term studies.

This phase is divided into three main levels:

1. A post-occupancy evaluation conducted through an online cross-sectional survey to a sample of 453 dwellings (149 answers received) launched in 2014.
2. Continuous measurements of physical indoor thermal conditions (during the entire year of 2016) and on-site interviews on 23 buildings
3. Calibrated Whole Energy Building Simulation on one selected nZEB house.

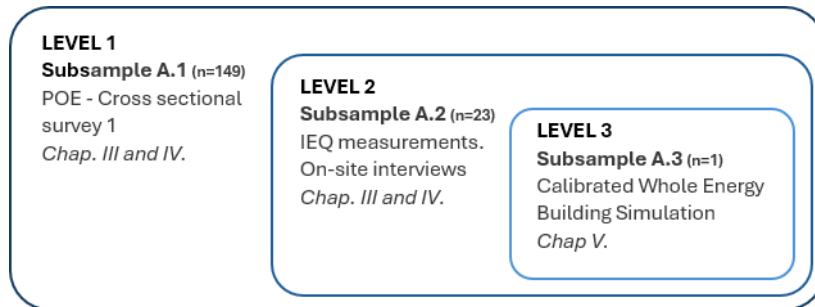


Figure II.2. The three steps of the adopted multilevel analytical framework (Part A of this manuscript).

At the first level, control of the independent variables was ensured through a dedicated link between the survey and a database containing all the geometrical and thermal characteristics of the dwellings (see Section II.3.2). For Levels 2 and 3, interviews, on-site inspections, and complementary measurements, including airtightness, U-values, heat-recovery efficiency, and energy consumption, were also used to verify the independent variables.

For the specific purposes of Part B of this research, which focuses on the integration and use of passive controls, an iterative process was developed within the framework of the SOFTSummer project to successively interview and survey different types of stakeholders involved in residential building construction processes (see Figure II.3). In total around 190 people took part in this process.

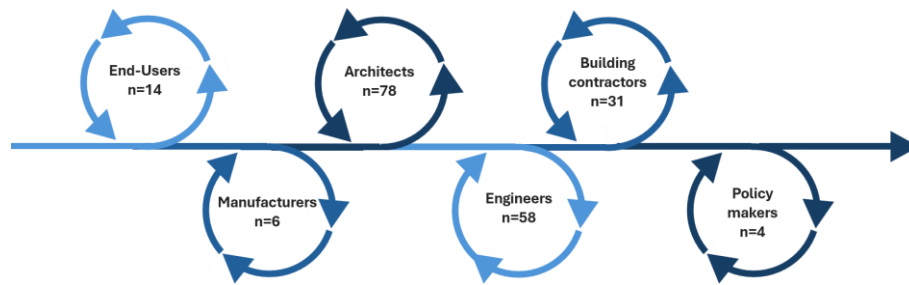


Figure II.3. The iterative methodological framework adopted for the analysis of practices, with the corresponding number of participants. (Part B - Chapter VII).

These research projects were approved by the Belgian Data Protection Authority. Appropriate data-management procedures were implemented to ensure the secure handling, storage, and use of the collected data, and no personal or identifiable data were disclosed.

II.3. Case study sampling and description

II.3.1. Samples definition

A sample of 458 low-energy houses built under the “Construire Avec l’Énergie” demonstration programme (CALE) [214] was initially selected for the multilevel analysis framework developed for Part A (see Section II.2). Implemented by the Walloon Region between February 2004 and 2012, the CALE initiative promoted a voluntary approach to constructing dwellings with higher energy performance than required by prevailing regulations. These dwellings were particularly suitable for the study because their technical characteristics were documented in a database validated by experts, enabling robust links to be established between measured results and building characteristics [202].

Some limitations were, however, identified in the use of this database, mainly related to the way it had been constructed. Although the main thermal characteristics of the dwellings were available, access to detailed design information was limited (e.g. the environmental shading associated with each opening).

The selected sample corresponds to the final phases of the CALE program, during which the requirements were the closest to current Energy Performance Standards [167]. In addition, only dwellings with a sufficiently long occupancy period (minimum two years) were selected, in order to ensure an objective assessment of the indoor environmental quality (IEQ) experienced by occupants [198]. A total of 149 valid responses were obtained from the post-occupancy evaluation survey (see Section II.4.2.1 p.100) conducted across this sample, constituting Subsample A.1 (see Figure II.2 p.81).

Twenty-three houses were subsequently selected for further investigation, forming Subsample A.2 (see Figure II.2 p.81). Although 25 dwellings were initially retained, two were excluded due to technical issues or participant withdrawal. This reduced subsample size was deliberately chosen to allow for detailed on-site measurements and verification of key characteristics (e.g., orientation, shading devices,

airtightness), as well as in-depth discussions with occupants regarding their perception of indoor environmental quality (IEQ), habits, and behaviours. The subsample was selected to reflect a similar rate of overheating complaints as Subsample A.1 and to be as close as possible to the evolution of nZEB requirements for the thermal envelope of the buildings [167].

Among the 23 dwellings included in Subsample A.2, three were included in a more detailed on-site measurement campaign. Although five dwellings were initially retained, two were excluded due to technical issues. This campaign comprised continuous monitoring of gas and electricity consumption, together with complementary spot measurements (see Section II.4.2.2 p.101). One single-family house was subsequently chosen from these three dwellings to constitute Subsample A.3 (see Figure II.2 p.81) and to support the detailed modelling analysis. Among the dwellings for which reliable data were obtained, this house was retained because its characteristics were representative of current nZEB requirements. As highlighted by the monitoring and survey campaigns, this house is not currently affected by significant overheating, likely due to its limited solar gains, (limited glazed area). A whole-building energy simulation model of this dwelling was then developed to assess the potential impact of climate change on indoor thermal conditions (see Section II.4.2.3 p.102).

For the second phase of the research, corresponding to Part B of this thesis, different stakeholder groups were selected to participate in the iterative interview and survey process (see Figure II.3 and Chapter VII). Participants were recruited on a voluntary basis through the contacts and dissemination channels of the SOFTSummer project steering committee (see Section II.1 p.77). The selection of participant groups was specifically discussed with the committee to ensure that they reflected current practices and trends.

In this phase, a new sample of dwellings was examined to specifically investigate the integration and use of passive control strategies through on-site visits and occupants-interview. This sample also served as a more recent comparison group relative to the previous findings.

It comprised 14 dwellings and was also selected based on opportunity and recommendations from professional associations, according to the following criteria:

- recently built or deeply renovated within the past 10 years;
- occupied for more than two years;
- compliant with, or close to nZEB requirements;
- independence of the participants from any economic interests related to the subject of the study.

Participation in the study was voluntary, and informed consent was obtained from all participants.

II.3.2. Building characteristics

The samples predominantly comprise newly built detached or semi-detached low-energy single-family houses. In Belgium, single-family houses represent 79.7% of the housing stock [215], of which 30% are detached houses [216].

All houses were located in the southern part of Belgium (Wallonia), at a latitude of approximately 50° North, and within a Cfb climatic zone (temperate oceanic climate) according to the Köppen–Geiger climate classification system [24]. They were situated in rural to semi-rural environments on relatively unobstructed sites, with little or no surrounding shading.

All analysed dwellings complied with energy performance requirements [167] which cover:

- Maximum U-values [$\text{W}/\text{m}^2\cdot\text{K}$];
- Maximum mean U-value [$\text{W}/\text{m}^2\cdot\text{K}$];
- Ventilation rates for each space [$\text{m}^3/\text{h}\cdot\text{m}^2$];
- Maximum primary energy consumption [$\text{kWh}/\text{m}^2\cdot\text{year}$];
- Limited overheating risk [%].

These buildings are therefore characterised by very high levels of insulation, improved airtightness, and mechanical ventilation systems. Mechanical ventilation with heat recovery was installed in 95% of the A.1 subsample and in all cases comprising the A.2, A.3, and B subsamples. They were all found to be sized solely to meet hygienic ventilation requirements, with maximum air-change rates below 1 air change per hour, and were equipped with a summer bypass. Only one house in Sample B was equipped with a fixed mechanical cooling system, and none were fitted with fixed ceiling fans.

The main qualitative and quantitative characteristics of the houses included in subsamples A.1, A.2 and A.3 are presented in Figure II.4 and Figure II.5 (pp. 87–89). Heated floor area, mean U-values, airtightness, annual heating demand, and the solar heat gain coefficient (SHGC) of windows were derived from the Belgian EPBD (Energy Performance of

Buildings Directive) calculation requirements [201]. Such detailed information was not available for Sample B; however, the newly built houses in this sample complied with EPBD requirements [167] (see also Chapter VII for further details).

For Subsamples A.2 and A.3, these characteristics were verified through on-site measurements and inspections. The measured data (including envelope thermal properties, airtightness, airflow rates, internal heat gains, and weather data) were subsequently used to develop the calibrated multi-zone whole-Building Energy Model. This house, which constitutes Sample A.3, is illustrated in Figure II.6 (p.90).

All dwellings were owner-occupied and mostly inhabited by families with children (average household size: 3.5 persons). Recently retired couples were also represented. As indicated by the socio-economic section of the survey, the sample typically comprised active, educated, and well-informed households, and relatively technically aware occupants.

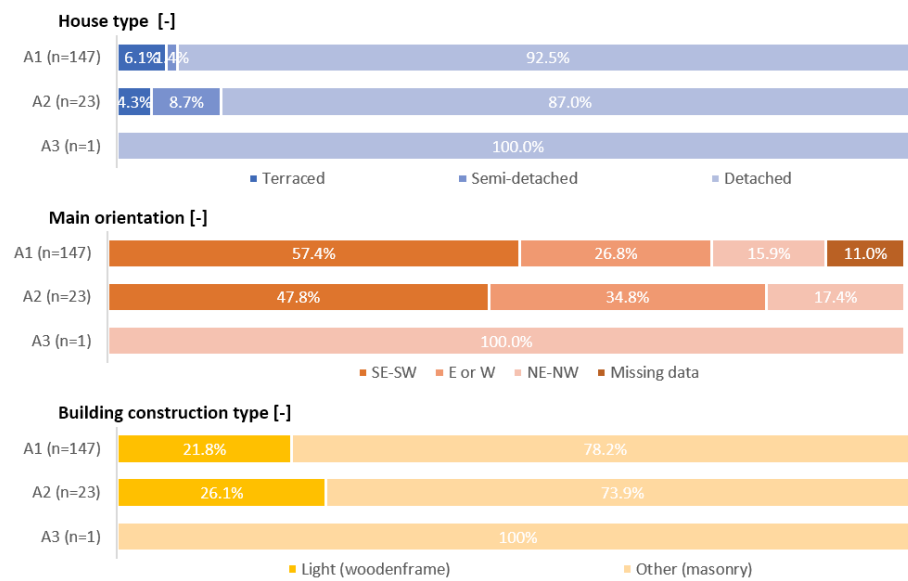
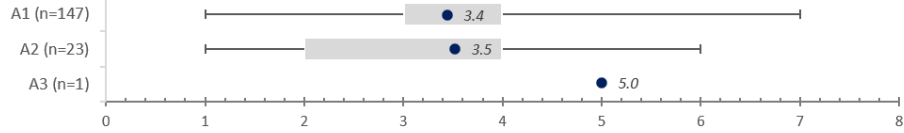
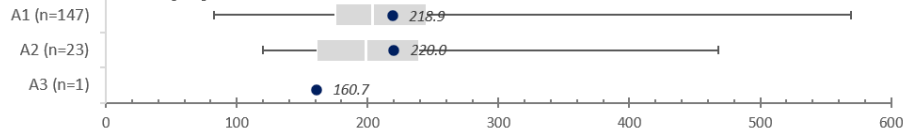
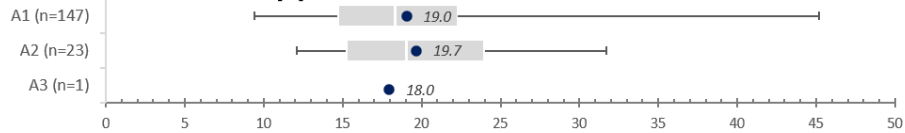
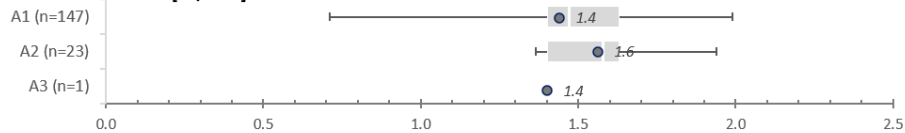
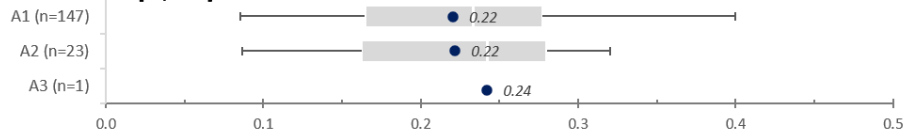
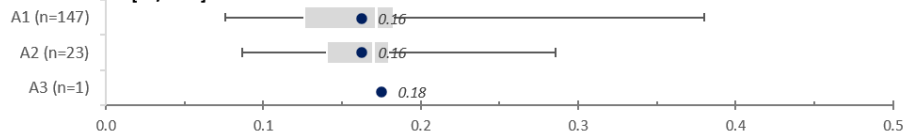
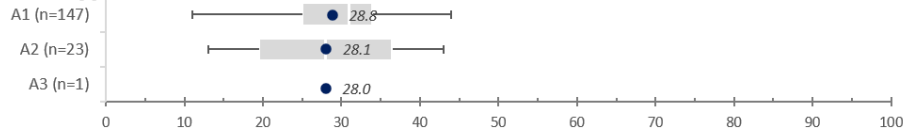


Figure II.4. Main qualitative characteristics of the buildings composing subsamples A1, A2 and A3.

Number of occupants [-]**Heated floor area [m²]****Window-to-floor surface ratio [%]****Windows U-value [W/m²K]****Walls U-value [W/m²K]****Roof U-value [W/m²K]****K-level [-]**

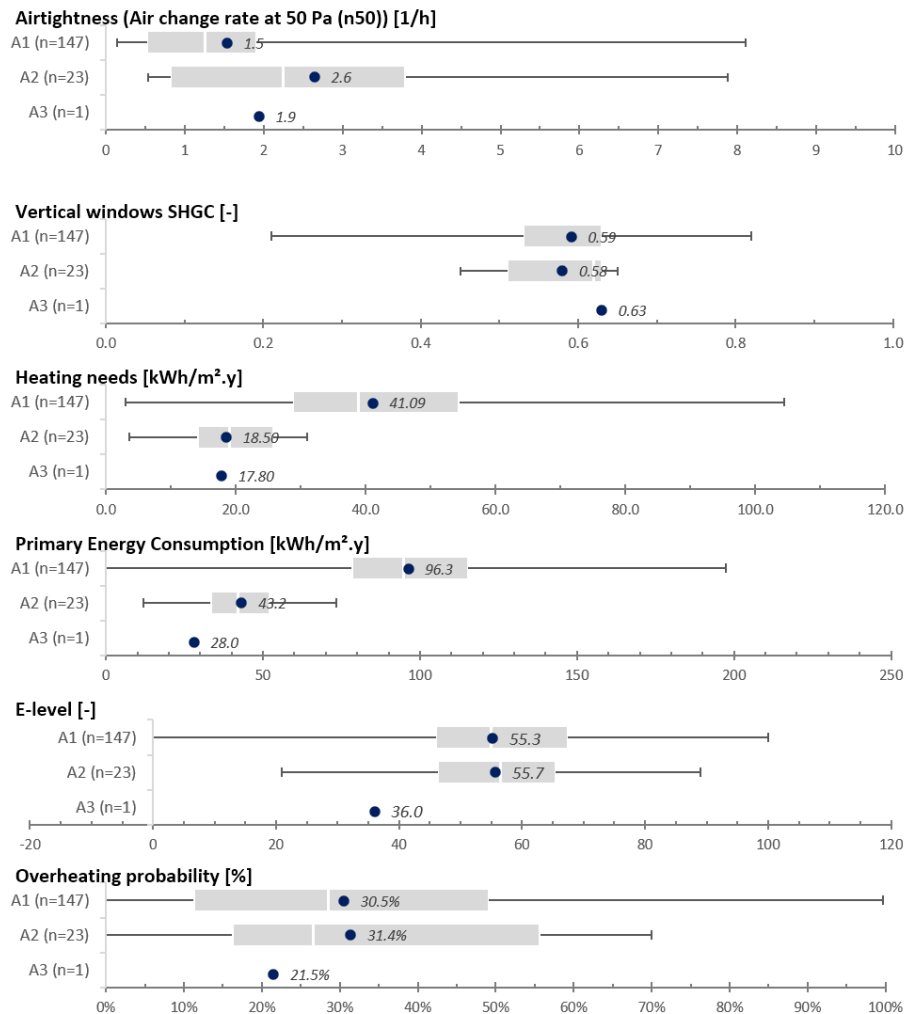


Figure II.5. Quantitative characteristics of the buildings composing subsamples A1, A2 and A3.



Figure II.6. Ground-floor and first-floor plans (respectively left up and left down) and main facades (front West façade (right up) and rear East façade right down) of the studied nZEB house (subsample A3).

II.4. Methods for data collection and analysis

II.4.1. General overview

Achieving the defined objectives (cf. Section I.3 p.69), which are mainly exploratory and descriptive in nature, requires interdisciplinary and cross-approach methods at the intersection of engineering and sociology.

Consequently, specific and appropriate data collection methods from these two disciplines are successively employed:

- Surveys
- IEQ Measurements
- Calibrated Whole Energy Building Simulations
- Semi-structured interviews
- Focus groups

Similarly, the qualitative and quantitative data collected (mixed methods research) are analysed using specific methods:

- Descriptive statistics
- Benchmark comparisons
- Statistical tests (hypothesis testing)
- Qualitative data analysis and Social Practices Theory lens

Figure II.7 to Figure II.14 detail how each research objective is addressed through the application of these methods.

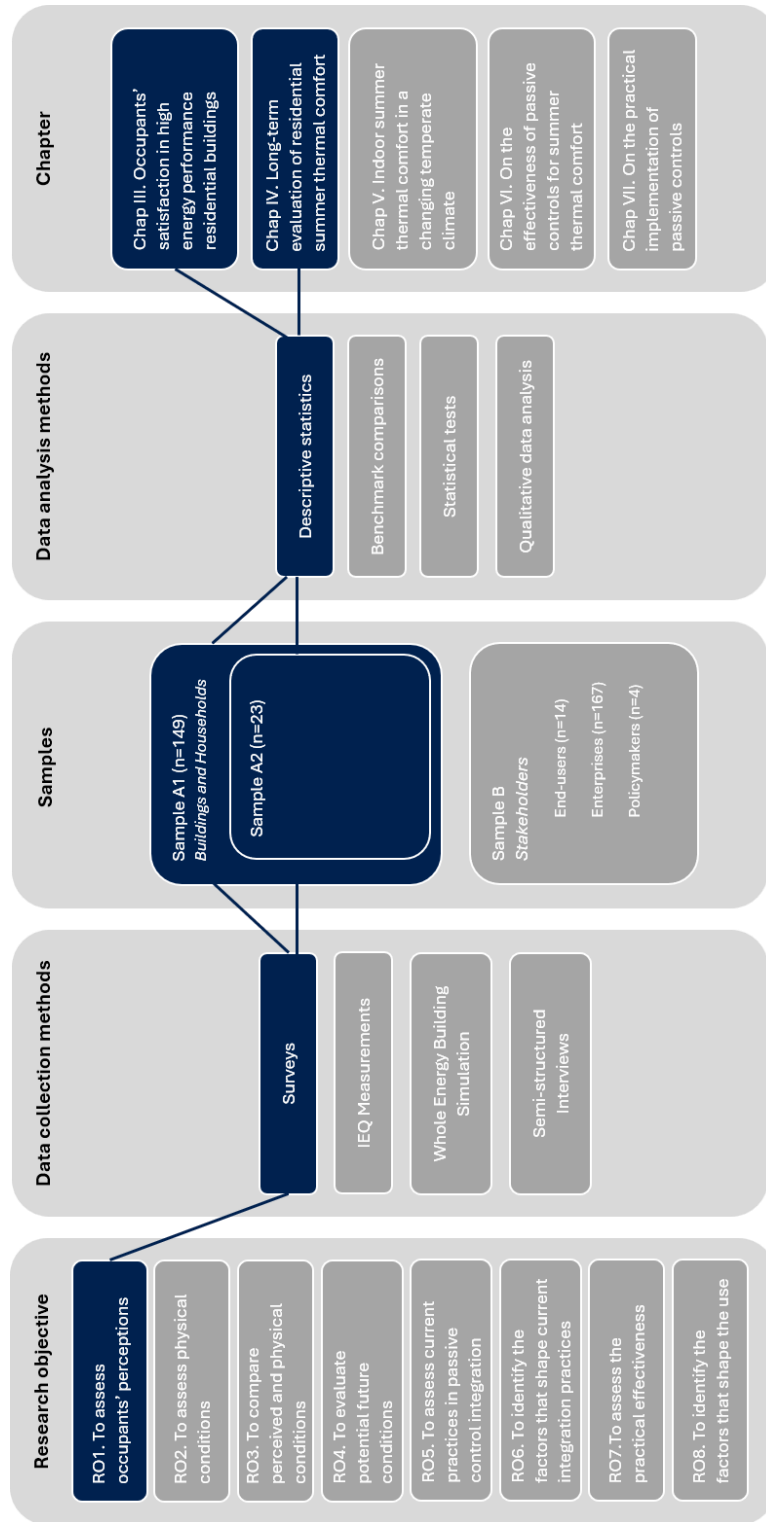


Figure II.7. Overview of data collection method, samples, data analysis method, and related chapters for Research Objective 1.

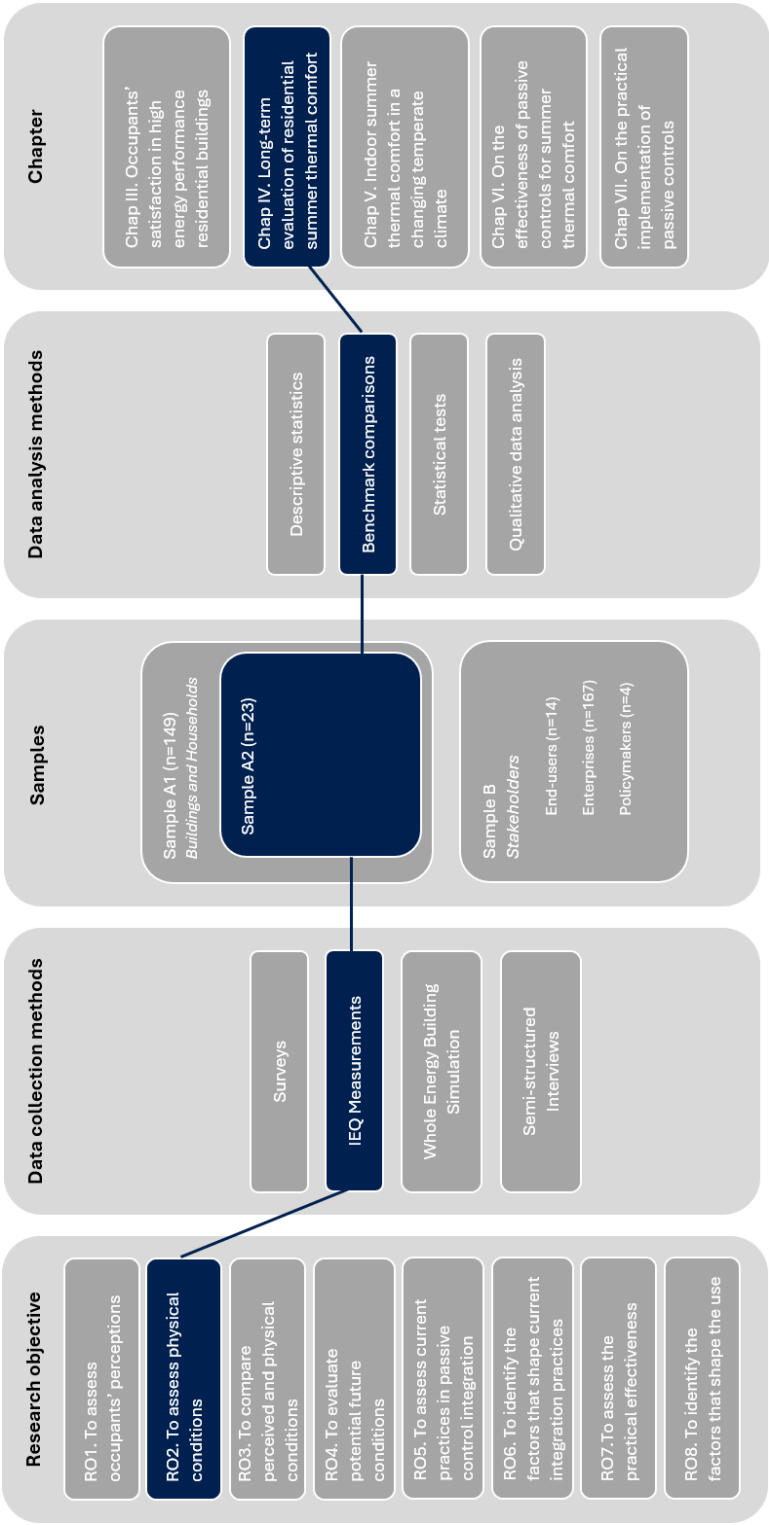


Figure II.8. Overview of data collection method, sample, data analysis method, and related chapter for Research Objective 2.

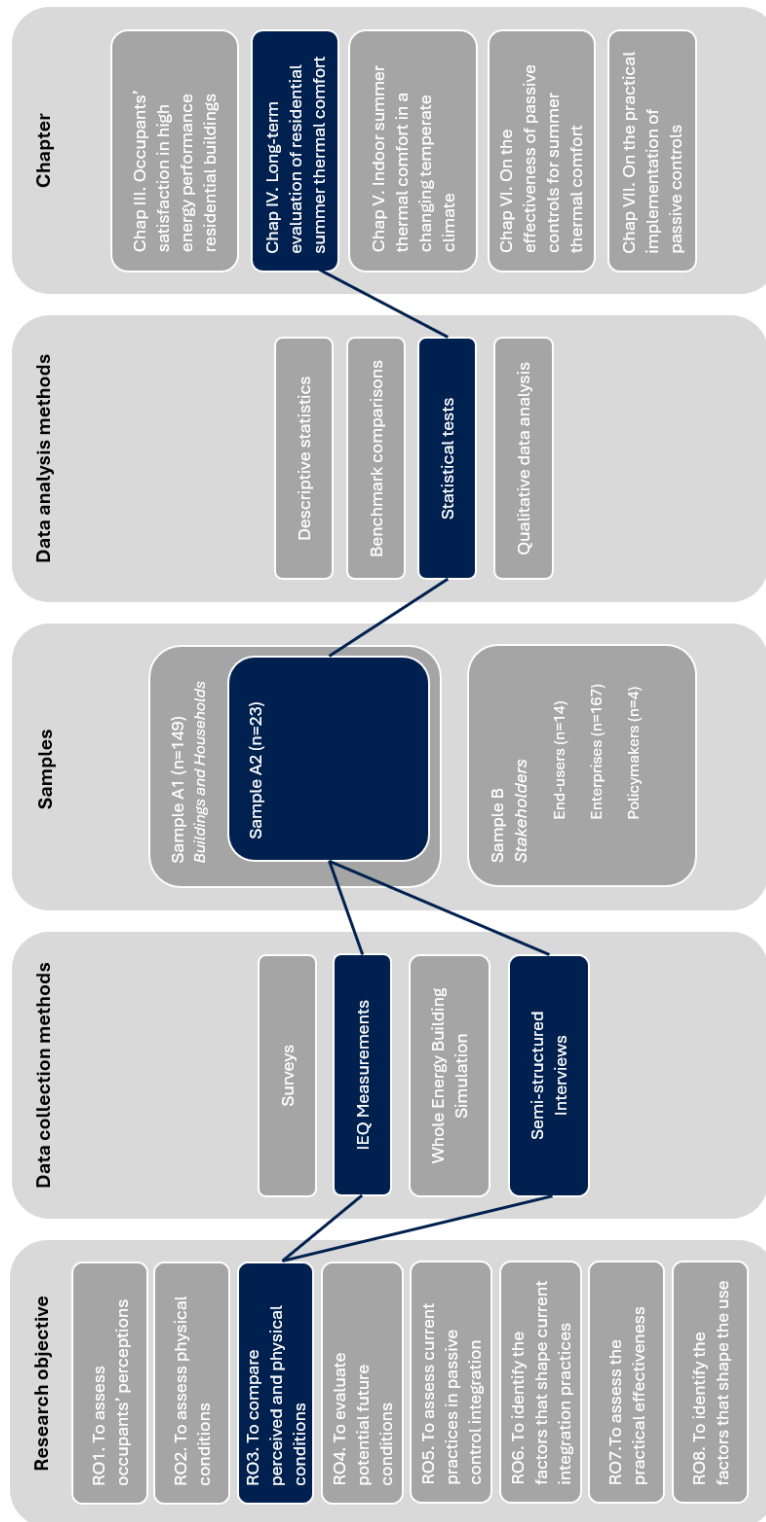


Figure II.9. Overview of data collection methods, sample, data analysis method, and related chapter for Research Objective 3.

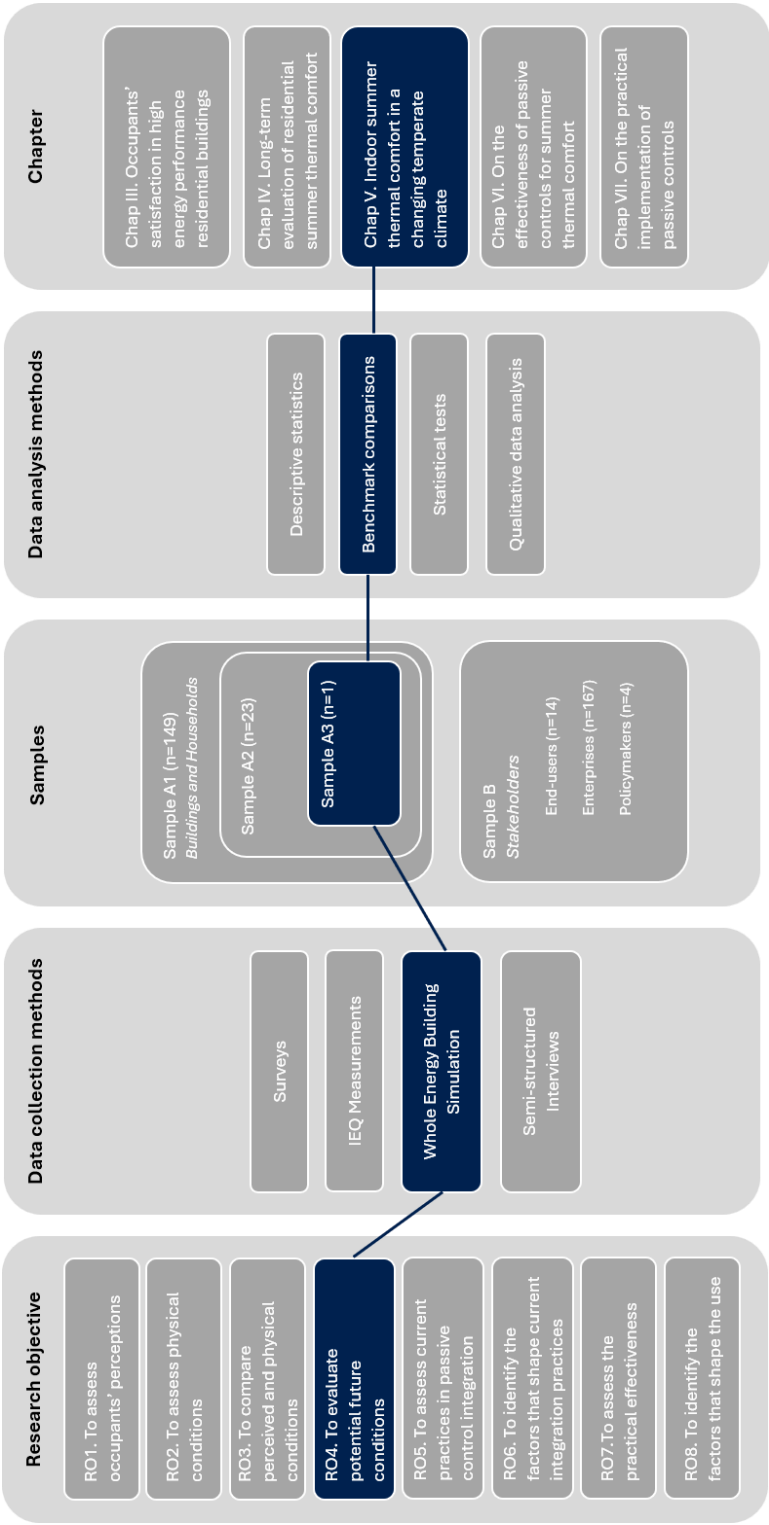


Figure II.10. Overview of data collection method, sample, data analysis method, and related chapter for Research Objective 4.

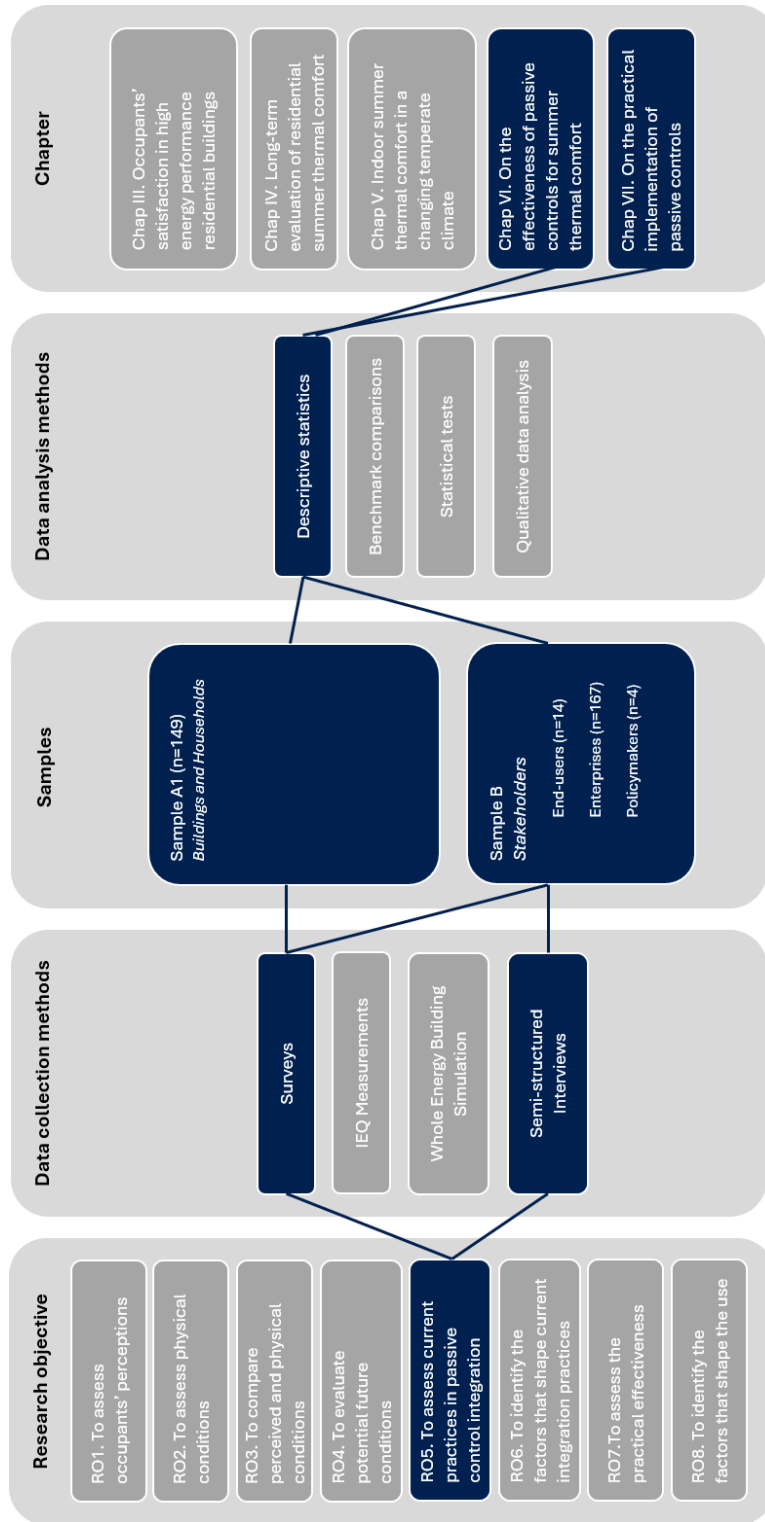


Figure II.11. Overview of data collection methods, samples, data analysis method, and related chapters for Research Objective 5.

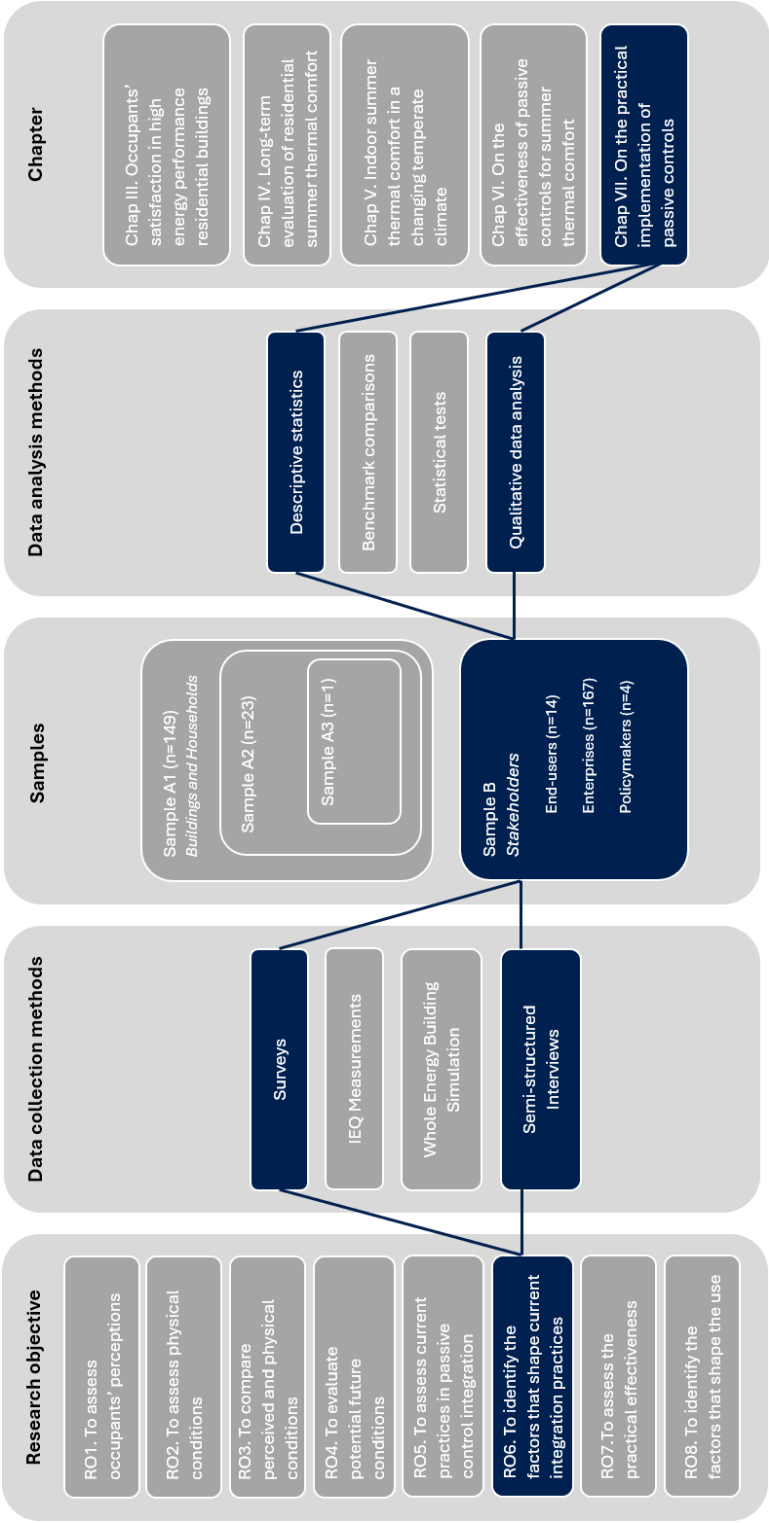


Figure II.12. Overview of data collection methods, samples, data analysis method, and related chapter for Research Objective 6.

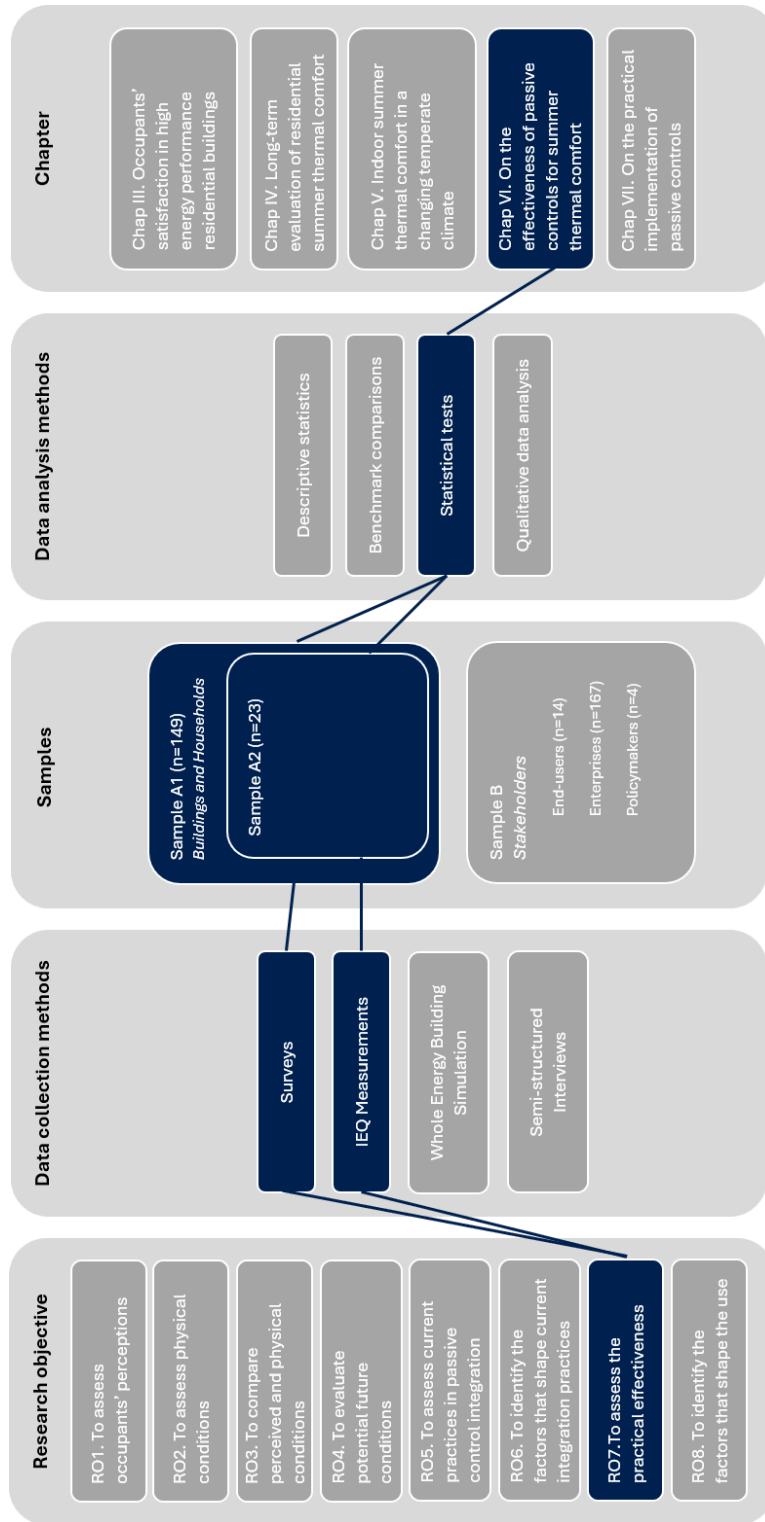


Figure II.13. Overview of data collection method, sample, data analysis method, and related chapter for Research Objective 7.

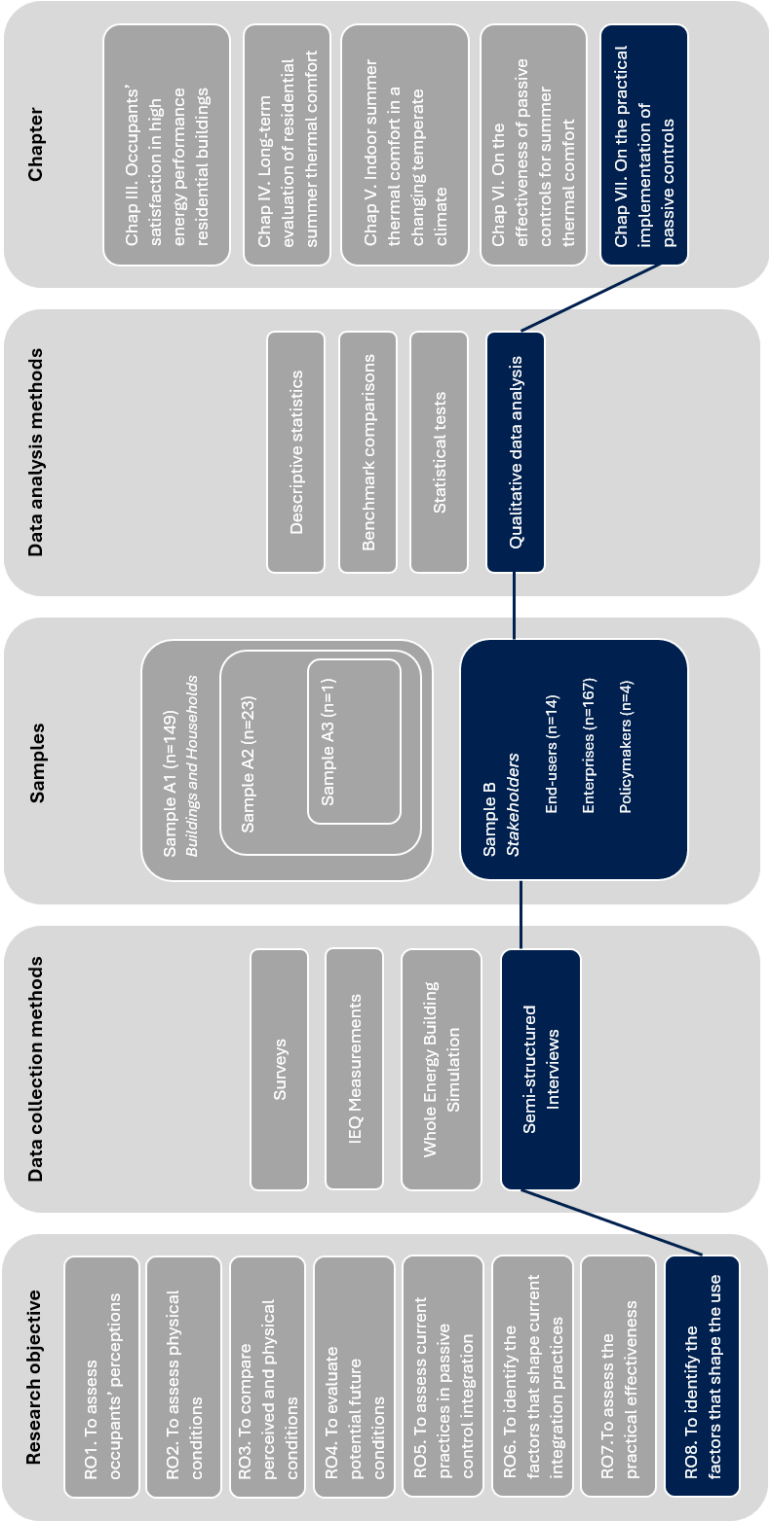


Figure II.14. Overview of data collection method, sample, data analysis method, and related chapter for Research Objective 8.

II.4.2. Data collection methods

The following sections present the main characteristics of the data collection methods adopted in this research and mainly realised within the framework the MEASURE and SOFTSummer projects (see Section II.1 p.77). Further details are provided in the chapters in which these methods are specifically employed (see Figure II.7 to Figure II.14 p.92. and corresponding chapters).

II.4.2.1 Surveys

Surveys were used at two different stages of the study.

First, an online survey was developed in the frame of the Measure project to assess occupants' satisfaction with indoor conditions, their use of the building and its systems, and behavioural factors likely to influence indoor conditions. It also collected information on occupants' profiles and habits, as well as on features and systems installed after construction.

The questionnaire comprised 59 questions divided into three sections: (1) appraisal of indoor environmental quality (IEQ), (2) verification of building and system characteristics, and (3) occupants' profiles and habits. It was designed to allow the survey responses to be linked to the technical information available in the CALE database (see Section II.3 p.83). Further methodological details about the survey development can also be found in [217].

The survey was conducted in 2015 among the initial sample of 453 houses (see Section II.3.1 p.83). A total of 149 valid responses were received corresponding to a response rate of approximately 33% and constituting Subsample A.1.

In 2023, a second online survey was developed in the frame of SOFTSummer project to investigate practices of enterprises involved in the design and construction of dwellings. The survey comprised 39 questions organized into different sections aimed at capturing the enterprise's activities, practical experience, and perceptions of summer thermal comfort, solar shading, and ventilative cooling. The

dissemination of the survey was facilitated by professional associations from members of the steering committee, through mailing lists and social media channels, with participation on a voluntary basis. A total of 167 responses were received (136 designers and 31 building trades).

Both surveys were administrated using LimeSurvey [218]. Appendices A and E present the surveys developed for the Post-Occupancy Evaluation and the analysis of professional practices, respectively, while Chapter III (Part A) and Chapter VII (Part B) further discuss the results obtained.

II.4.2.2 IEQ Measurements

An on-site monitoring campaign was conducted in 2016 within the framework of the MEASURE project on a subsample of 25 dwellings. Key indicators of indoor environmental quality (IEQ) – including air temperature, relative humidity, CO₂ concentration, and sound level – were monitored at 10-minute intervals throughout the entire year. Outdoor air temperature was also monitored locally at each dwelling, allowing the calculation of the running mean outdoor temperature (T_{rm}) according to EN15251 [[219]]. Although 25 dwellings were initially selected, only 23 provided sufficiently reliable data for analysis (Subsample A.2).

In addition, five dwellings were selected for complementary measurements aimed at verifying their thermal performance and capturing the interdependent variables likely to influence their indoor environmental conditions. These complementary investigations included both spot measurements, such as thermal transmittance (U-values), airtightness (n_{50}), heat-recovery efficiency, and hygienic ventilation airflow rates, and longitudinal measurements, including gas and electricity consumption. Five dwellings had initially been selected, but only three provided sufficiently reliable data for long-term measurements.

The year 2016 was broadly representative of the average conditions observed over the preceding 30 years in terms of outdoor temperature and solar radiation [220]. The monitoring period also included the late-

August 2016 heatwave, which lasted from 22 to 28 August according to the on-site measurements, with the maximum temperature reaching 35°C.

The air-temperature measurements, analysed using the adaptive comfort model defined in EN 15251, are presented in Appendix B. Appendix C focuses on the thermal behaviour of two similar houses during the 2016 heatwave. More comprehensively, the compliance of the measured indoor thermal conditions with commonly used overheating benchmarks is further analysed and discussed in Chapter IV (Part A).

II.4.2.3 Calibrated Whole Energy Building Simulations

A simulation-based approach was adopted to investigate the potential effects of future climate conditions on indoor summer thermal performance.

A whole-building energy model of an nZEB house (subsample A.3), integrating the data collected during on-site visits and IEQ measurements (see previous Section) was therefore developed using the TRNSYS 18 simulation engine [75].

A two-step calibration procedure (see Section IX.3.3.1 p.251) was first conducted to ensure that the model provided a realistic representation of indoor summer thermal conditions.

As presented in Chapter V (Part A), the calibrated model was then simulated using available high-resolution future climate projections (based on ALARO Regional Climate Model [20]). Complementary analyses of the sensitivity to passive-control characteristics and of the building's summer thermal autonomy under future climatic conditions were also conducted and are presented in Appendices E and F, respectively.

II.4.2.4 Semi-structured interviews

Questionnaire-based semi-structured interviews were conducted face-to-face at two different stages of the study.

Interviews were first carried out with occupants from Sample A.2 at the end of the summer period of 2016 to assess their retrospective appraisal of indoor thermal conditions over the entire summer season. General information was also collected on occupants' habits and behavioural actions, including window-opening practices and the presence and use of solar shading. These interviews were primarily based on selected questions from the post-occupancy evaluation questionnaire presented in Appendix A.

Semi-structured interviews were also conducted to investigate the practices of the different stakeholder groups presented in Chapter VII (Part B). An example of semi-structured-interview guide developed for the purpose of this study is presented in Appendix D. This interview guide, developed to characterize occupant's practices, comprised 42 questions organized into several parts: perceived summer thermal comfort; everyday habits for mitigating heat in summer and during heatwaves; barriers and opportunities for the effective implementation of passive controls, such as the placement and use of solar shading and ventilative cooling.

II.4.2.5 Focus groups

Focus groups were conducted at several stages of the research. First, they were organised prior to the development of surveys to inform and guide the design of the questionnaires. Second, they were used to discuss and critically assess the practical recommendations arising from the study with practitioners and other stakeholders involved in the building process (see Section IX.2 p.246).

II.4.3. Data analysis methods

The following sections present the methods adopted in this research to analyse the collected data. Further details are provided in the chapters in which these methods are specifically employed (see Figure II.7 to Figure II.14 p.92. and corresponding chapters).

II.4.3.1 Descriptive statistics

Descriptive statistics and appropriate graphical representations, such as box plots, were systematically used to analyse the quantitative data collected throughout the study.

II.4.3.2 Benchmark comparisons

Various long-term static and adaptive summer comfort criteria and benchmarks were used to assess measured air temperatures and simulated indoor thermal conditions (see Chapter IV and Chapter V).

II.4.3.3 Statistical tests (hypothesis testing)

Several statistical tests were used throughout the study to test research hypotheses. Non-parametric tests based on ranked data were selected because the variables did not follow normal distributions. For each test, statistical significance was assessed using a threshold of ($p < 0.05$), and Pearson's (r) effect size was calculated to estimate the magnitude of the observed differences. Reporting effect sizes also helped account for the limited statistical power and increased risk of Type II errors associated with the small subsample sizes. Further details on the application of these methods are provided in Chapter IV and Chapter VI.

II.4.3.4 Qualitative data analysis

Qualitative data analysis (QDA) was supported by the use of the dedicated software NVivo [221].

*" We shape our buildings;
thereafter they shape us."*

Winston Churchill

**PART A. ON CURRENT AND FUTURE
INDOOR SUMMER THERMAL CONDITIONS**

A.1. Scope and research objectives

Summer thermal comfort in low-energy dwellings is becoming an increasing concern in temperate climates. While this phenomenon has already been identified in other countries (see Section I.1.3), Part A of this thesis focuses on its assessment in the Walloon context.

As illustrated by Figure A.1, Chapter III and Chapter IV first provide an overview of perceived and measured summer thermal conditions in low-energy dwellings, addressing Research Objectives 1 and 2 (RO1 and RO2). Chapter IV, by crossing these results, also includes a critical discussion on the ability of commonly used overheating evaluation criteria to predict occupant satisfaction regarding summer thermal comfort (RO3). Finally, Chapter V offers an overview of the possible evolution of summer thermal conditions induced by climate change (RO4).

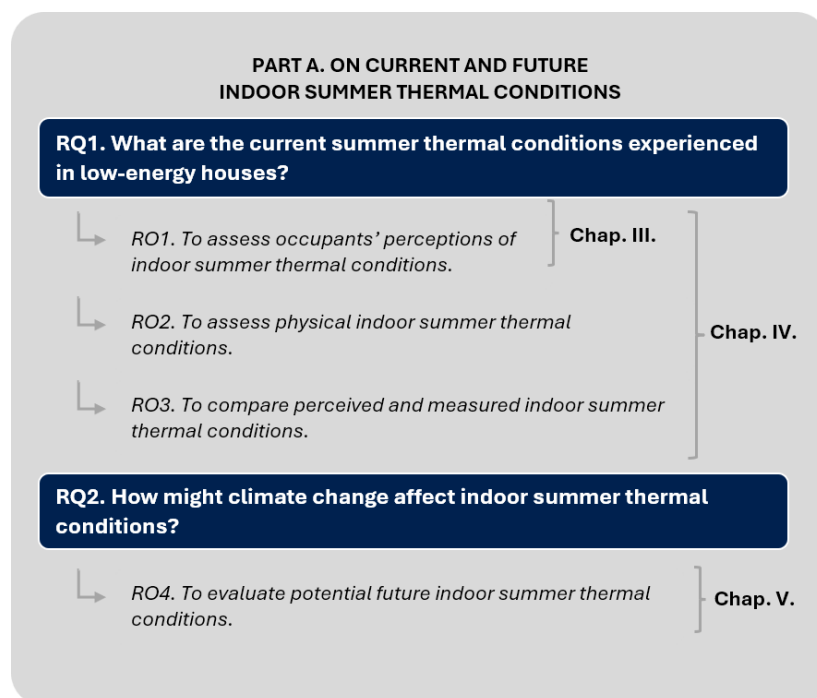


Figure A.1. Research sub-questions addressed in Part A. with their corresponding research objectives and chapters.

Chapter III. Occupants' satisfaction in high energy performance residential buildings

This chapter is based on the following publication:

Title: *Occupants' Satisfaction in High-Energy-Performance Residential Buildings.*

Conference: PLEA 2016 - Cities, Buildings, People: Towards Regenerative Environments: Proceedings of the 32nd International Conference on Passive and Low Energy Architecture.

Year: 2016.

Role of the thesis author: Lead author. Table III.1 further details the author's contributions to this publication.

Table III.1. Contributions of the thesis author to the paper constituting Chapter III, according to the CRediT taxonomy [213].

Contribution Type	Chapter III
Conceptualization	✓
Data curation	✓ ¹
Formal analysis	✓ ¹
Funding acquisition	✓ ²
Investigation	✓ ¹
Methodology	✓
Software	✓ ¹
Validation	✓
Visualization	✓
Writing – original draft	✓
Writing – review & editing	✓ ^{1,3}

1: In collaboration with Sophie Obyn (Research Assistant - UCLouvain).

2: In collaboration with Buildwise (formerly Belgian Building Research Institute).

3: In collaboration with Véronique Vanwelde (Research Engineer - Buildwise).

Citations: 5 citations according to Google Scholar (July 2026).

Reference:

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Occupants' Satisfaction in High Energy Performance Residential Buildings:

Results from the action Construire Avec l'Energie in Belgium.

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ABSTRACT: In Europe, energy requirements are even stronger leading the construction sector to design buildings whose energy consumption is continuously reduced. Mainly, the global challenge today is to identify lacks in construction processes and misuse or misunderstanding on the side of the occupants in order to improve the design of efficient and comfortable high energy performance buildings.

This paper presents the results of a large post occupancy evaluation (POE) by means of a survey questionnaire conducted on a sample of 458 Walloon high performances houses built within the frame of the action "Construire Avec l'Energie" (CALE). The results of the POE allow to qualify and discuss: the satisfaction regarding thermal and respiratory comfort; the occupants' behaviour and satisfaction in relation to the use of the building and its systems; the actual consumptions compared with the predicted ones.

Keywords: Post Occupancy Evaluation, comfort, energy consumption, dwellings.

INTRODUCTION

Since the implementation of the European Energy Performance of Buildings Directive (EPBD), energy requirements have been even stronger, pushing the construction sector to design buildings with continuously lower energy consumption.

In Belgium, a Western Europe country characterised by a cold temperate climate, high energy performance buildings are mainly characterised by reduced heating needs, a south orientation, a very high insulation level, an improved air tightness and a mechanical ventilation. Moreover, "Passive House Standard" buildings are becoming more frequent in Belgium. Indeed, if in Wallonia energy requirements for new dwellings tend to approach the passive standard (maximum U-value of $0.24 \text{ W}/(\text{m}^2\cdot\text{K})$ for roofs and walls – maximum primary energy consumption of $130 \text{ kWh}/\text{m}^2\cdot\text{year}$, etc. (Gouvernement-wallon, 2014)), in Brussels, the regulation for new buildings called Bruxelles passif 2015 (Bruxelles-passif!) is directly inspired by the passive standard (Building-Research-Establishment-Ltd., 2011; Feist, Schnieders, Dorer, & Haas, 2005; Passive-House-Institute, 2015).

Furthermore, in Belgium as in all European countries, regulations impose the use of specific calculation methods to theoretically describe the energy quality of the buildings from the design phase on. However, while studies in neighbouring countries (Gupta & Kapsali, 2014; Itard, Majcen, & Visscher, 2012) show that the expected performance may not be obtained, no large-scale experience feedbacks on the effectiveness of the performance and on the satisfaction of the occupants are available in the Walloon context. Many questions remain thus largely unanswered for the construction sector: *Are high energy-efficient dwellings always comfortable*

in our context? Do actual energy consumptions correspond to calculated consumptions?

Trying to answer these questions, this paper presents the results of a large post occupancy evaluation conducted on high energy performance residential buildings built in Wallonia and occupied for several years.

METHODOLOGY

The main goal of the conducted Post Occupancy Evaluation is to verify if the current construction techniques (insulation, air tightness, mechanical ventilation, etc.) used in the construction of high energy performance residential buildings in Wallonia (Belgium) satisfy the occupants regarding indoor comfort and building energy consumptions. To achieve that, an online survey questionnaire was sent to the occupants of a sample of 458 Walloon high performances houses (Belgium) built within the frame of the action "Construire Avec l'Energie" (CALE).

Initiated by Wallonia since February 2004, the CALE action sets a voluntary approach to build more efficient dwellings than is required by the regulations. Mainly, these requirements cover (with progressive steps):

- Maximum U- values [$\text{W}/\text{m}^2\text{K}$].
- Maximum mean U-Value [$\text{W}/\text{m}^2\text{K}$].
- Ventilation rates for each space [$\text{m}^3/\text{h}\cdot\text{m}^2$]
- Maximum Primary Energy Consumption [$\text{kWh}/\text{m}^2\cdot\text{an}$]
- Limited overheating risk [%]

(For details and description of the steady state calculation method see (Gouvernement-wallon, 2008)).

The CALE dwellings present the advantage for this study to have been occupied for several years, nullifying the enthusiastic effect of the first years of occupation (Mlecnik et al., 2012). Also, all the technical information about these buildings has been checked by experts after the construction and implemented in a specific database.

The setup of the questionnaire and a complete description of the measured notions are presented in *Measure: establishment of a questionnaire to evaluate occupants' satisfaction adapted to high energy performance residential buildings* (Dartevelle, Obyn, 2015). Mainly, in addition of information available from the database, the questionnaire was designed to qualify: the occupant's behaviour and satisfaction regarding comfort, the use of the building and its systems, and the parameters influencing the satisfaction (Figure 1).

A total of 149 responses have been received, representing a response rate of nearly 33%. Table 1 presents the main characteristics of the corresponding dwellings obtained from the CALE database. The presented Energy Performance values were calculated according the CALE software based on European standards (Langendries, Lethé, 2010) and are representative of the complete sample of CALE (458 buildings): similar mean value and distributions far almost all characteristics. Mainly,

we can noticed: a big part of detached houses (92.5%), an average heating surface area of 219m², an average U value of 0.32 W/(m².K), ranging from 0.12 to 0.48 W/(m².K), a mechanical ventilation with heat recovery installed in 95% of the cases; an average heating demand of 40 kWh/(m².year), ranging from 0 to 105 kWh/(m².year).

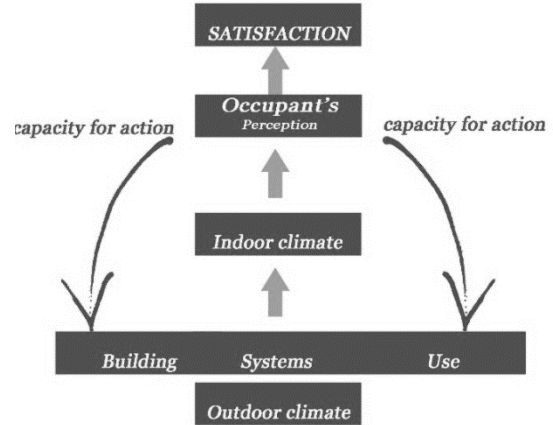


Figure 1: factor of influence of occupant's satisfaction

Table 1: main geometrical and technical characteristics of the 149 studied dwellings

		4	3	2
Number of facades	[% of cases]	92.5	1.3	6.2
Main Orientation	[% of cases]	South (from SE to SW) 59.9	E or W 26.5	North (from NE to NW) 13.6
Ventilation System	[% of cases]	Mech. Vent. with heat exchanger 95.6	Mech. Vent. exhaust air only 3.4	Nat. Vent. 1.0
Heating System	[% of cases]	Oil or Gas boiler 47.1 Elec. resistance on ventilation 1.3	Heat pump 28.1 Wood or pellet- boiler 6.1	Electric heater 2.0 None 15.4
Solar shading	[% of cases]	Int., Ext. or Both 51.5	None 48.5	
Thermal Mass	[% of cases]	Very Low 0.7	Low 25	Medium 52.1
Protected volume	[m ³]	Mean 677	Min 238	High 1672
Heating surface area	[m ²]	219	83	569
Compactness Ratio	[m]	1.38	0.98	2.71
Glazed Surf. /Heated Surf ratio	[%]	19.0	9.4	45.1
Main orientation Glazing Surface	[m ²]	24.8	8.1	96.1
Airtightness	[m ³ /(h.m ²)]	1.5	0.1	8.1
Mean Uvalue	[W/(m ² .K)]	0.32	0.12	0.48
Heating Demand	[kWh/m ²]	40.1	0	105
Overheating risk	[%]	33	0	100
Calculated primary energy Consumption for Heating, Cooling and DHW (incl. renewables).	[kWh/m ²]	96.2	-19.1	197.6

SURVEY RESULTS

The survey allows to first obtain more details about the profile and habits of the occupants, the building and the system and secondly to measure the occupants' satisfaction.

Occupants Profile

The survey shows that, on average, the respondents' households are composed of 3.5 people with children/students. Also, the sample is characterised by a quite high socioeconomic level of the occupants, generally well informed about the Energy Performance of Building issues (e.g. 99% of respondents own their dwellings, most adults (99%) are employed, 92-95% of people feel they understand or are familiar with the technical aspects of their home (heating, ventilation, insulation)).

In terms of **occupancy**, the majority of homes are occupied in the evening and on weekends (61%), while 33% of homes occupied continuously. The remaining 6% have intermediate or variable occupancy (part-time work). **Intermittence is common practice**: more than 50% practice intermittent heating. Of these, 62% do so at night and 53% if they are not present. 67% of respondents declare that they vary their level of air ventilation (mainly when using the kitchen or the bathroom or depending on weather conditions).

With regard to **opening windows**, while 90.6% state that they never open the living room windows during the winter, there is an reverse trend for the rest of the year with 71.2% of respondents opening the windows (during the day, night or both). The same trend can be seen in the bedroom with 72.3% never opening the windows in the wintertime and 74.8% opening them during the rest of the year. The main purpose of windows opening - is to cool down the premises, followed by opening to the outside, ensuring good air quality and to expel smells. Only 15.4% of respondents never open their windows.

Also, some respondents seem to have **adapted the way they dress** (mainly in winter) since living in their high energy performance house. They state that they usually dress less (or much less) warmly during the winter (in 56% of cases) and dress more (or much more) lightly the rest of the year (in 34% of cases).

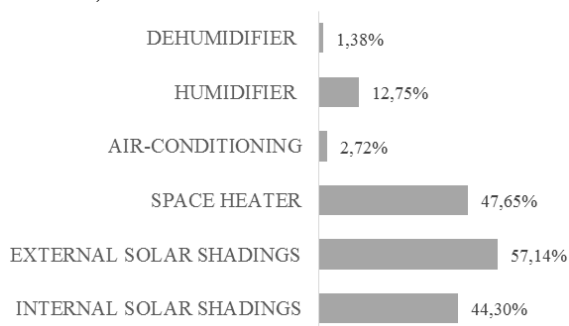


Figure 2: systems added after some times of occupation

Additional systems

Figure 2 presents the system that were finally added after some times of occupation. It shows that a **supplementary heating system** (space heater) has been added in 47% of the homes. They were originally planned in 17% of the cases, and were added to improve comfort in 30%.

Based on the open comments provided by respondents, there is often an electrical backup located in the bathroom. Moreover, it is likely that a number of cases planned, from the design stage, a central heating system only on the ground floor of the building.

Respondents state that **sunscreens** were directly installed for only 26% of cases. Ultimately, 77% of cases are fitted with sunscreens (external: 44%; internal 57%; both 25%). Counteracting sun heat is the main reason for adding a sunscreen (84%).

The installation of a **dehumidifier and air-conditioning** system is marginal (1 and 2% respectively). The installation of a **humidifier**, on the other hand, is more common (13% of cases).

Overall satisfaction

Figure 3 illustrates the overall satisfaction regarding the main notions measured in the survey.

Global satisfaction rates (from slightly to very satisfied) reach 98% for the dwellings, 96% for indoor air quality, 98% for thermal comfort. However, respondents' satisfaction in terms of systems is slightly lower (93% for heating and ventilation system, 91% for sunscreens). In terms of acoustics, the insulation between rooms (interior) has generated less satisfaction (82%) than the insulation from outside noise (95%). The daylight supply has gained 100% satisfaction. 89% are satisfied with the cost of construction/rental price, and 98% are satisfied with their energy consumption.

A large majority of respondents are also satisfied with their global control level over the indoor environments (air quality and temperatures).

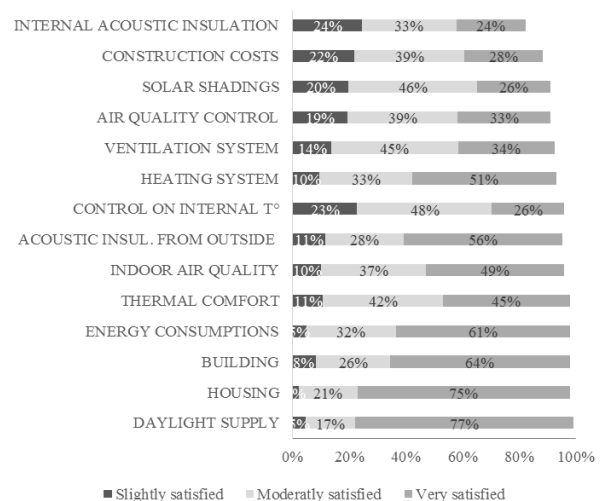


Figure 3: satisfaction rates regarding the main notions measured in the survey.

Satisfaction regarding thermal and respiratory environments

Figure 5 illustrates the frequency of encountered discomfort related to thermal and respiratory environments. It shows that discomforts associated with **overheating** is very common (73% of respondents state that they experience overheating problems). (Specific questions in the survey show that they are primarily related to the summer period in the living areas: bedroom (60%), living room (62%) and kitchen (51%).)

Excessive heat from sunlight is encountered in 65% of cases. Furthermore, 38% of cases state that **temperatures decrease too slowly** and that they **increase rapidly** in 25% of homes.

Problems of **discomfort in relation to cold floors** (19% of cases), **cold windows** (12% of cases) and **overly cold air ventilation** (23% of cases) are **present** albeit to a lesser extent. 17% of respondents mention airflow problems in the joinery (doors/windows) and 17% in grids and vents.

Dry air is mentioned in 32% of cases. Logically, these problems are related to dry living areas (bedroom and living room) and are more significant in wintertime. Conversely, very **few problems relate to air being too damp** have been found.

In terms of **air quality**, we can see that the most common problems encountered by respondents are the presence of large amounts of dust (32%), the presence of persistent odours (11%) and bad air quality (9%), mainly in the bedrooms and living room all year round, and in the kitchen during the summer.

Figure 4 presents the appreciation of the respondents regarding the usual temperature of several rooms. It shows that **in wintertime**, the problem of **(slightly) too cold temperatures** arises mainly in the **bathroom** (36%) and bedroom (20%). Winter temperatures are almost unanimously deemed to be pleasant in the living room and kitchen.

During the summer, respondents state that they feel **temperatures that are slightly high or too high** mostly in **living areas**: bedroom (63%), living room (54%) and kitchen (48%).

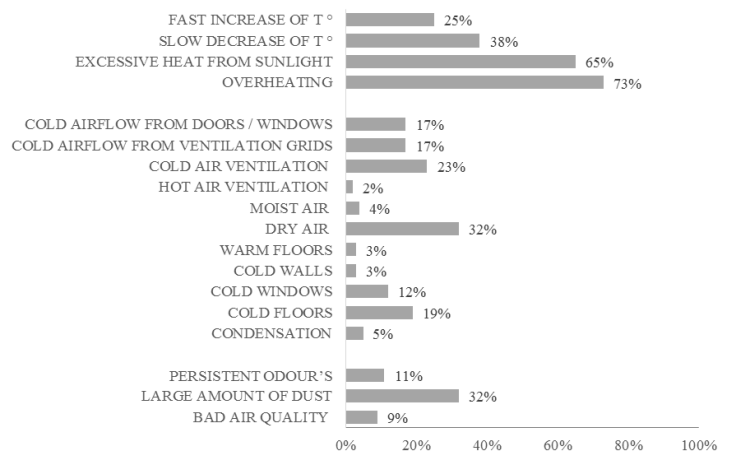


Figure 5: frequency of encountered discomforts.

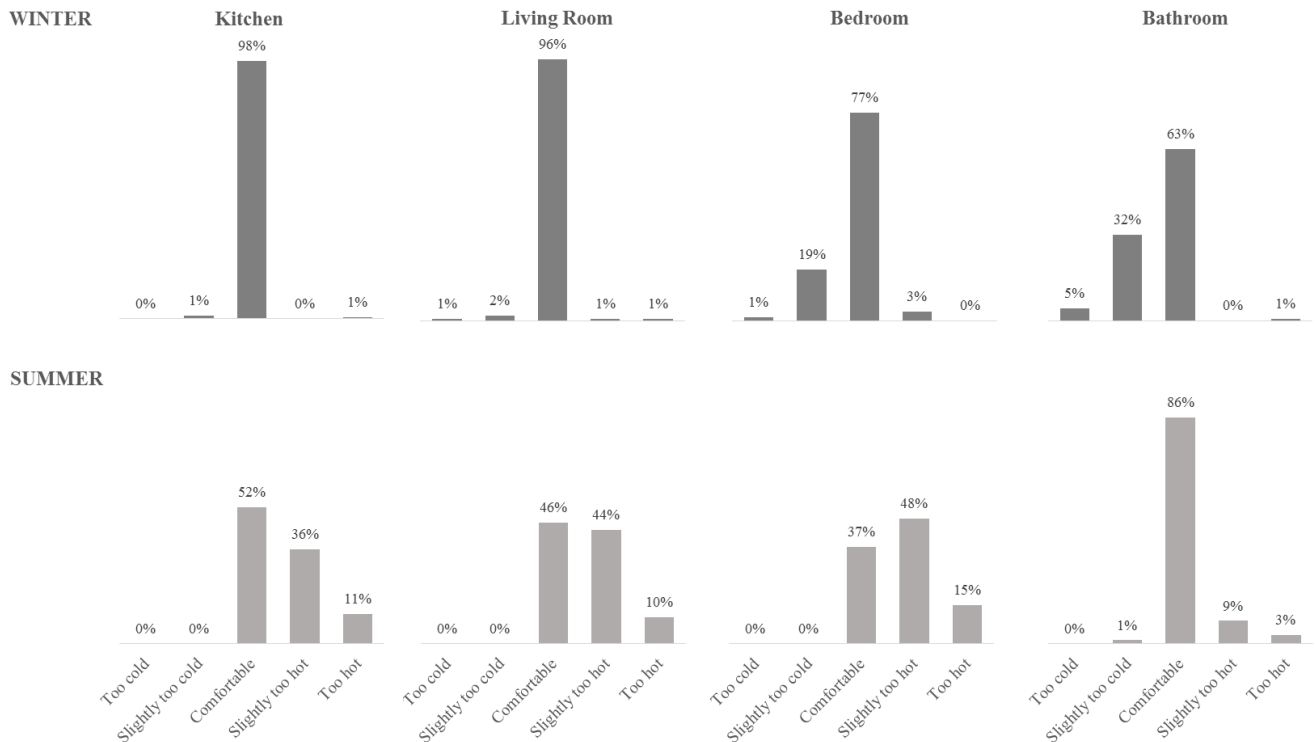


Figure 6: appreciation of the respondents regarding the seasonal usual temperature

Satisfaction regarding the systems

Overall, the **systems tend to be satisfactory for their users in terms of efficiency** (99% are globally satisfied with the efficiency of heating systems, 96% with ventilation and 100% with the automated sunscreens (present in 18% of the cases). However, they often require a **subsequent setup** (1 in 4 cases for ventilation and sunscreens and more than 1 in 3 cases for heating).

Figure 6 describes more in depth the reasons for dissatisfaction regarding the use of heating, ventilation and automated solar shadings systems.

In terms of **ease of understanding**, heating is what causes the most dissatisfaction (14% as opposed to 6% for ventilation and 0% for automated sunscreens).

The **available documents** also raise a certain degree of dissatisfaction among respondents: there is a dissatisfaction rate of 22% for heating systems, 19% for ventilation and 10% for sunscreens.

In relation to their **ability to make adjustments**, 17% of respondents are dissatisfied with the heating and also 17% with ventilation (none with sunscreens).

The **noise generated** by the ventilation system is a source of dissatisfaction for 17% of respondents, and is of 8% for the heating system.

The **frequency and duration of maintenance** seems to be satisfactory, albeit to a slightly smaller extent for the ventilation system (83% satisfaction for the ventilation system and 94% for the heating system).

Conversely, the **cost of maintaining** the ventilation system proves less satisfactory (63%) than for heating (80%).

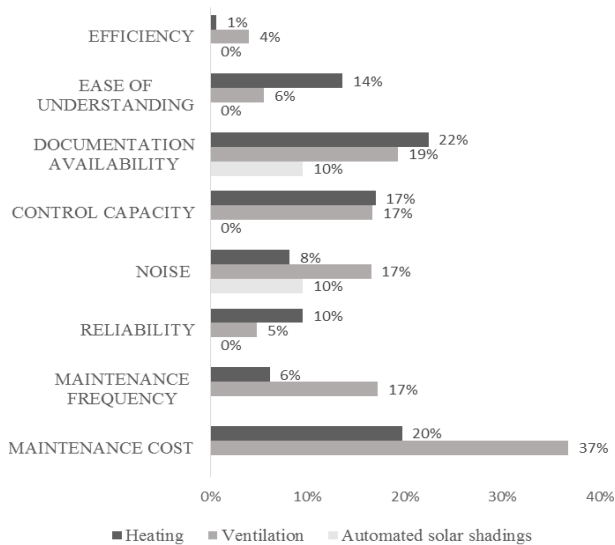


Figure 6: dissatisfaction rates regarding the use of the systems.

Actual consumption

Figure 7 presents the normalised actual energy consumption for heating reported by the respondents compared to the previsions.

Even if there is an important uncertainty regarding the reliability of these data, the calculated average consumption estimate seems correct (+3%) when compared with the actual figures provided by the occupants. However, a high degree of variance can be seen (from -73% to +185%).

On the other hand, the main value obtained regarding electricity consumption (2.580 kWh) seems to be higher than the national average (around 10% excluding heating (Consommation moyenne d'électricité en Belgique, 2015)), but the homes are also larger on average (210m² as opposed to 150m²).

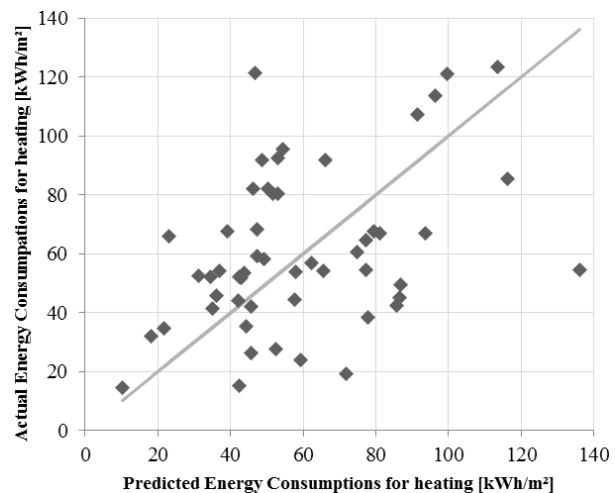


Figure 7: comparison of the normalised actual energy consumption for heating VS previsions.

CONCLUSIONS

The analysed houses seem to have gained high satisfaction among the occupants, with a certain degree of variability.

However, it appears that these **homes are more thermally comfortable during the winter than the summer**. Whilst the temperature in the living room and kitchen is found, almost across the board, to be pleasant in wintertime, supplementary heating seems necessary in almost half of cases (mainly in the bathroom and upstairs rooms). This shows the necessity to take into account at the design stage the specific heating needs of each space of the dwellings even if the insulation levels is very high.

Cold floors, cold windows and draft problems are present, albeit to a small extent (less than 1 in 5). However, the discomfort associated with ventilation air being too cold (1 in 4) and air dryness (1 in 3) is more common.

Furthermore, **management of overheating and, in particular, solar gains does not seem to have been resolved**. Few sunscreens were directly installed during construction but in most cases have proven to be a necessity. While few air-conditioning systems are present (2%), windows are opened by most occupants in summertime (7 out of 10 cases), mainly to cool down the premises. More generally, this shows the importance to properly consider the overheating risk at the conception stage and to install solar shadings in order to guarantee thermal summer comfort in such houses. It also suggests that the current standard method for the evaluation of overheating risk could be improvable.

The **general indoor air quality** is almost always perceived positively. We can see, however, that the most common problems encountered by respondents are the presence of large amounts of dust (1 in 3), the presence of persistent odours and the feeling of not having clean air (1 in 10), mainly in the bedrooms and living room.

Compared to their attitude in their former home, it seems that the occupants have **adapted their behaviour**, and focus on energy consumption (e.g. by lowering the set temperature), but not always in the appropriate way (wearing fewer clothes even in winter for example).

It is also worth noting that the **systems** are generally well-received by the occupants and that there is ultimately little difference between the heating and ventilation systems in terms of the available documentation and adjustability. In terms of ease of understanding, the heating is what causes the most dissatisfaction. Whereas, generated noise is still a relatively common problem (1 out of 6 cases) in the case of ventilation. In comparison with heating systems, the frequency, duration and cost of maintaining the ventilation systems are perceived less positively by occupants. The systems require a subsequent setup in about 1 in 4 cases (24%) for ventilation and sunscreens, and more than 1 in 3 cases for heating (35%).

The **temperature level and air quality control** prove widely satisfactory (more than 9 out of 10 occupants are satisfied). Intermittence is also common practice especially for ventilation (67% as opposed to 50% for heating). In this regard, the wide awareness of the majority of respondents, and their particularly sound technical knowledge should be recalled.

Moreover, average **heating energy consumption**, at this stage, seems to match expectations (although with a high degree of variance). Electricity consumption (excluding heating) proves higher than average (around 10%) but the homes are generally larger.

In addition to these findings, the survey results show a **high level of overall satisfaction** in terms of the housing, construction system, acoustic insulation (to a slightly lesser extent for insulation between

rooms), energy consumption and natural light (100% satisfied).

FUTURE WORKS

A statistical analysis (multiple factor analysis) will be conducted on these data in order to identify the potential impact of some parameters on satisfaction levels. In parallel, this qualitative analysis will be compared with quantitative data obtained from the complete monitoring of a representative sample of 25 selected dwellings. Finally, this analysis should contribute to identify possible lacks and necessary improvements of the current Belgian building energy regulations.

ACKNOWLEDGMENTS

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Chapter IV. Long-term evaluation of residential summer thermal comfort

This chapter is based on the following publication:

Title: *Long-term evaluation of residential summer thermal comfort: Measured vs. perceived thermal conditions in nZEB houses in Wallonia.*

Journal: Building and Environment.

Year: 2021.

Role of the thesis author: Lead author. Table IV.1 further details the author's contributions to this publication.

Table IV.1. Contributions of the thesis author to the paper constituting Chapter IV, according to the CRediT taxonomy [213].

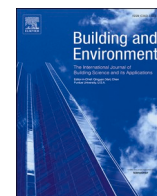
Contribution Type	Chapter IV
Conceptualization	✓
Data curation	✓
Formal analysis	✓
Investigation	✓
Methodology	✓ ¹
Software	✓
Validation	✓
Visualization	✓
Writing – original draft	✓
Writing – review & editing	✓ ¹

¹: In collaboration with Erwin Mlecnik (TU Delft), Geoffrey van Moeseke, Gabrielle Masy and Sergio Altomonte (UCLouvain).

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Long-term evaluation of residential summer thermal comfort: Measured vs. perceived thermal conditions in nZEB houses in Wallonia

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ABSTRACT

In a context of global warming, summer thermal comfort is a key issue for the design and operation of nearly zero-energy buildings (nZEBs). Although there are various methods and benchmarks for the long-term evaluation of summer thermal conditions in free-running buildings, their application to the residential sector is still debated. Based on data from post-occupancy measurements and survey campaigns, this paper evaluates the compliance with commonly used overheating criteria defined by existing standards (CIBSE and Passive House Institute) of 23 nZEB houses in Wallonia (Belgium). The quantitative relationship between measured and perceived comfort is statistically analysed, and building characteristics leading to the most critical overheating situations are qualitatively discussed. The results show that summer thermal discomfort is frequent in nZEB houses in Wallonia, despite its temperate climate. In living rooms, the long-term appraisal of thermal conditions appears to be related to the frequency of extreme temperatures, while occupants' thermal perception in bedrooms seems to be more affected by smaller temperature deviations. These results imply a critical review of the capacity of the criteria commonly used for the evaluation of overheating risks in free-running residential buildings to predict the satisfaction of occupants with their summer thermal comfort. More generally, the findings reinforce the importance of a better integration, even in temperate climates, of environmental controls – and their required operation by the occupants – to properly mitigate overheating risks in nZEB houses.

1. Introduction

Summer thermal comfort in buildings is today an emerging challenge also in countries characterised by temperate climates. Climate change, in fact, leads to warmer summers and more frequent heat waves [1], these having an increasingly more critical impact particularly in consideration of the higher sensitivity [2] of an ageing population [3]. Conversely, the evolution of building construction techniques (e.g., with higher thermal insulation, airtightness and enhancement of solar gains) driven by the evolution of energy performance standards [4–6] can also severely impinge on the summer thermal behaviour of buildings [7,8].

While in temperate countries such as the UK, the study of summer thermal indoor conditions in new buildings has acquired a consistent tradition [9–13], in Belgium – which shares a similar climate to the UK – and more particularly in Wallonia, this domain of research is still at its infancy. The MEASURE project [14], which conducted POE surveys in 149 Walloon residential energy efficient single-family houses, recently revealed a high frequency of complaints related to overheating

discomfort. Among other results, 73% of occupants ($n = 149$) reported perception of discomfort, mainly in living rooms and bedrooms [15].

In this context, the criteria for the assessment of summer thermal comfort in buildings that are not mechanically conditioned are particularly crucial. When used at the design stage for the analysis of whole building energy simulation, they can provide guidelines for the optimization of strategies to mitigate overheating risks [16]. Conversely, when used for the analysis of monitoring data, they can offer benchmarks for the verification and comparison of indoor conditions [9]. The criteria recommended by CIBSE (Chartered Institution of Building Services Engineers) [17] and PHI (Passive House Institute) [18] are among the most commonly used for the study of summer thermal comfort in free-running residential buildings in temperate climates [10,11]. Nevertheless, their capacity to predict the satisfaction of occupants with their summer thermal comfort [19], the applicability of adaptive principles in residential buildings (especially in bedrooms [4]), the limits of this adaptivity [5] and the consequences of the criteria formulation [1], are still debated.

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Building on the granular data collected in 23 single-family nZEB houses in Wallonia, this paper offers an overview of measured and perceived summer thermal conditions. This analysis provides robust evidence of the extent of overheating situations that can be encountered in these buildings in a temperate climate. Then, the relationship between perceived and measured summer thermal comfort, described through common criteria for overheating assessment, is statistically analysed. This evaluation is carried out distinctly in living rooms and in bedrooms so that differences and specific trends can be identified and discussed. On these bases, the paper presents a critical evaluation of the capacity of common overheating criteria to predict the satisfaction of occupants in a residential context. Finally, the factors and building characteristics that lead to the worst encountered overheating situations are discussed.

2. Method

Building characteristics and methods for data collection and analysis are illustrated in detail in the following paragraphs.

2.1. Buildings' sample

Twenty-three (23) nZEB houses were analysed for the purpose of this study. The majority of these dwellings were detached single-family houses (20 out of 23 cases). In Belgium, single-family houses represent the 79.7% of the housing stock [20], of which 30% are detached houses [21]. The houses included in our sample were all situated in the Cfb climatic zone (temperate oceanic climate) of Wallonia (southern part of Belgium, corresponding to a latitude of around 50° North) according to the Köppen-Geiger climate classification system [22]. They were all located in rural to semi-rural environments on relatively unobstructed sites, with little or no surrounding environmental shading.

These houses had been occupied for a minimum of 3 years before the beginning of this study. This selection criterion was established to avoid the potential bias that can appear during the first years of occupation of a building [23]. Dwellings were mostly occupied by families with children. The number of children is presented in Table 1 based on their age category. Houses 4 and 17 were occupied by recently-retired couples. All houses were owner-occupied. The study was submitted for approval to the Belgian Data Protection Authority. In this context, an informed consent form was obtained from all participants.

Requirements for nZEB houses in Wallonia rely on the definition provided in the European Directive 2010/31/EU on the energy performance of buildings [4], which primarily focuses on reducing heating demands. The volumetric and thermal characteristics of the envelope of the buildings analysed are described in Table 1. Heated floor areas, mean U-values, airtightness, yearly heating needs, and SHGC (Solar Heat Gain Coefficient) of windows were taken from the requirements of the Belgian EPBD (Energy Performance of Buildings Directive) calculation [24] (further description of the buildings' characteristics can be found in Ref. [25]).

All houses were equipped with a heating system (of variable type) and were mechanically ventilated (with a summer bypass in the presence of a heat recovery system). None of the ventilation systems was found to be sized to allow effective purge ventilation in summer (that is, maximum air change per hour was less than 1 per hour).

Internal sources of heat gains have not been detailed, but no extreme case was encountered (e.g., high internal gains due to specific appliances or large indoor hot water storage). Also, no mechanical cooling system or fixed ceiling fan was detected in any of the houses.

The size of the sample was defined by the practical need to offer an in-depth and accurate knowledge of the case studies. The relatively limited number of nZEB houses included in the analysis was, in fact, chosen to allow direct on-site measurements and verifications of key buildings' characteristics (e.g., orientation, house and construction type, solar shading, location of the bedroom, airtightness of the thermal

envelope, ventilation rates, etc.) as well as to enable focused discussions with the occupants about, among other aspects, their habits and behaviours (e.g., presence during the day, windows opening). These data are reported in Table 1.

2.2. Measurements

Air temperatures were recorded every 10 min in the living rooms and in the main bedrooms of each house during an entire year (2016), resulting in approximately 52,560 data points for each room. Following recommendations from the literature [10], sensors were placed by the research team on top of existing furniture at a minimal height of 80 cm, away from windows (to avoid direct solar radiation) and from any other internal heat sources. Data were recorded using a dedicated wireless/4G router. The Belgian Building Research Institute (BBRI) conducted preliminary calibration tests of the measuring devices before the measurement campaign and verified compliance with the maximum errors declared by the manufacturer. These tests confirmed a maximum error of ± 0.3 °C after calibration.

Outdoor temperatures were monitored for each dwelling to calculate a local running mean temperature θ_{rm} . This calculation was done according to the EN15251 standard [28] using the following equation based on the daily mean external temperature θ_{ed-i} of the previous days (31 previous days were used with a constant α of 0.8):

$$\theta_{rm} = (1 - \alpha) \cdot (\theta_{ed-1} + \alpha \cdot \theta_{ed-2} + \alpha^2 \cdot \theta_{ed-3} + \dots) \quad (1)$$

As reported by the Royal Meteorological Institute of Belgium [29], the weather data over the measurement period (calendar year 2016) can be considered broadly in line with the average of the last 30 years, both in terms of temperatures and solar radiation. The average temperatures for most months of the year, particularly during the meteorological summer period, are generally consistent with seasonal norms, although a remarkably hot month of September was recorded (Fig. 1). Over the year, 97 days recorded maximum temperatures higher than 20 °C, 25 days exceeded 25 °C, and 6 days exceeded 30 °C.

2.3. Criteria for overheating assessment

Two groups of long-term summer comfort criteria exist according to the type of threshold not to be exceeded: *static* (based on a fixed temperature) and *adaptive* criteria. The latter are based on a comfort temperature evolving in function of the history of outdoor temperatures in accordance with the theory of adaptive comfort [30]. Various limits, accepted frequencies, and periods of calculation can be found in the literature (see for example the work of [31]), discussing the different overheating criteria and the strengths or weaknesses of their formulation (discontinuity, etc.).

Among the criteria based on a static temperature limit, the Belgian Passive House Platform (PHP) recommends not to exceed 5% of the time of occupancy above 25 °C [32], while the Passive House Institute (PHI) brings this threshold to 10% of occupancy time [33]. The Chartered Institution of Building Services Engineers (CIBSE) in UK, in a previous version of its environmental Guide A [34], suggested the use of maximum 1% of the time above 28 °C for living rooms and 26 °C in bedrooms. These criteria, which needed to be evaluated over the period of a year, were mainly conceived to inform the design phase of a building. It should also be noticed that the assessment of the Passive House criteria is based on a single thermal zone modelling of the building, using the Passive House Planning Package (PHPP) [35]. Nevertheless, these criteria are also often used for the analysis of measured temperatures, since they are simple to apply and allow easy comparisons between different cases and studies [8–10,13,26,27]. These criteria rely on a static characterisation of thermal comfort based on thermal neutrality [36]. The accuracy of such model in real buildings is, however, largely questioned [37].

Table 1
Main characteristics of the buildings analysed.

ID	House type*	Construction Type*	Number of occupants**	Presence during working hours**	Heated floor area***	Window-to-floor surface ratio***	Mean U-value (windows included)***	Air change rate at 50 Pa (n ₅₀)*	Main window SHGC***	Heating needs***	Living room			Bedroom			
											Main windows orientation*	Solar shading Type*	Windows opening **	Main windows orientation*	Under roof location*	Solar shading type*	Windows opening **
—	[—]	[—]	[—]	[—]	[—]	[%]	[W/m².K]	[1/h]	[—]	[kWh/m².y]	[—]	[—]	[—]	[—]	[—]	[—]	[—]
1	Attached	Masonry	5 < 12 y/o: 3	No	330.0	15.2	0.24	1.25	0.51	14.8	W	In	Day and Night	W	No	No	Day and Night
2	Semi-attached	Masonry	4 < 12 y/o: 2	Yes	119.7	13.2	0.15	0.82	0.54	8.8	S	In	Never	S	No	In	Day and Night
3	Semi-attached	Masonry	3 < 12 y/o: 1	No	151.7	19.0	0.15	0.68	0.54	5.0	S	In	Never	S	No	No	Day
4	Detached	Masonry	2 (>65 y/o)	Yes	275.3	12.1	0.35	3.50	0.63	29.4	NE	Out	Day and Night	SW	No	In	Day
5	Detached	Masonry	3 < 12 y/o: 2	No	364.7	16.3	0.32	6.03	0.62	18.6	S	Out	Never	E	No	In	Never
6	Detached	Wooden Frame	5 < 12 y/o: 3	Yes	212.6	22.6	0.43	5.24	0.64	26.9	SE	In	Day and Night	SW	No	No	Day and Night
7	Detached	Masonry	4 < 24 y/o: 2	No	201.1	24.0	0.19	0.74	0.5	7.6	SW	No	Day and Night	SW	Yes	No	Day
8	Detached	Wooden Frame	3 < 12 y/o: 1	No	186.5	26.0	0.25	1.77	0.49	14.3	SW	Out	Never	SW	Yes	In	Never
9	Detached	Masonry	4 < 24 y/o: 2	No	156.6	20.9	0.28	0.70	0.45	14.0	SE	No	Never	SW	Yes	No	Day
10	Detached	Masonry	2	Yes	149.8	19.1	0.43	2.91	0.63	31.0	SE	In	Day and Night	W	Yes	No	Day and Night
11	Detached	Masonry	4 < 12 y/o: 2	No	198.4	19.9	0.32	1.40	0.63	16.7	W	No	Never	W	No	Out	Day
12	Detached	Masonry	4 < 12 y/o: 2	No	196.4	15.0	0.47	4.21	0.65	29.5	E	No	Day and Night	SW	Yes	No	Day and Night
13	Detached	Masonry	6 < 24 y/o: 4	No	216.8	27.0	0.15	0.54	0.51	3.6	SW	Out	Day and Night	SW	No	Out	Day and Night
14	Detached	Wooden Frame	4 < 12 y/o: 2	No	194.2	28.0	0.42	2.18	0.56	26.0	NE	Out	Day and Night	NE	No	No	Never
15	Detached	Masonry	2	No	160.7	18.0	0.37	2.32	0.63	19.8	NW	In	Day and Night	NW	Yes	In	Day and Night
16	Detached	Masonry	5 < 12 y/o: 3	Yes	233.8	19.9	0.31	1.01	0.63	17.8	E	In	Never	E	No	In	Never
17	Detached	Wooden Frame	2 (>65 y/o)	Yes	203.0	18.7	0.35	3.80	0.65	20.3	S	In	Day and Night	W	Yes	In	Day and Night

(continued on next page)

Table 1 (continued)

ID	House type*	Construction Type*	Number of occupants**	Presence during working hours**	Heated floor area***	Window-to-floor surface ratio***	Mean U-value (windows included)***	Air change rate at 50 Pa (n ₅₀)*	Main window SHGC***	Heating needs*** [kWh/m ² .y]	Living room		Bedroom		Windows opening**	Under roof location*	Solar shading type*	Windows opening**
											Main windows orientation*	Solar shading Type*	Main windows orientation*	Solar shading type*				
18	Detached	Masonry	5 <12 y/o;	No	239.5	14.3	0.39	7.88	0.63	30.1	S	In	Never	SW	Yes	In	Never	
19	Detached	Masonry	4 <12 y/o;	No	265.3	18.2	0.16	0.82	0.52	6.1	E	In	Never	E	No	No	Day and Night	
20	Detached	Masonry	1 <12 y/o;	No	190.6	31.7	0.40	2.24	0.5	19.4	N	No	Never	NW	Yes	In	Day	
21	Detached	Masonry	3 <12 y/o;	Yes	467.8	13.3	0.35	4.76	0.6	20.8	SW	In	Day	W	No	In	Day	
22	Detached	Wooden Frame	1 <12 y/o;	No	160.0	15.6	0.28	2.34	0.65	14.5	S	In	Never	S	No	No	Never	
23	Detached	Wooden Frame	4 <12 y/o;	No	186.59	24.7	0.40	3.69	0.63	23.8	SW	In	Day	NW	Yes	Out	Day	

Source of data: * On-site verification/measurements; ** Questionnaire-based interviews; *** Belgian EPBD calculation.

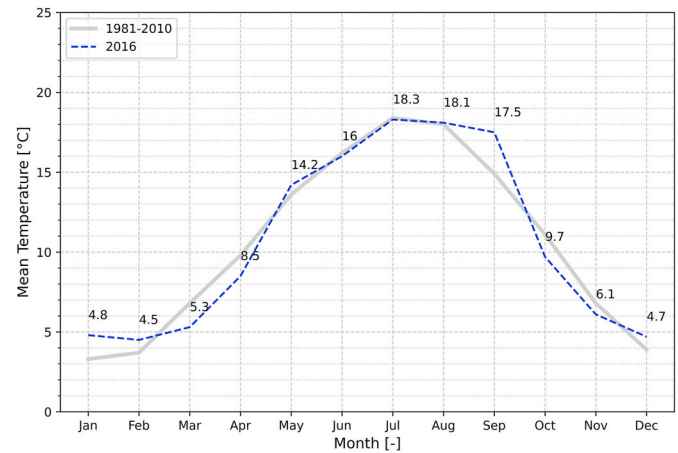


Fig. 1. Comparison of monthly mean temperatures of 2016 with the climate normal (1981–2010).

It has for long been recognized in the scientific literature that the adaptive capacity of occupants (afforded by physiological, psychological, and behavioural factors) can allow a wider thermal tolerance in free running buildings [38]. In this case, comfort temperature can be defined in function of a running mean temperature, which is linked to the evolution of daily outdoor temperatures. The adaptive thermal comfort model is embedded in standards such as the EN15251 in Europe [30]. This standard [28] defines different comfort categories corresponding to a percentage of dissatisfied people as a function of the difference between operative and comfort temperatures. This allows calculating the time of occupancy spent in each comfort category at design stage by simulation or by the analysis of data collected in existing buildings.

Although defined primarily for office buildings, adaptive capacities – for example, linked to the possibility of opening windows or adjusting solar protection devices – also exist in other building types where the adaptive thermal comfort approach can be applied [17,39]. Despite some limiting factors depending on the surrounding environment (e.g., presence of noise, safety, pollution, etc.) or to the mobility of the occupants, studies have postulated that single-family dwellings might effectively entail more adaptive opportunities than offices [40,41].

In the most recent 8th edition of environmental Guide A [42], CIBSE introduced the use of the adaptive comfort categories defined by EN15251 for the quantification of the risk of overheating. This document refers to the Technical Memoranda TM52 [17] presenting three criteria founded upon *hours of exceedance* (T_{max+1}), a *daily weighted exceedance* (W_e), and an *upper limit temperature* (T_{upp}). These criteria are based on the frequency, duration, and intensity of the deviations from the EN15251 comfort categories and, more generally, take consideration of the upper limit of the comfort Category II, which is recommended for new buildings and major refurbishments in absence of particularly sensitive and fragile persons [43]. In residential buildings, as specified in its Technical Memoranda TM59 [44], CIBSE only imposes compliance with the first criterion, *hours of exceedance*, for living rooms, kitchens and bedrooms, although at least two criteria must be met for other types of buildings [17].

Some authors have argued, however, that the adaptive capacity is limited during the night [45] and that the quality of sleep decreases at temperatures above 24° Celsius [46]. For this reason, CIBSE adds, for the bedroom, a criterion based on an absolute threshold of 26 °C [34,44]. The general CIBSE approach is widely used for overheating analysis both in cases of monitoring studies and simulations [11,47–51].

In our study, static and adaptive *hours of exceedance*, as well as the number of *daily weighted exceedance* and *upper limit temperature* criteria, have been analysed for both living rooms and bedrooms. Table 2 presents a summary of the discussed criteria and clarifies their application.

These criteria are generally based on the evaluation of the operative

Table 2
Common overheating criteria for non-air-conditioned residential buildings.

Type	Thresholds	Overheating criterion	Source
Hours of exceedance	25 °C	10% of annual occupied hours over temperature of 25 °C	PHI
Hours of exceedance	28 °C living areas 26 °C bedrooms	5% of annual occupied hours over temperature of 25 °C 1% of annual occupied hours over operative temperature of 28 °C (living areas) or 26 °C (bedrooms)	PHP Guide A, CIBSE 2006 TM59, CIBSE 2017 (bedrooms only)
Hours of exceedance	$(T_{op} - T_{max})^a > 1K$ $T_{op} - (EN15251 \text{ Cat. II upper limit}^b) > 1K$ $T_{op} - (0.33 T_{rm} + 21.8 \text{ °C}) > 1K$	3% of occupied hours during the non-heating period (May to September included) when T_{op} exceeds EN15251 Cat. II upper limit by 1K ^b	TM52, CIBSE 2013 Guide A, CIBSE 2015 TM59, CIBSE 2017
Daily weighted exceedance	$We = \sum (he) \times WF \text{ with } WF = \min(0; \frac{T_{op} - T_{max}}{T_{upp} - T_{max}})$ and he : corresponding time [h]	Max 6 in any one day during occupied hours ^c	TM52, CIBSE 2013
Upper limit temperature	$T_{upp} = T_{max} + 4K$	Absolute maximum value during occupied hours ^c	TM52, CIBSE 2013

^a Rounded to the nearest unit.

^b For spaces that are occupied by very sensitive and fragile persons upper limit of Category I is recommended.

^c May fail to be met in dwellings (TM59, CIBSE 2017).

temperature (T_{op}), which can be seen as the manifestation of the combined effect of mean radiant temperature and air temperature in a space [42]. As in many other studies [10–13,26,27,49,52], since only air temperatures could be consistently measured in our POE campaign, these data were used for comparison with the different thresholds described in Table 2.

Although this might represent a limitation, similar to other studies [27,49], it was assumed that, in highly insulated nZEB houses, the temperature of the walls can be very close to the air temperature, even if some local discomfort caused by radiative exchanges (due, for example, to high solar exposition of glazing) could also influence instantaneous thermal sensation. Air velocity was also not recorded and, therefore, it was not considered in the analysis, although this is also a parameter that could affect the reported thermal sensation. Other important factors that could influence thermal perception, such as activities and clothing levels, were discussed with the occupants and were found to be in accordance with the conditions for application of the overheating criteria (that is, sedentary activities and possibility to freely adapt the clothing to the thermal environment) [28].

According to their definition, the criteria need to be evaluated when occupants are present. Known periods of prolonged absence (e.g., vacations) were, thus, removed from the data in order to limit the bias that could be induced by periods of uncontrolled and non-evaluated thermal conditions (see section 2.4).

Room occupancy was found to considerably vary across days and houses. As a consequence, similar to many other studies [10,26,27], based on the discussions with the households and due to the absence of continuous high resolution spatio-temporal models of occupants' localisations, realistic occupancy assumptions had to be made. A general occupancy between 7am and 10pm in the living rooms, and between 10pm and 7am in the bedrooms, was assumed for the 7 cases that were occupied during working hours (cf. Table 1). Conversely, for the 16 houses that were not occupied during the day, occupancy of the living room was limited to 7am–9am and 5pm–10pm on business days. The implications of these assumptions might depend on the type (e.g., percentage based, maximum temperature, daily weighted exceedance) and the evaluation period for each criterion (year/summer) and they cannot be easily quantified with certainty. It would be interesting to conduct sensitivity analyses on real cases to weigh these implications, but these are beyond the scope of this study.

2.4. Questionnaire-based semi-structured interviews

Face-to-face semi-structured interviews were conducted on the basis of a questionnaire that had been previously sent to all the occupants. All interviews were conducted by the same researcher who personally

reported the results directly on-site. The questionnaire, focusing on the general perception of indoor environmental quality, was conceived to capture both the satisfaction of the occupants and the main parameters that could influence their evaluations (e.g., socio-economic profiles, habits, etc.). It was developed in French in the context of a Post Occupancy Evaluation (POE) project funded by the Walloon region in Belgium [14].

At the end of the summer period, and without knowing the results of the measurement campaign, occupants were requested to provide a general evaluation of the indoor thermal conditions they had experienced. This intended to offer a retrospective appraisal of the thermal conditions over the entire summer season, and not an instantaneous thermal sensation vote, as it is commonly captured using the ASHRAE thermal sensation scale [53]. A single concerted vote per household, representing the perception of the whole family, for each room was requested in response to the question: *How do you evaluate thermal comfort during last summer in the living room and in the main bedroom?* The evaluation was reported on a 5-point scale, presented in Fig. 2, which was designed on the basis of the Bedford comfort scale [54]. The implementation of this scale was decided following preliminary focus group tests with building occupants. Compared to the original Bedford scale, the “comfortably warm” and “comfortably cool” votes were grouped within a single “comfortable” vote, for this to be more easily understood by the respondents and to allow focusing specifically on their (eventual) reported degrees of discomfort. The main implication of using this scale consisted in the need to adopt statistical tests suitable for the analysis of ordinal data (see 2.5).

Since people seldom report the same thermal experience, and considering that inter (and intra)-individual differences of perception would require a much larger sample to be quantified, these methodological choices (single family vote and votes ($n = 23$) reported on a scale with a limited number of points) were made to limit the influence of extreme individual evaluations. Habits and behavioural actions taken by the occupants that can influence thermal conditions were also discussed during the questionnaire-based interviews. In this context, the presence of solar shading was verified in each room, while presence during the day and general adaptive responses were recorded (*“Do you open windows to cool down the living room/bedroom? If yes, when? (day and/or night)”*). This information is reported in Table 1.

2.5. Statistical analysis

Statistical tests were applied to analyse the relations between the data gathered. As the data resulting from the application of overheating criteria to the measurements had distributions that were significantly different from normal (p -value of Kolmogorov-Smirnov test < 0.001

Too cold	Slightly too cold	Comfortable	Slightly too hot	Too hot
□	□	□	□	□

Fig. 2. Scale used for indoor thermal conditions appraisal (administered in its French translation).

[55]), non-parametric statistical tests were used, based on ranked values. Due to the limited size of the sample, and therefore the risk that an effect could not be detected when it actually exists (Type II error), the analysis of data calculated, for each test, both the statistical significance (p -value at the alpha level of 0.05) and the effect size of the differences detected. Without being subjected to some of the limitations of null hypothesis significance testing (NHST), the effect size offers a standardised method to estimate the magnitude and the substantive relevance of the differences or deviations between groups of data [56].

The relationships between the frequency of temperature deviations in bedrooms and in living rooms were analysed using the Spearman Rho test [57]. The test calculates the correlation between two quantitative data and the probability that the same correlation can occur between the two if the relation does not exist in the population. In this case, the Rho value of the test was used for an estimation of the effect size of the influence detected.

The relationships between occupants' thermal appraisal and compliance of the building with the overheating criteria were analysed through the Jonckheere-Terpstra test [58,59]. This test evaluates the probability that the (ascending or descending) trend of the median

values of the overheating criteria through the ordinal groups of thermal conditions appraisal (vote of the occupant on the scale mentioned in section 2.4) could have occurred by chance. Inferences from the data were based on statistical and practical significance of the influences detected, and were derived from the estimation of the Pearson's r effects size [60].

For both the Spearman Rho and the Pearson's r effect sizes, the benchmarks proposed by Cohen [61] were used in this study: ≥ 0.1 = small effect, ≥ 0.3 = medium effect; ≥ 0.5 = large effect.

3. Results and discussion

3.1. Compliance with overheating criteria

Table 3 and Table 4 show, respectively, for the living rooms and the bedrooms, the results concerning the fulfilment of the criteria presented in Table 2 for the 23 houses. The time exceeding comfort Category II of the EN15251 is also presented.

It is worth noting a relatively high base temperature in these buildings: mean of 8.9% (median, mdn: 6.4%; standard deviation, sd: 8.1%)

Table 3

Appraisal of indoor thermal conditions and compliance with overheating criteria in the living rooms (7am–10pm or 7am–9am and 5pm–10pm on business days).

ID	Occupants' thermal appraisal	PHI	CIBSE 2006	EN15251	CIBSE TM52 2013		
		% of time >25°C	% of time >28°C	% of time>Cat. II	% of time>Cat. III (>Tmax +1K)	Number of daily weighted exceedance We	Number of Tupp exceedance
		Period: year	Period: year	Period: May to September	Period: May to September	Period: May to September	Period: May to September
[–]	[–]	[%]	[%]	[%]	[%]	[–]	[–]
8	Comfortable	6.3	0.0	0.2	0.0	0	0
13	Comfortable	7.8	0.4	0.8	0.0	0	0
14	Comfortable	8.7	0.4	1.1	0.1	0	0
15	Comfortable	15.3	0.2	1.4	0.1	0	0
16	Comfortable	0.9	0.0	0.0	0.0	0	0
20	Comfortable	6.6	0.5	0.8	0.0	0	0
22	Comfortable	3.6	0.4	0.9	0.3	1	0
1	Slightly too hot	5.0	0.3	2.2	1.1	2	1
2	Slightly too hot	3.4	0.0	0.0	0.0	0	0
3	Slightly too hot	24.4	0.0	0.5	0.0	0	0
4	Slightly too hot	3.6	0.8	0.8	0.1	0	0
5	Slightly too hot	12.0	0.5	0.1	0.0	0	0
10	Slightly too hot	3.9	0.0	0.0	0.0	0	0
11	Slightly too hot	6.0	0.1	0.1	0.0	0	0
12	Slightly too hot	4.2	0.4	0.1	0.0	0	0
17	Slightly too hot	1.5	0.0	0.2	0.0	0	0
18	Slightly too hot	3.8	0.8	1.0	0.1	0	0
19	Slightly too hot	4.3	0.0	0.0	0.0	0	0
21	Slightly too hot	11.1	0.3	0.2	0.0	0	0
6	Too hot	8.1	1.0	2.3	0.5	0	0
7	Too hot	33.9	6.0	15.7	7.7	20	5
9	Too hot	7.5	0.5	0.1	0.0	0	0
23	Too hot	22.3	7.2	20.9	14.4	40	68
<i>Mean</i>		8.9	0.9	2.1	1.1	2.7	3.2
<i>Mdn</i>		6.4	0.4	0.4	0.0	0.0	0.0
<i>Sd</i>		8.1	1.8	5.2	3.3	9.1	14.2
<i>Min</i>		0.9	0.0	0.0	0.0	0	0
<i>Max</i>		33.9	7.2	20.9	14.4	40	68
<i>Jonckheere–Terpstra test:</i>							
<i>p-value</i>		n.s.	n.s.	n.s.	n.s.	n.s.	<0.05*
Pearson's r effect size		0.23	0.39	0.08	0.24	0.28	0.45

*** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$, n.s. = not significant ($p \geq 0.05$); $r < 0.10$ = negligible; $0.10 = r < 0.30$ = small; $0.30 = r < 0.50$ = moderate; $r \geq 0.50$ = large. Data reported in bold italic correspond to failed criteria.

Table 4

Appraisal of indoor thermal conditions and compliance with overheating criteria in the main bedrooms (10pm–7am).

ID	Occupants' thermal appraisal	PHI	CIBSE 2006, 2017	EN15251	CIBSE TM52 2013	Number of daily weighted exceedance <i>We</i>	Number of <i>Tupp</i> exceedance
		% of time >25 °C	% of time >26 °C	% of time >Cat. II	% of time >Cat. III (> <i>Tmax</i> +1K)		
		Period: year	Period: year	Period: May to September	Period: May to September	Period: May to September	Period: May to September
[–]	[–]	[%]	[%]	[%]	[%]	[–]	[–]
5	Comfortable	2.2	0.0	0.1	0.0	0	0
15	Comfortable	9.0	3.1	0.8	0.1	0	0
1	Slightly too hot	1.7	1.1	0.0	0.0	0	0
2	Slightly too hot	0.7	0.0	0.0	0.0	0	0
4	Slightly too hot	2.4	0.8	0.0	0.0	0	0
8	Slightly too hot	10.3	5.2	1.2	0.3	0	0
11	Slightly too hot	6.4	2.3	0.0	0.0	0	0
12	Slightly too hot	4.4	2.5	0.0	0.0	0	0
14	Slightly too hot	5.4	2.6	0.0	0.0	0	0
16	Slightly too hot	1.6	0.5	0.0	0.0	0	0
17	Slightly too hot	2.0	0.6	0.3	0.0	0	0
19	Slightly too hot	8.7	1.6	0.0	0.0	0	0
21	Slightly too hot	4.5	1.9	0.0	0.0	0	0
22	Slightly too hot	12.2	4.1	0.3	0.0	0	0
23	Slightly too hot	18.5	12.1	7.6	1.2	4	0
3	Too hot	31.7	20.5	17.5	1.5	7	0
6	Too hot	6.4	2.7	0.1	0.0	0	0
7	Too hot	23.1	15.0	7.3	2.9	6	0
9	Too hot	7.8	4.4	1.3	0.3	0	0
10	Too hot	5.2	2.3	0.0	0.0	0	0
13	Too hot	7.1	3.0	0.7	0.0	0	0
18	Too hot	9.1	5.1	2.9	0.1	1	0
20	Too hot	3.9	1.1	0.1	0.0	0	0
<i>Mean</i>		8.0	4.0	1.7	0.3	0.8	0
<i>Mdn</i>		6.4	2.6	0.1	0.0	0.0	0.0
<i>Sd</i>		7.5	5.1	4.0	0.7	2.0	0
<i>Min</i>		0.7	0.0	0.0	0.0	0	0
<i>Max</i>		31.7	20.5	17.5	2.9	7	0
<i>Jonckheere–Terpstra test</i>							
<i>p-value</i>		n.s.	<0.05*	n.s.	n.s.	n.s.	–
Pearson's <i>r</i> effect size		0.31	0.43	0.35	0.26	0.38	–

*** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$, n.s. = not significant ($p \geq 0.05$); $r < 0.10$ = negligible; $0.10 = r < 0.30$ = small; $0.30 = r < 0.50$ = moderate; $r \geq 0.50$ = large. Data reported in bold italic correspond to failed criteria.

of the time of occupancy above 25 °C in the living room and a mean of 8% of occupancy time (mdn: 6.4%; sd: 7.5%) in bedrooms. The criteria based on static lower temperatures appear, therefore, more demanding to achieve. Eighteen (18) cases do not meet the criterion of less than 5% of time of occupancy above 25 °C for at least one room (8 cases, if we consider 10% of the time of occupancy as set by the PHI). This criterion is not met in 14 living rooms (6, if we consider 10% of time of occupancy) and 14 bedrooms (5, if we consider 10% of time of occupancy). Three (3) cases (IDs 6, 7 and 23) present a percentage of the time of occupancy above 28 °C exceeding 1% in the living room. In terms of bedrooms, 18 cases do not meet the criterion of 1% of occupancy time above 26 °C. If excluding building ID 12, these cases do not meet the criterion of 5% of occupancy time above 25 °C for at least one room.

In comparison, only four cases do not fulfil at least one of the CIBSE TM52 adaptive criteria for the living room (cases ID 1, 7 and 23, regarding *hours of exceedance Tmax + 1*, *daily weighted exceedance (We)* and *upper limit temperature (Tupp)*), and case ID 22 regarding *We*). In the bedrooms, 4 cases do not fulfil at least one of the CIBSE adaptive criteria (*Tmax + 1* is not met for cases IDs 3, 7 and 23; *We* for cases IDs 3, 7, 18 and 23; and *Tupp* is never reached).

Case ID 3 is noteworthy in the sense that, although having a very high percentage of time above 25 °C in the living room (24.4%), it fulfils the CIBSE TM52 criteria for this room. In the bedroom, on the contrary, this is the case with the highest daily weighted exceedance *We* and

proportion of time above 26 °C.

Only 5 buildings (IDs 2, 4, 5, 16 and 17) meet all the criteria suggested by CIBSE, mainly because the temperatures in the bedroom exceed 26 °C for more than 1% of time of occupancy.

These results confirm a tendency documented in the recent literature [13,50], which suggests that nZEB houses in temperate climates might be particularly at risk of overheating.

3.2. Appraisal of indoor thermal conditions

Fig. 3 shows the results of the appraisal of indoor thermal conditions as provided by the occupants. The appraisal is organised according to the season (winter and summer) and the room (living room and bedroom). Six (6) cases experience “slightly too hot” to “too hot” conditions in the living room, and a vast majority (20 out of 23) of the surveyed households report these conditions in the bedrooms. Frequencies of “too hot” conditions are also higher in bedrooms compared to living rooms (8 out of 23 vs. 4 out of 23). This situation differs from the winter season for which participants indicated comfortable thermal conditions in 17 cases in bedrooms (6 cases as “slightly too cold”), and in all cases in living rooms. Bedrooms appear, thus, to present the most variable conditions between winter and summer. In only 2 cases (IDs 5 and 15), bedroom summer thermal conditions were appraised by participants as “comfortable”.

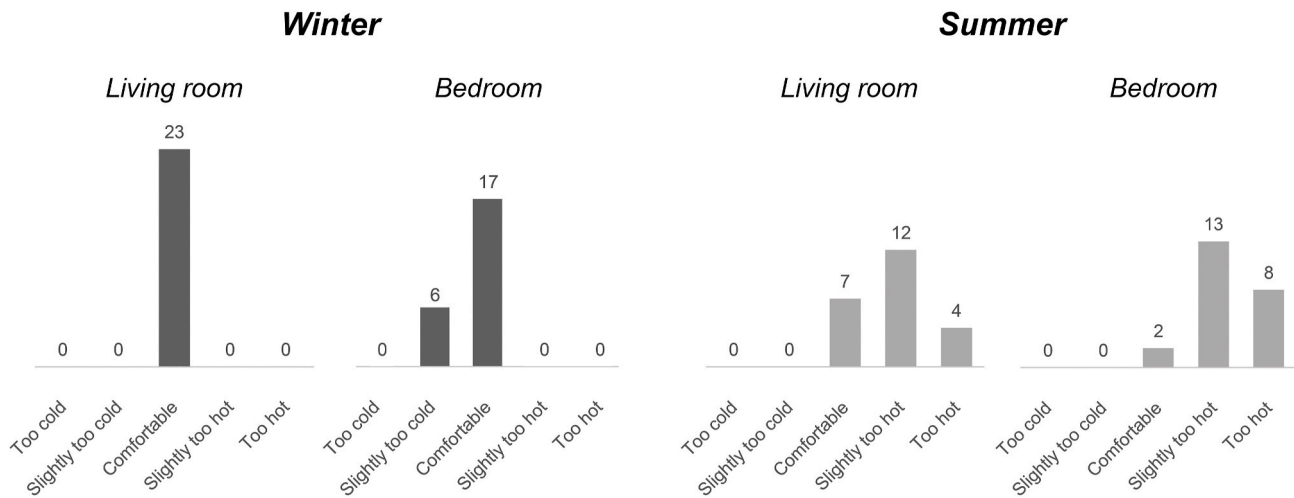


Fig. 3. Appraisal of indoor thermal conditions provided by the occupants according to the season and the room.

The results of the survey support the evidence found in the literature leading to postulate that occupants are not always satisfied with summer thermal conditions in nZEB houses, and that the lowest satisfaction is often found in bedrooms during summer [23]. Further investigations could be conducted to identify when this discomfort is specifically reported by the occupants (e.g., before or during sleep, or when waking up).

3.3. Relationship between summer thermal conditions in living rooms and in bedrooms

Table 5 presents the results of the statistical non-parametric tests on the percentages of time of occupancy above certain thresholds in bedrooms and in living rooms. The Spearman Rho analysis investigated the significance and effect size of the relationships between the frequency of temperature deviations in bedrooms and in living rooms. Statistically significant (p -value < 0.05) correlations of large magnitude ($Rho > 0.5$)

could be detected for small temperature deviations (that is, percentage of time of occupancy exceeding 25°C and comfort Category II of EN15251). Conversely, larger temperature deviations (that is, percentage of time of occupancy exceeding 28°C and Category III of EN15251) led to non-significant and weaker ($0.214 < Rho < 0.273$) correlations between thermal conditions in living rooms and in bedrooms. Despite a certain homogeneity of temperatures in nZEB houses can be expected, local variations have therefore to be carefully considered. This supports the interest towards an evaluation of the frequency of occurrence of small and large temperature deviations from the comfort zone by room in order to offer a better understanding of buildings' summer thermal behaviour (e.g., combining percentage of the time over 25°C and 28°C (or EN15251 Cat. II and III) as done in previous studies [10,26]). The combination of criteria suggested by CIBSE TM52 [17] appears globally in line with this finding.

Alternatively, cumulative indexes (for example in Kelvin hours (K. h)) could be used by room to quantify the intensity (in Kelvin) and the

Table 5

Non-parametric correlations between percentages of time of occupancy above 25°C , 28°C and class II and III of EN15251 in bedrooms and in living rooms.

		Bedrooms			
Living rooms	% of time $> 25^{\circ}\text{C}$	Spearman Rho	% of time $> 25^{\circ}\text{C}$	% of time $> 28^{\circ}\text{C}$	% of time $> \text{EN15251 Cat. II}$
		p -value	< 0.01	< 0.05	< 0.05
	% of time $> 28^{\circ}\text{C}$	Spearman Rho	0.253	0.362	0.389
		p -value	n.s.	n.s.	n.s.
	% of time $> \text{EN15251 Cat. II}$	Spearman Rho	0.440	0.453	0.508
		p -value	< 0.05	< 0.05	< 0.05
	% of time $> \text{EN15251 Cat. III}$	Spearman Rho	0.265	0.214	0.273
		p -value	n.s.	n.s.	n.s.

			Bedrooms			
Living rooms	% of time $> 25^{\circ}\text{C}$	Spearman Rho	% of time $> 25^{\circ}\text{C}$	% of time $> 28^{\circ}\text{C}$	% of time $> \text{EN15251 Cat. II}$	% of time $> \text{EN15251 Cat. III}$
			0.544	0.476	0.491	0.552
	% of time $> 28^{\circ}\text{C}$	Spearman Rho	$< 0.01^{**}$	$< 0.05^{*}$	$< 0.05^{*}$	$< 0.01^{**}$
			0.253	0.362	0.389	0.229
	% of time $> \text{EN15251 Cat. II}$	Spearman Rho	n.s.	n.s.	n.s.	n.s.
			0.440	0.453	0.508	0.367
	% of time $> \text{EN15251 Cat. III}$	Spearman Rho	$< 0.05^{*}$	$< 0.05^{*}$	$< 0.05^{*}$	n.s.
			0.265	0.214	0.273	0.226

*** $p \leq 0.001$, ** $p \leq 0.01$, * $p \leq 0.05$, n.s. = not significant ($p \geq 0.05$).

$Rho < 0.10$ = negligible; $0.10 \leq Rho < 0.30$ = small; $0.30 \leq Rho < 0.50$ = moderate; $Rho \geq 0.50$ = large.

duration of the temperature deviation (in hours), as suggested by EN15251 [28] in order to simplify the use of indicators.

3.4. Relationship between the appraisal of summer thermal conditions and overheating criteria

3.4.1. Living rooms

As presented in Table 3, four cases were appraised by occupants as being “too hot”. Among them, cases IDs 7 and 23 were particularly extreme as they did not meet any criterion and reached the highest proportion of time spent outside of comfort Category III (up to 14.4% of occupancy time). This fraction of time is more limited (0% (case ID 9) and 0.5% (case ID 6)) in the other two cases that fulfil other adaptive criteria (*daily weighted exceedance* $T_{max} + 1$ and *upper limit temperature* T_{upp}). Among the 12 cases considered as “slightly too hot”, only case ID 1 exceeded the adaptive CIBSE criteria (*hours of exceedance* $T_{max} + 1$, *daily weighted exceedance* We and *upper limit temperature* T_{upp}) but in a more moderate way when compared to cases IDs 7 and 23. The other cases presented limited percentage of the occupied time outside Category III (ranging from 0% to 0.1% of time (case IDs 4 and 18)) and fulfilled all the CIBSE adaptive criteria. The 7 cases reported as “comfortable” by the occupants showed very limited percentage of the occupied time outside of comfort Category III (ranging from 0% to 0.3% of time (case ID 2)). Apart from case ID 22 that did not fulfil the *daily weighted exceedance* criterion ($We = 1$), all other CIBSE adaptive criteria were met.

The results of the Jonckheere–Terpstra tests, evaluating the relationships between occupants’ thermal appraisal and compliance with overheating criteria, are presented in the rows at the bottom of Table 3. The only test for which statistical significance was detected is related to the *adaptive upper limit temperature* T_{upp} criterion (a criterion that may fail to be met in residential buildings [44]). This means that, in the sample analysed, the frequency of these extreme values clearly increases with the perceived discomfort. The size of the effect detected is practically relevant, with moderate magnitude ($r = 0.45$). The effect size related to the statistical tests applied to the 28 °C criterion test (although this was found as statistically non-significant) also detected a moderate magnitude of influence ($r = 0.38$). This reflects the importance of considering the frequency of extreme events when evaluating long-term summer thermal conditions in living rooms. Li et al. have recently found similar results in air-conditioned office buildings [19].

No other statistical test led to the detection of significant differences in the data, this reflecting the similarity of the values encountered in the sample for the other overheating criteria in the “comfortable” and “slightly too hot” categories of appraisal, as showed above. This leads to question the thresholds and the acceptable frequency of the criteria.

In general, the occurrence of perceived discomfort in living rooms (“slightly too hot” or “too hot” votes) was found to be similar to the number of buildings that did not meet the static criterion *percentage of the time of occupancy above 25 °C exceeding 5%*. However, among these 14 buildings, five were reported as being “comfortable”, this suggesting thermal satisfaction, or a possible adaptation from the part of the occupants, which is not captured by static criteria [38].

On the other hand, the CIBSE TM52 adaptive overheating risk assessment methodology was only able to identify dwellings presenting the most severe overheating situations. It should be considered here that CIBSE adaptive criteria [17] are based on the difference between T_{op} and T_{max} (here, represented by the upper limit of EN15251 comfort Category II). This difference (rounded value) has to reach 1-degree K for it to be considered. To some extent, this could be seen as considering the percentage of time outside of comfort Category III, a category that should only be exceeded for a limited part of the year [43]. This situation, which is tolerated up to 3% of the occupied time, appears therefore not to be limiting in the cases encountered. The removal of the tolerated difference of 1K, or a lower accepted frequency, should allow to be more in line with the number of complaints found under these conditions.

Finally, the noticed absence of a strong link with the percentage of time exceeding the adaptive EN15251 Category II also leads to question the applicability of these comfort categories in a residential context. In this regard, de Dear et al. found, in a humid subtropical climate, a larger tolerance to temperature ranges but a lower acceptability to higher thresholds in homes compared to what the ASHRAE adaptive model would define for offices [41].

These results reflect, therefore, the need to re-evaluate, in the case of residential buildings in a temperate climate, the acceptable temperature thresholds in living rooms based on larger samples where significant and practically relevant differences in individual preferences and adaptation can be detected and measured.

3.4.2. Bedrooms

As presented in Table 4, only two bedrooms (case IDs 5 and 15) were considered “comfortable” in summer. Case ID 15 was the only one to be deemed comfortable, although presenting a temperature above 26 °C for more than 1% of the occupied time (3.1%). The other criteria were all met for both cases.

Among the 13 cases with a “slightly too hot” evaluation in bedrooms, four did not exceed 1% of the time of occupancy above 26 °C. Only case 23 presented extreme values: 12% of the time above 26 °C, 1.2% over EN15251 comfort Category III, and four times above the *daily weighted exceedance* (We).

The eight cases presenting a “too hot” appraisal all exceeded a percentage of occupied time above 26 °C of 1%. Among these, three cases also did not meet the *daily weighted exceedance* criterion (We), and two exceeded 1% of the time of occupancy over EN15251 comfort Category III.

The results of the Jonckheere–Terpstra tests are presented in the rows at the bottom of Table 4. The only test that returned statistical significance was the one related to the percentage of occupied time with a temperature above 26 °C. The effect size of $r = 0.43$ indicates a moderate increase in the encountered frequency with the perceived discomfort. Even though the tests were found not to be statistically significant, the magnitude of the effects related to small temperatures deviations (>25 °C and $>$ EN15251 category II) was estimated as moderate ($r > 0.3$), while only effects of small size were detected in living rooms ($r > 0.1$). These results confirm that lower temperatures are generally preferred in bedrooms compared to the living rooms [62], and that smaller temperature deviations lead to perception of discomfort, probably due to the fact that adaptive opportunities are reduced during sleep [45].

This supports the use of the CIBSE *hours of exceedance* criterion based on a threshold of 26 °C [44] to describe the occurrence of discomfort in bedrooms, although this criterion seems to be difficult to meet in practice (18 cases out of 23 showed temperatures above 26 °C for more than 1% of the time of occupancy).

3.5. Thermal behaviour and building characteristics

Table 6 summarizes the characteristics of the buildings that did not comply with any of the CIBSE criteria (cases IDs 1, 7 and 23), or that presented the highest values for all the criteria in the bedroom (case ID 3). The table also presents the characteristics of buildings IDs 2, 4, 16 and 17 that complied with all the criteria (CIBSE and PHI). As already mentioned, all the buildings were located in rural or semi-rural areas in relatively unobstructed sites. The management of solar gains was, therefore, particularly crucial, and the potential for heat dissipation by window opening was largely available.

Due to the small size of these sub-samples, the comparison of their characteristics was uniquely based on qualitative criteria. This analysis showed that house type, number of occupants, heated floor area, construction type, window Solar Heat Gain Coefficient (SHGC), windows’ opening practice, as well as the location of the bedroom under the roof, are relatively similar in the two groups of buildings. Only small

Table 6

Main characteristics of the buildings presenting the weakest (cases IDs 1, 3, 7 and 23) and strongest (cases IDs 2, 4, 16 and 17) compliance with overheating criteria.

	Building IDs 1, 3, 7, 23 (weakest compliance with criteria)	Building IDs 2, 4, 16, 17 (strongest compliance with criteria)
	n or mean [min-max]	n or mean [min-max]
House type	Detached: 2 Semi-detached:1 Attached:1	Detached: 3 Semidetached:1
Type of construction	Masonry:3; Wooden Frame:1	Masonry:3; Wooden Frame:1
Number of occupants	4 [3-5]	3.3 [2-5]
Presence during the working hours	No: 4	Yes: 4
Heated floor area [m²]	217.3 [151.7–330]	207.9 [119.7–275.3]
Window-to-floor surface ratio [%]	20.7 [15.2–24.7]	16 [12.1–19.9]
Mean U-value (windows included) [W/m².K]	0.2 [0.2–0.4]	0.3 [0.2–0.4]
Airtightness (n50) [1/h]	1.6 [0.7–3.7]	2.3 [0.8–3.8]
Main window SHGC	0.5 [0.5–0.6]	0.6 [0.5–0.7]
Heating needs [kWh/m².K]	12.8 [5–23.8]	19.1 [8.8–29.4]
Living room		
Orientation	SW:2; S:1; W:1	S:2; E:1; NE:1
Solar shading type	In:3; No:1	In:3; Out:1 (Id: 4)
Windows opening practice	Day and Night: 2 Day: 1 Never:1	Day and Night: 2 Never:2
Bedroom		
Under roof situation	Yes: 2; No:2	No:3; Yes:1
Orientation	S: 1; SW:1; W:1; NW:1	S:1, SW:1, W:1, E:1
Solar shading type	No:3; Out:1 (Id: 23)	In: 4
Windows opening practice	Day: 3 Day and Night: 1	Day and Night: 2 Day: 1 Never:1

differences could be noticed for the buildings that complied with all the CIBSE criteria, since they had slightly higher heating needs and smaller glazing surfaces. Heating needs corresponded to a mean of 19.1 kWh/m² against 12.8 kWh/m² due, among other factors, to a higher mean U-value (0.3 vs. 0.2 W/m². K) and a lower airtightness (n₅₀ mean of 2.3 vs.

1.6 1/h) of the thermal envelope. Glazing surfaces corresponded to a mean of 16% vs. 20.7%, less often west-oriented (i.e., with sun exposure in the late afternoon).

Solar gains were mainly controlled by internal shading devices (manually-operated) in both groups. When solar shading was not available, especially in bedrooms, higher occurrences of overheating were recorded. Windows' opening behaviour, as reported by the occupants, did not differ substantially. The main difference that can be noticed between the two groups is related to the presence of the occupants during the day. In fact, the buildings presenting overheating problems were usually those not occupied during the day. This difference – other than potentially influencing the physiological adaptation of the occupants if they were exposed to a mechanically-controlled environment during the day – could also affect the possibility to operate properly the solar shading devices and provide natural cooling by windows' opening at the times needed. This last hypothesis could not be further investigated in our study, but it should probably be considered for future research on residential thermal comfort.

Fig. 4 presents the thermal summer conditions encountered in the living room of two lightweight buildings (cases IDs 17 and 23) that share similar building characteristics (cf. Table 1). The proper use of shading devices, combined with an adequate day and night ventilation by windows' opening (as reported by the occupant), appears to be effective in limiting the risk of overheating situations (Fig. 4 - left). On the opposite, opening the windows only during the day, combined with a probably inadequate operation of internal shadings (the occupants reported to be mostly absent during working hours), leads, in the south west oriented living room of building ID 23 (vs south for building ID 17), to extreme overheating situations (Fig. 4 - right).

Even if further research is still needed, these preliminary results confirm the importance of properly considering the integration of specific design strategies [52] to prevent or mitigate risks of overheating (e.g., solar shading and natural cooling) even in a temperate climate, as well as the active role that should be played by the occupants in the operation of environmental controls [11].

4. Conclusions

This paper has presented the results of a post-occupancy evaluation measurement and survey campaign conducted in 23 nZEB houses in Wallonia (southern part of Belgium). To the authors' knowledge, this is the first study of summer thermal comfort in nZEB houses that has been reported from this part of Europe. Analysis of the data collected in living

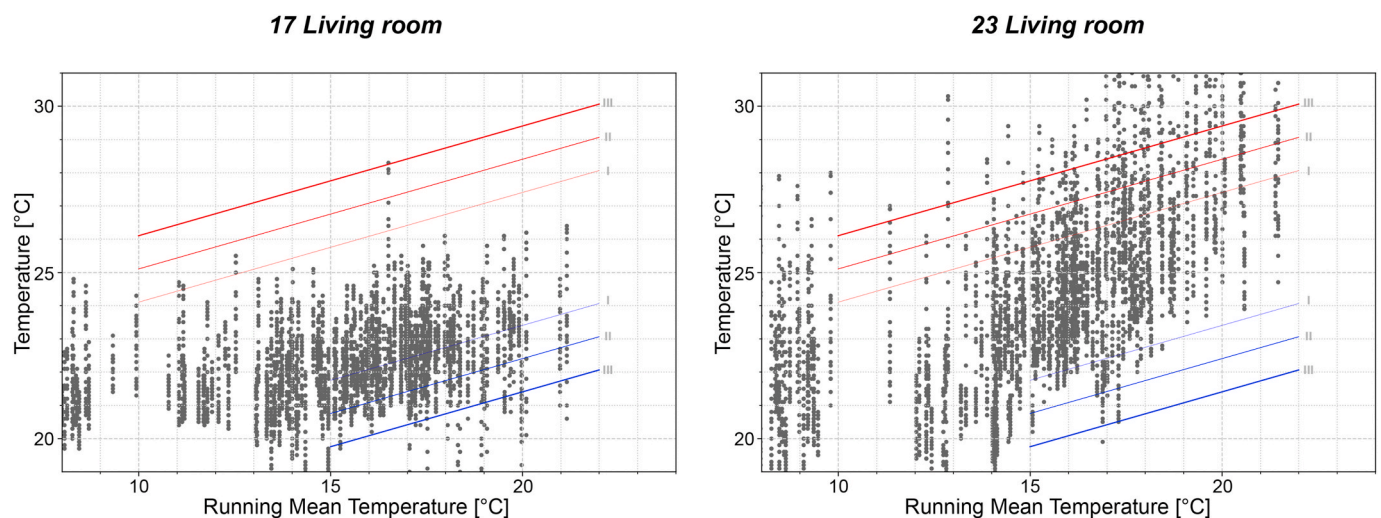


Fig. 4. Measured hourly temperatures (y-axis) between May and September in the living rooms of building IDs 17 (left) and 23 (right) plotted against the running mean temperature (x-axes, Trm) of EN15251 adaptive standard (and indication of comfort categories I, II, III limits).

rooms and in the master bedrooms was first conducted by applying criteria commonly used for the evaluation of indoor summer thermal conditions in free-running buildings. Rigorous statistical tests were then carried out to analyse the relationships between the achievement of different overheating criteria and the appraisal of indoor summer thermal conditions provided by the occupants. On such bases, the study provided a critical review of the capacity of current criteria to predict the satisfaction expressed by building occupants with their summer thermal comfort.

The results have emphasised the difficulty in maintaining comfortable thermal conditions in nZEB houses despite the temperate climate of Wallonia. Only five buildings met all the criteria suggested by CIBSE, mainly due to the high temperatures recorded in bedrooms. The analyses showed that the frequency of occurrence of small and large temperature deviations from the comfort zone should be quantified by room, in order to offer a complete understanding of summer thermal conditions and of the overall thermal behaviour of the buildings.

In living rooms, the long-term appraisal of summer thermal conditions appeared to be more related to the frequency of extreme temperatures. Conversely, the appraisal of summer thermal conditions in bedrooms seemed to be more influenced by smaller temperature deviations with respect to the living rooms, probably due to the fact that adaptive opportunities are reduced during sleep. Nevertheless, the adopted overheating criteria were found not to be able to properly predict the occurrence of perceived moderate discomfort, especially in living rooms. Larger studies, possibly also measuring and quantifying inter-individual differences of perception, are therefore needed to re-evaluate the boundaries and/or the tolerable frequencies of the adaptive criteria within the residential context.

Although cases presenting higher risks of overheating were found to require slightly less heating, to present larger unshaded glazing surfaces, and to be more often west-oriented (hence requiring a better integration of bioclimatic strategies to mitigate overheating risks), the findings from this study also emphasise the importance of considering the behaviour of occupants (e.g., operation of shading systems and other environmental controls) in the reduction of overheating risks. Further research aiming towards a better understanding of how environmental controls are operated by the occupants to maintain comfortable indoor summer thermal conditions appears necessary to tackle overheating issues in nZEB houses.

Declaration of competing interest

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

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Chapter V. Indoor summer thermal
comfort in a changing temperate climate

This chapter is based on the following publication:

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Year: 2022.

Role of the thesis author: Lead author. Table V.1 further details the author's contributions to this publication.

Table V.1. Contributions of the thesis author to the paper constituting Chapter V., according to the CRediT taxonomy [213].

Contribution Type	Chapter V
Conceptualization	✓
Data curation	✓
Formal analysis	✓
Investigation	✓
Methodology	✓
Software	✓
Validation	✓
Visualization	✓
Writing – original draft	✓
Writing – review & editing	✓ ¹

1: In collaboration with Erwin Mlecnik (TU Delft), Geoffrey van Moeseke, Gabrielle Masy and Sergio Altomonte (UCLouvain).

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Article

Indoor Summer Thermal Comfort in a Changing Climate: The Case of a Nearly Zero Energy House in Wallonia (Belgium) [†]

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Abstract: While the potential impact of climate change mitigation measures is well documented in building sciences literature, there are only relatively sparse studies focusing on the efficiency of adaptation strategies. This paper aims to contribute to this topic by evaluating the extent to which the design of a typical nearly Zero Energy Building (nZEB) house in Wallonia (Belgium), and its current operation, could provide summer thermal comfort in a changing climate. Based on calibrated whole building energy simulations, and on the integration of future climate data directly derived from a high-resolution climate model, this study evaluates the potential evolution of overheating risks in the living room and in the main bedroom of the house. Discussing the compliance with existing overheating criteria, the study shows that the passive strategies currently deployed in the house might not be sufficient to guarantee summer thermal comfort especially in the bedroom, and that other strategies might be necessary in the future to limit the use of active cooling systems and curb their environmental impacts. This study concludes that considering the potential of these strategies to guarantee summer thermal comfort in a changing climate should be a priority for the design of nZEB houses (and their related policies) also in temperate oceanic climates.

Keywords: nearly Zero Energy Buildings; climate change; summer thermal comfort; overheating



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1. Introduction

“Warming of the climate system is unequivocal and the effects of anthropogenic greenhouse gas emissions, together with those of other anthropogenic drivers, are extremely likely to have been the dominant cause of the observed warming since the mid-20th century”, the Intergovernmental Panel on Climate Change (IPCC) writes in its Fifth Assessment Report (AR5) in 2014 [1]. In this context, a drastic reduction of greenhouse gas emissions is needed to mitigate climate change effects. For the building sector, Wallonia (southern part of Belgium), like many other European regions, aims to reach a carbon neutral building stock by 2050 [2]. This implies achieving nearly Zero Energy Buildings (nZEB) standards for all buildings, including existing ones [3]. According to the definition provided in the European Directive 2010/31/EU on the energy performance of buildings [4], nZEB implies that “the very low amount of energy required is covered to a very significant extent by energy from renewable sources”.

In a region such as Wallonia, characterized by a temperate oceanic climate with pre-dominant heating energy use (more than 70% of the energy used in residential buildings [4]), nZEB performance requirements aim first to drastically reduce heating energy needs of buildings. Practically, measures to increase the insulation and airtightness of the thermal

envelope, mechanized hygienic ventilation (with heat exchanger) and the search for a favourable orientation have become essential for the design of nZEBs in Wallonia.

Nevertheless, while undoubtedly allowing for winter comfort conditions with lower energy costs [5], these construction techniques entail other risks of discomfort, and might even require some adaptation/understanding from the part of the occupants [6–8]. Many studies have, for example, shown that such techniques (modifying the thermal behaviour of the building) tend to keep the warmth inside and, therefore, increase the risk of overheating, even under the current climate [9].

Furthermore, there is strong consensus that the frequency and intensity of heatwaves will increase in the future [1]. As a consequence, global warming will have a worsening impact on overheating risk [10] in buildings, potentially compromising comfort, well-being and health, particularly for more sensitive occupants [11].

Today, simple strategies (such as the use of solar shading and the opening of windows) are often seen as key to prevent and guarantee summer thermal comfort in nZEB residential buildings within the considered climatic zone [12]. The use of these passive strategies (as they “do not use or use only small amounts of external energy”, in opposition to active strategies that “use electrical or mechanical systems” [13]) is encouraged by Walloon building standards [3]. It allows, for example, to comply with a specific requirement of nZEB dwellings by lowering an overheating risk indicator [14].

In this context, a question emerges today in the building sector: will the implementation of these passive strategies—which still appears quite limited in practice [15]—be sufficient to avoid in the future a generalised use of active cooling systems, with their energy consumption [16] and environmental impacts [17], in a country with no such tradition?

While the potential impact of climate change mitigation measures is now well documented in the literature of building sciences, studies focusing on the efficiency of these adaptation strategies are only at their infancy for a number of reasons: slow knowledge transfer from climate modelling to building engineering science; stochastic behaviours and uncertainties associated with future climates that induce large datasets and specific methods to deal with; substantial computational time needed; etc. [16]. These studies are, however, crucial to define proper building energy standards that will effectively reduce energy demands without compromising thermal comfort. This paper aims to provide a contribution to answer this question. Based on a real case study, it evaluates the extent to which the design of a typical nZEB house in Wallonia, and its current operation, could guarantee summer thermal comfort in a changing climate.

2. Method

2.1. Case Study

The case study is a real detached single-family house (Figure 1). In Wallonia, detached houses represent the most frequent type (39%) of single-family housing (approximately 80% of the total housing stock [18]). The house, constructed in 2011, is composed of 2 levels of around 83 m² (net floor area) each and is occupied by 2 adults and 3 children (1 baby). The main thermal characteristics of its building envelope are presented in Table 1.

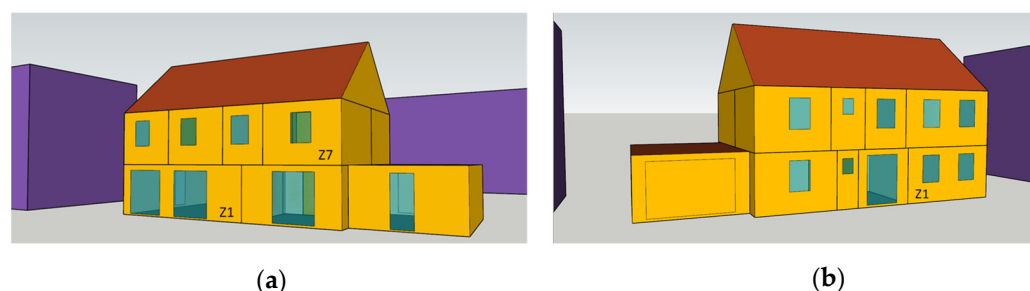


Figure 1. Views of the main facades with indication of the thermal zones considered (Z1: living room, Z7: main bedroom). (a) Rear façade (east oriented). (b) Front façade (west oriented).

Table 1. Characteristics of the calibrated thermal model.

Characteristics	Units	Value	Source of Value *	Instrumental Uncertainties Considered	Used Uncertainty for Calibration
Construction type	[-]	Masonry	1	n.a.**	n.a.
Number of occupants	[-]	5 (<12 y/o: 3)	2	n.a.	n.a.
Presence during working hours	[-]	Yes	2	n.a.	n.a.
Net heated floor area	Total	[m ²]	166	3	n.a.
	Living room	[m ²]	42.3	3	n.a.
	Main bedroom	[m ²]	14.2	3	n.a.
Window-to-floor surface ratio	Total	[%]	19.9	3	n.a.
	Living room	[%]	29.2	3	n.a.
	Main bedroom	[%]	7.9	3	n.a.
Mean U-value (windows included)	[W/m ² K]	0.31	3 (Walls: 1)	[−20%; +20%]	−7%
Air change rate at 50 Pa (n ₅₀)	[1/h]	1.1	1	[−5%; +5%]	−5%
Mechanical ventilation airflow (Air change rate)	[1/h]	0.25	1	[−6%; +6%]	−6%
Efficiency of heat recovery	[%]	85	1	[−6.2%; +6.2%]	−2%
Solar Heat Gain Coefficient (SHGC) (windows)	[-]	0.63	3	[−5%; +5%]	−5%
Main windows orientation (living room and main bedroom)	[-]	E	1	n.a.	n.a.
Living room total SHGC (glazing + internal shading)	[-]	0.35	2, 3	[−5%; +5%]	+5%
Bedroom total SHGC (glazing + internal shading)	[-]	0.35 (usually not used)	2, 3	[−5%; +5%]	+5%
Internal gains (electrical)	[W/m ²]	2.2 (mean value)	1	[−3%; +3%]	−3%
Additional thermal capacity of zones (furniture)	[kJ/K.m ²]	26.5	4	[−100%; +100%]	+100%
Windows opening for summer thermal control (living room)	[Ach]	3 (Cross ventilation)	2	[−100%; +100%]	+30%
Windows opening for summer thermal control (bedroom)	[Ach]	0 (Not usual) (One side ventilation)	2	[0; +6]	+0%
Heating needs	[kWh/m ² ·y]	17.8	1	[−6%; +6%]	−6%
Dry bulb outdoor temperature (annual mean)	[°C]	10.8		[−0.3; +0.3]	−0.3
Radiation (Global Horizontal)	[kWh/m ² ·y]	1035	1	[−10%; +10%]	+0%
Setpoint temperature (mean value September to May)	[°C]	20.1	1	[−0.3; +0.3]	+0.3
Living Room	[°C]				
Main Bedroom	[°C]	19.1	1	[−0.3; +0.3]	+0.3
Primary energy use (Mainly heating and domestic hot water —PV production)	[kWh/m ² ·y]	61 kWh/m ² ·y	3	n.a.	n.a.

* 1 On-site verification/measurements; 2 Questionnaire-based interviews; 3 Belgian EPBD calculation; 4 Literature.

** n.a.: not applicable.

In terms of thermal performances, the house complies with the current requirements for nZEB in Wallonia [19] relying on the definition provided in the European Directive 2010/31/EU on the energy performance of buildings [20]. These requirements imply a primary energy use of a maximum $85 \text{ kWh/m}^2 \cdot \text{year}$ (mainly including heating, domestic hot water consumption as well as on site electricity production, here supplied by photovoltaics cells covering the roof). The nZEB standard also requires compliance with a simplified overheating risk indicator based on a static thermal calculation under the current climate [14].

Following an initial measurement of its main characteristics, the performance of the house has been monitored during one full year (2016), including: air temperatures, electricity use (internal gains), heating demands, airflows induced by mechanical ventilation, efficiency of the heat recovery system, U values of the walls and airtightness. Some weather data have also been monitored on site (dry bulb temperature and relative humidity) and complemented by data from the Royal Meteorological Institute of Belgium (RMI) (radiation, cloud cover, etc.). The characteristics of the house presented in Table 1 derive, thus, from on-site verifications, interviews with the occupants (e.g., about windows opening behaviours) and calculations from the Walloon EPBD (Energy Performance of Buildings) tool [19]. In the framework of this study, two main rooms were analysed: the living room (Z1) and the main bedroom (Z7). A description of their spatial characteristics is included in Table 1 and illustrated in Figures 1 and 2.

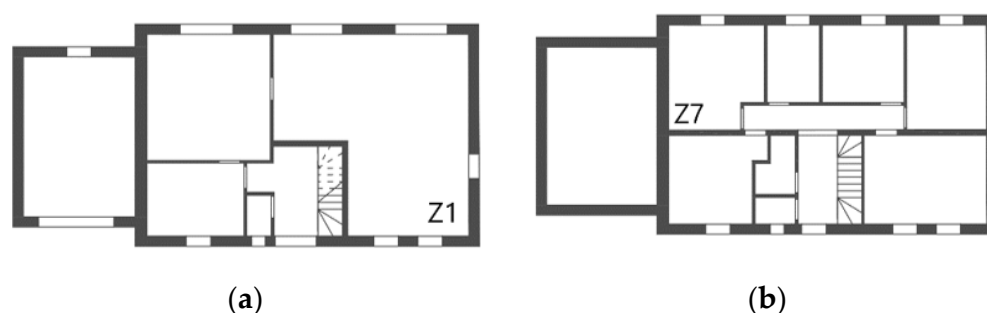


Figure 2. Plans of the house with indication of the considered thermal zones (Z1: living room, Z7: main bedroom). (a) Floor plan. (b) First floor.

Based on the behaviours reported by the occupants, the closure of the white internal curtain to protect from solar radiation and the opening of windows to dissipate the heat in the living room have been integrated in the thermal model (except during the periods of absence of the occupants). According to the occupants, no such strategies were regularly applied in the main bedroom and, therefore, they have not been integrated for this room in the thermal model. Globally, no (severe) overheating problems have been measured during the year 2016. The house complied with all the summer thermal comfort criteria (see Section 2.4) defined by the Chartered Institution of Building Services Engineers (CIBSE) (UK), even if the occupants perceived the bedroom temperature in summer as slightly too hot. The methodologies implemented for interviews and data collection are described in more detail in a previous publication [21].

The house is located in a suburban area of Namur (the capital city of Wallonia), in the city of Erpent in the southern part of Belgium (50° North) (see Figure 3) and is exposed to a temperate oceanic climate (Cfb zone according to the Köppen–Geiger climate classification system [22]). Section 2.3 presents an overview of the current and potential future characteristics of this climate.



Figure 3. Localisation of the city of Erpent (Wallonia, south part of Belgium) (Reprinted from Ref. [23]).

2.2. Calibrated Thermal Model

A whole building energy simulation of the house has been carried out (Figure 1) using the TRNsys18 simulation engine [24]. In order to ensure a realistic evaluation of the indoor summer thermal conditions, a calibration process of the model was performed. The calibration consisted in two main steps. First, measured values (thermal properties, weather data, etc.) (cf. Table 1) were introduced in the model (=base model). Then, a variation of the entries data within the range of their estimated instrumental uncertainties (obtained from manufacturers) was performed in order to minimise the deviation of simulated temperatures (hourly values) from measured values according to the widely used (see for example [25]) indicators defined by ASHRAE guideline 14 [26]. These indicators are based on the Coefficient of Variation of the Root Mean-Square Error (CV-RMSE) and the Mean Bias Error (MBE). This last calibration step was performed using an optimisation algorithm (Particle Swarm Optimization (PSO) [27]) and has involved more than 900 simulations. Table 2 presents the compliance of the final model with ASHRAE indicators. The last column of Table 1 illustrates in detail the related entries data.

Table 2. Final model compliance with calibration criteria defined in ASHRAE guideline 14.

	Living Room Temperature	Bedroom Temperature	Calibration Criteria
NMBE [%]	0.64	0.68	± 10
CV-RMSE [%]	3.39	3.41	30

Figure 4 illustrates the capability of the calibrated model to estimate the time exceeding 25 °C in the living room and in the main bedroom compared to the values that were measured in 2016. The year 2016 can be considered broadly in line with the average of the last 30 years, both in terms of solar radiation and of temperatures [28] (for an overview of climatic historical data, see Figure 5).

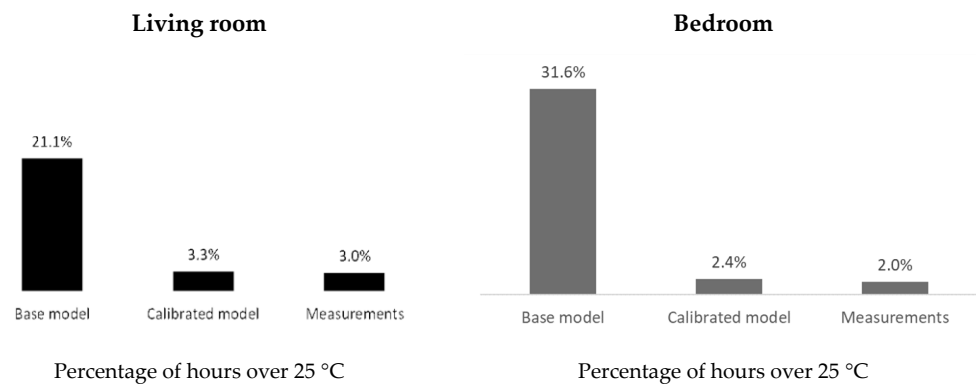


Figure 4. Models' capability to estimate the time exceeding 25 °C in the living room (**left**) and in the main bedroom (**right**) compared to the measured values.

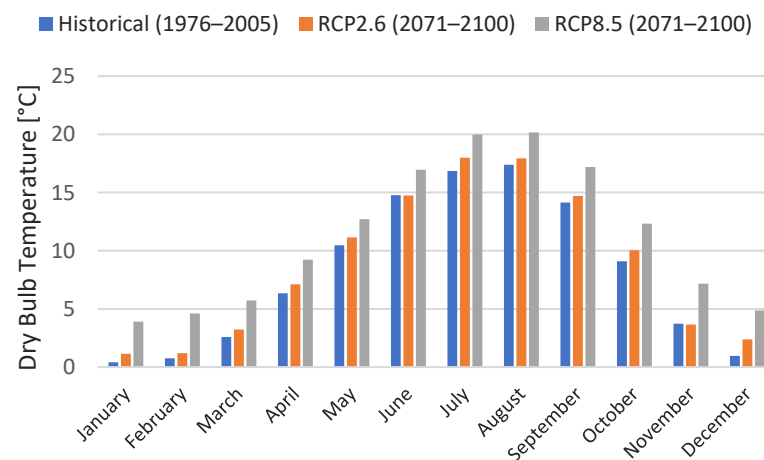


Figure 5. Monthly mean dry bulb temperature evolution under historical, RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios according to ALARO Model [29].

2.3. Climate Change Model

Data for future and historical (here intended as similar to current) climatic conditions (temperature, humidity, radiation, wind speed and direction, etc.) have been directly derived from high-resolution climate modelling. These models, dynamically downscaled from Global Climate Models (GCMs), consider local climate variations and anomalies and allow a detailed temporal and geographical resolution (horizontal grid spacing <4 km). Compared to the classical use of morphed weather data [30], this method allows for accounting the variability in occurrence and intensity of heatwaves phenomena throughout the years. Today, these data based on the ALARO model are available in Belgium for different representative concentration pathways (RCP) [29]. For the purpose of this paper, two future climates scenarios—Representative Concentration Pathway (RCP) 2.6 and 8.5—for the period 2071–2100 were considered and compared to historical data (1976–2005) (also derived from the same climate model) for the city of Uccle (the main meteorological station of Belgium, located in the southern part of Brussels, about 50 km from Namur). These two RCPs scenarios were chosen since they represent opposite (and extreme) perspectives with respect to the deployment of mitigation strategies and, consequently, the severity of induced climate change: a stringent mitigation scenario (RCP2.6) that would keep global warming likely below 2 °C above pre-industrial temperatures, which is in line with the objectives of the Paris agreement [31], and a very high Green House Gas (GHG) emissions scenario (RCP 8.5), leading to an increase of global mean temperature comprised between 2.6 °C to 4.8 °C (95% confidence interval) by the end of the 21st century (2081–2100) relative to 1986–2005 [1]. Figure 5 shows the monthly mean outdoor temperature evolution according

to these scenarios compared to the historical one (yearly global horizontal radiation remains stable—around 1040 kWh/m²·year—under these different scenarios).

As mentioned in the introduction, there is wide consensus that these scenarios will impact the frequency and the duration of heat waves [1]. In Belgium, heatwaves are defined as a period of minimum 5 consecutive days with air temperature reaching at least 25 °C and more than 30 °C for at least 3 days [32]. Figure 6 presents the evolution of the number of heat waves per year as well as the number of days reaching 25 °C and 30 °C according to RCP 2.6 and 8.5 for the end of the century (2071–2100) compared to the historical period (1976–2005) for Uccle. A standard boxplot representation has been used to illustrate the distribution (min, 25th percentile, median, 75th percentile, max) of the encountered values for the considered period. Median values have also been specified to increase the readability of these graphs. These sets of data, covering a period of 30 years each, were directly introduced in the TRNsys simulation software with an hourly resolution (using an IWE format [33]) in order to provide a detailed overview of their implications on the building indoor climate.

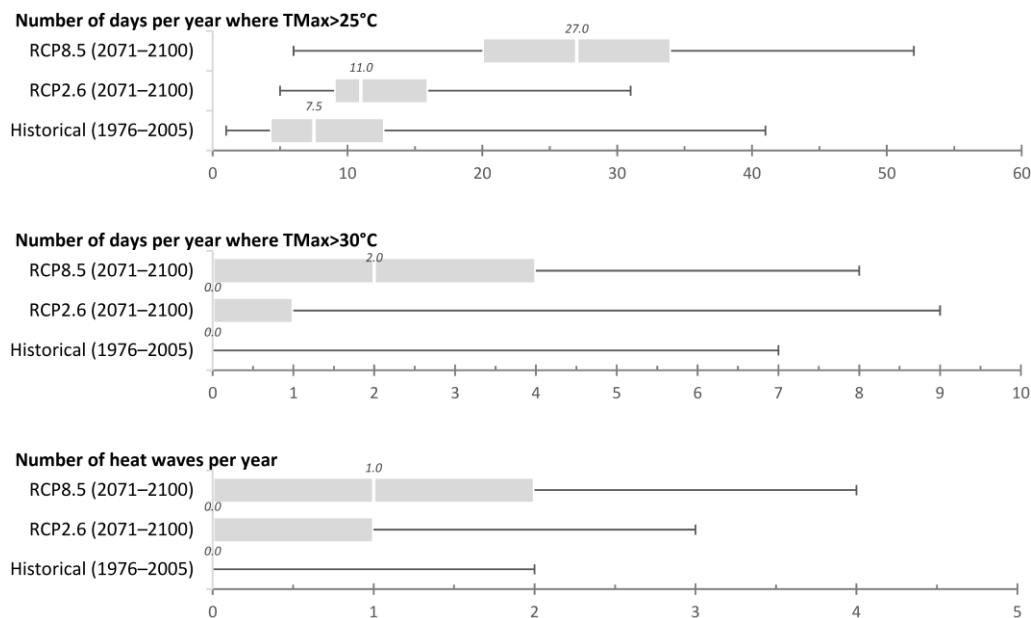


Figure 6. Evolution of the number of days reaching 25 °C or 30 °C and the number of heatwaves per year according to historical (1976–2005), RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios in Uccle (Belgium).

2.4. Summer Thermal Comfort Evaluation

The evaluation of summer thermal comfort has been conducted according to CIBSE Technical Memoranda TM52 [34] and TM59 [35], as they offer a comprehensive and widely-used method for overheating risk analysis in buildings (see for example [36]). The first document (TM52) presents three criteria based on the frequency, duration and intensity of the deviations of operative temperature from the EN15251 comfort categories [37]: *Adaptive hours of exceedance* ($T_{\max} + 1$); *Daily weighted exceedance* (W_e) and *Upper limit temperature* (T_{upp}) [34]. In the context of climate change scenarios, these criteria—based on the theory of adaptive comfort—seem particularly appropriate as they already imply a physiological, behavioural and psychological adaptive capacity of humans [38,39]. In homes, CIBSE only imposes compliance with the first criterion (*Adaptive hours of exceedance*) for living rooms, kitchens, and bedrooms [35]. Nevertheless, all these criteria have been considered in this study with respect to the limit of the comfort Category II [37], recommended for new buildings and major refurbishments in the absence of very sensitive and fragile persons [40]. For bedrooms, a criterion based on an absolute threshold of 26 °C was also considered as suggested by TM59 [35]. This static criterion is based on the fact that thermal adaptation

is considerably reduced during sleep [41]. Table 3 illustrates in detail the application of these criteria. In accordance with TM59, occupied hours were considered to be from 7 am to 10 pm for the living room and from 10 pm to 7 am for the bedroom [35].

Table 3. Criteria for summer thermal comfort evaluation.

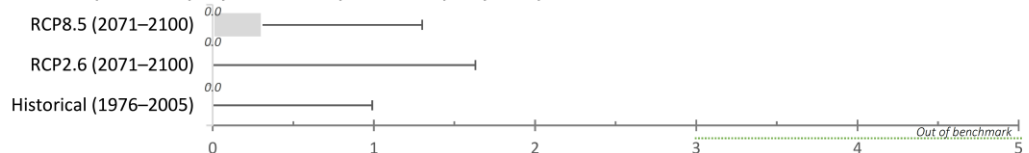
Name	Thresholds	Benchmark (Maximum)	Source
Static hours of exceedance	$T_{op} > 26\text{ }^{\circ}\text{C}$	1% of annual occupied hours (10 p.m.–7 a.m.) (bedrooms only)	TM59, CIBSE 2017
Adaptive hours of exceedance	$T_{op} - T_{max} > 1\text{ K}$ $T_{max} = \text{EN15251 Cat II upp. limit}$	3% of occupied hours (May to September inclusive)	TM52, CIBSE 2013 TM59, CIBSE 2017
Daily weighted exceedance	$W_e = \sum h_e \times WF$ $WF = \max(0; T_{op} - T_{max})$ h_e : corresponding time [h]	6 in any one day during occupied hours	TM52, CIBSE 2013
Upper limit temperature	$T_{upp} = T_{max} + 4\text{ K}$	Absolute maximum value during occupied hours	TM52, CIBSE 2013

3. Results

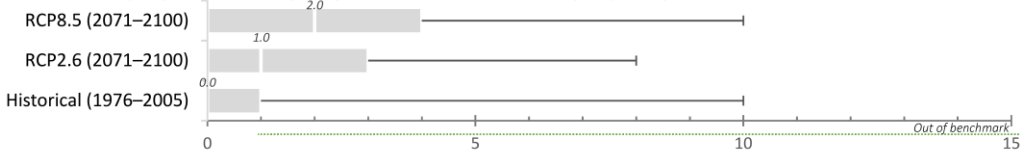
Figures 7 and 8 present the summer thermal comfort evaluation under historical (1976–2005), RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios resulting from the application of the criteria presented in Table 3 for the living room (Figure 7) and for the main bedroom (Figure 8) of the house.

Living room

% of occupied hours per year where $T_{op} - T_{max} > 1\text{ K}$ | May to September



Nbre of times per year where daily weighted exceedance is reached | May to September



Nbre of times per year where Upper limit temperature is exceeded | May to September

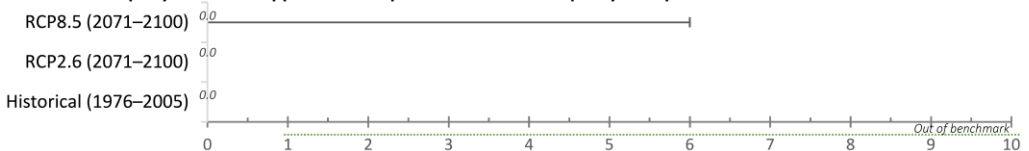


Figure 7. Summer thermal comfort evaluation under historical (1976–2005), RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios resulting from the application of the criteria presented in Table 3 for the living room.

Bedroom

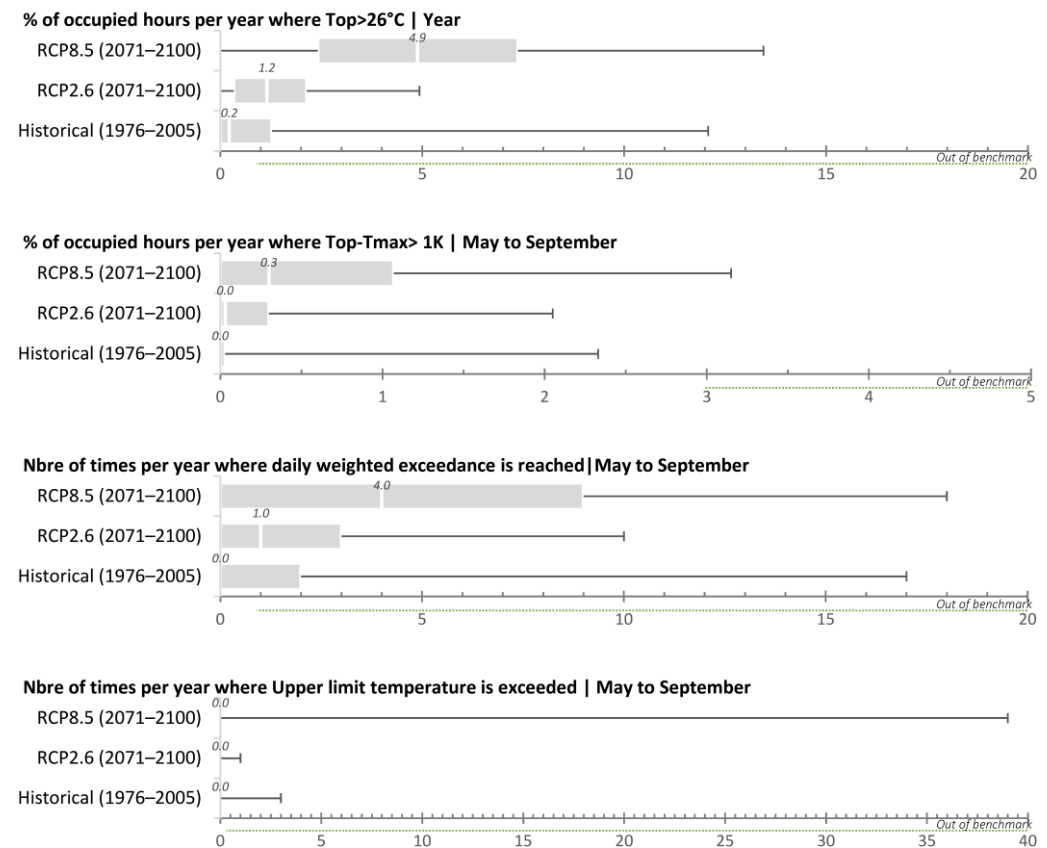


Figure 8. Summer thermal comfort evaluation under historical (1976–2005), RCP2.6 (2071–2100) and RCP8.5 (2071–2100) scenarios resulting from the application of the criteria presented in Table 3 for the bedroom.

For the living room, Figure 7 shows that the *Adaptive hours of exceedance* criteria (not more than 3% of occupied hours where $T_{op} - T_{max} > 1\text{K}$) is met under the three climatic scenarios. The *Daily weighted exceedance* criterion is met for 75% of years between 1976 and 2005, but this result could drop under 50% of the years between 2071–2100 (38% under RCP8.5 scenario). Moreover, this criterion is not met for more than 2 days per year for half of the years between 2071 and 2100 under the RCP8.5, while it is only exceeded once per year in 25% of the years between 1976 and 2005. The *Upper limit temperature* criteria is only exceeded under the RCP8.5 scenario (three times and up to 6 K). For the main bedroom, Figure 8 shows that the *Static hours of exceedance* criterion (max 1% of occupied hours per year where $T_{op} > 26^{\circ}\text{C}$) is only exceeded 25% of the years during the historical period. The non-compliance with this criterion could, however, become systematic: 25 years are exceeding this criterion over the period 2071–2100 under the RCP8.5 scenario. On the contrary, the *Adaptive hours of exceedance* criterion (not more than 3% of occupied hours where $T_{op} - T_{max} > 1\text{K}$) is exceeded only one year out of four under this scenario (while it is met under the other scenarios). The median value of the number of days exceeding the *Daily weighted exceedance* reaches 4 between 2071–2100 (under RCP8.5 scenario), while it is 0 for the historical period. The *Upper limit temperature* criterion is not frequently exceeded but it reaches higher frequencies per year under the RCP8.5 scenario (up to 39 times per year).

4. Discussion

As shown in Figure 6, days over 25°C and heat waves will become quite common in the future in Belgium: around 27 days reaching 25°C and one heatwave (up to four) on average per year should be expected under the RCP8.5 scenario. Conversely, these

phenomena were very exceptional in the historical data (only one year with heatwaves and a mean value of less than 11 days per year reaching 25 °C).

The analysis of the historical period shows that the implementation of passive strategies in the building (e.g., internal shading devices and natural cooling by windows opening only practiced in the living room) generally allows compliance with the CIBSE overheating criteria. It should also be remembered here that the configuration of the building analysed for this study (east oriented, limited glazing area, suburban area, etc.) allowed to reduce the occurrence of overheating phenomena.

The evolution of the climate could have, however, a clear impact on future indoor climate conditions, as shown in Figures 7 and 8. The severity of this evolution depends on the criterion and on the studied room. In this way, the results confirm the observation made in a previous study [42].

More specifically, the CIBSE *Daily weighted exceedance* criterion appears to be difficult to meet in the future (more than 50% of the years during the period 2071–2100 under RCP2.6 do not comply with this criterion for both the living room and the bedroom). This shows an increasing difficulty in dissipating the heat accumulated inside the building, probably linked to higher external temperatures. The bedroom suffers particularly from this phenomenon (median value of 4 days per year where the *Daily weighted exceedance* criterion is reached under the RCP8.5 scenario, versus 2 for the living room). The *Static hours of exceedance* ($T_{op} > 26$ °C) criterion in the bedroom appears to be the most difficult to comply with in the future (criterion exceeded more than 50% of the years during the period 2071–2100 under the RCP2.6 scenario, and more than 75% of the years under the RCP8.5).

The *Adaptive hours of exceedance* and *Upper limit temperature* criteria are, however, rarely exceeded. These CIBSE criteria based on adaptive comfort appear, thus, easier to meet than benchmarks based on a fixed static value. It has been already shown that these criteria, based on a significant deviation from the comfort limits set by EN15251, are not very restrictive for this type of building and are not always representative of the number of complaints reported by the occupants [21]. It is, therefore, crucial to properly (re)consider (this also probably depending on the room type) the applicability and the limits of adaptive thermal comfort principles and strategies in residential buildings (EN15251 was originally established from data collected in offices) [43,44].

More generally, the passive strategies currently deployed (internal solar shading and natural cooling by windows opening in the living room only) might not be sufficient in the future. The widespread use of window curtains (which could be replaced by external solar shadings) and natural cooling by windows opening in all rooms (including bedrooms) could certainly contribute to improve the summer thermal comfort of the house, and probably limit the need of active cooling systems in the future. In this context, the potential decrease of (night)ventilative cooling efficiency due to higher (night)temperatures induced by climate evolution (as illustrated by Figure 5) should be explored in detail.

Further research focusing on the potential of such strategies in a global warming context is, therefore, needed. A more thorough understanding appears crucial to limit the potential global increase in cooling energy consumption [16] and to properly define policies and standards aiming at a better resilience of the building stock to heat waves [45].

5. Conclusions

Based on a whole building energy simulation, this paper investigated the potential evolution of summer thermal comfort in a typical nZEB house under different climate evolution scenarios (RCP2.6 and RCP8.5).

The study, based on compliance with CIBSE TM52 and TM59 summer thermal comfort criteria analyses, has shown that the passive strategies currently used in the selected case study (internal solar shading and intensive natural ventilation in the living room only) will not be sufficient in the future (especially in the bedroom) and that other strategies will be necessary to guarantee summer thermal comfort.

It has also been noticed that CIBSE criteria based on the theory of adaptive thermal comfort are much less restrictive in a context of changing climate than criteria based on a fixed static value. It is, therefore, crucial to verify the applicability of adaptive thermal comfort defined in EN15251 to the residential sector and its limits in the context of a changing climate.

More generally, the paper shows that considering summer thermal comfort, and its possible evolution, should be a priority for the design of nZEB houses (and related standards and policies) to avoid the generalised use of active cooling systems, with their induced environmental impacts, in temperate oceanic climates. Therefore, the full potential of passive design strategies to ensure summer thermal comfort under future climate scenarios have to be analysed more in depth.

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A.2. Contributions to the research sub-questions

What are the current summer thermal conditions experienced in low-energy houses (RQ1)?

Current summer thermal conditions in low-energy houses have been characterised, through Chapter III and Chapter IV, by combining two complementary perspectives: occupants' experiences of indoor thermal conditions and measured indoor temperatures.

From the occupants' perspective, summer thermal discomfort emerged as one of the main sources of dissatisfaction with Indoor Environmental Quality (IEQ). The post-occupancy evaluation conducted on subsample A.1 (n= 149; see Section II.3 p.83) highlighted that:

- low-energy houses were generally rated as more thermally comfortable in winter than in summer;
- overheating was the main source of IEQ-related discomfort, reported by 73% of respondents;
- overheating issues mainly occurred during the summer period in bedrooms, living rooms and kitchens, reported in 60%, 62%, and 51% of cases, respectively.;
- excessive heat from sunlight was identified in 65% of cases;
- 25% of respondents indicated that indoor temperatures increased rapidly;
- 38% stated that indoor temperatures decreased too slowly.

These results suggest that summer discomfort is not only associated with high indoor temperatures, but also with the difficulty of limiting solar heat gains and evacuating accumulated heat once the dwelling has warmed up.

The on-site interviews conducted with the 23 households of subsample A.2 confirmed this tendency and revealed important differences between rooms:

- bedrooms showed the highest level of dissatisfaction, with 20 out of 23 households reporting conditions ranging from slightly too hot to too hot;
- only two households appraised bedroom summer thermal conditions as comfortable;
- living rooms were also affected, although to a lesser extent, with six households reporting conditions ranging from slightly too hot to too hot.

The IEQ measurements, presented in Chapter IV, confirmed elevated summer indoor temperatures in the analysed dwellings (Subsample A.2, n=23):

- in living rooms, the mean percentage of occupied time above 25°C reached 8.9%;
- in bedrooms, the mean percentage of occupied time above 25°C reached 8.0%;

These values indicate a relatively high base temperature and led to widespread non-compliance with static overheating criteria:

- 18 cases out of 23 did not meet the Passive House Institute criterion, which limits the percentage of occupied time above 25°C to 5%, for at least one monitored room;
- this criterion was exceeded in 14 living rooms and 14 bedrooms;
- three living rooms exceeded the CIBSE Guide A criterion of 1% of occupied time above 28°C;
- 18 bedrooms exceeded the criterion of 1% of occupied time above 26°C, as defined by CIBSE Guide A and TM52.

The analysis based on adaptive overheating criteria provided a more nuanced picture, but still confirmed the relevance of overheating risks:

- in living rooms, four cases did not fulfil at least one of the CIBSE TM52 adaptive criteria;
- in bedrooms, four cases did not fulfil at least one of the CIBSE TM52 adaptive criteria, mainly related to $T_{max}+1$ and weighted exceedance;

Overall, only five buildings met all the criteria suggested by CIBSE TM52. Non-compliance was mainly related to bedroom temperatures exceeding 26°C for more than 1% of the occupied time.

The comparison between measured indoor conditions and occupants' appraisals also showed that the relationship between measured overheating and perceived discomfort appeared to vary according to the type of room:

- in living rooms, long-term appraisal of summer thermal conditions appeared to be more closely related to the frequency of extreme temperatures, especially exceedances of the adaptive upper limit temperature and of the 28°C threshold;
- in bedrooms, occupants' appraisal appeared to be more sensitive to smaller temperature deviations;
- the percentage of occupied time above 26°C was the only measured factor showing a statistically significant relationship with bedroom discomfort appraisal.

These results corroborate that occupants' perception of summer thermal conditions is room-dependent.

Taken together, these findings suggest that current summer thermal conditions in low-energy houses can be characterised by:

- a tendency towards elevated indoor temperatures, expressed not only through extreme peaks but also through relatively high base temperatures;
- significant perceived discomfort, particularly in bedrooms and main living spaces;
- a room-dependent relationship between measured overheating and perceived discomfort, with living rooms being more sensitive to higher temperature peaks and bedrooms being more sensitive to moderate exceedances.

How might climate change affect indoor summer thermal conditions (RQ2)?

Based on calibrated whole-building energy simulations and the integration of high-resolution climate data under low- and high-emission scenarios (RCP2.6 and RCP8.5 [222]), Chapter V aimed to evaluate the extent to which the design of a typical nearly Zero Energy Building (nZEB) house, and its current operation, could provide summer thermal comfort in a changing climate.

Under the historical climate scenario, the simulations confirmed the limited occurrence of overheating of the selected house (sample A.3), mainly because of its low exposure to solar gains, owing to its limited glazed area, and the passive-control strategies implemented, namely daily ventilative cooling in the living room and the use of white internal curtains as solar-shading devices.

Across the future climate scenarios, the Adaptive Hours of Exceedance criterion (maximum 3% of occupied hours where $T_{op} - T_{max} > 1$ K) continued to be met in the living room. By contrast, the Daily Weighted Exceedance criterion became increasingly difficult to satisfy under both RCP scenarios, indicating a reduced capacity to dissipate accumulated heat where ventilative cooling is typically not practiced during night.

The main bedroom showed particular vulnerability. The Static Hours of Exceedance criterion (maximum 1% of occupied hours where $T_{op} > 26$ °C) was exceeded in over 50% of the years during 2071–2100 under the RCP 2.6 scenario, and in more than 75% of the years under RCP 8.5. Non-compliance with this static threshold could thus become almost systematic under RCP 8.5.

These results therefore call for greater consideration of summer thermal adaptation and for the reinforcement of the strategies currently implemented.

Appendices F and G further explore the sensitivity of passive-control characteristics and the feasibility of achieving thermal autonomy in this dwelling under future climatic conditions through improvements to the implemented strategies. Together, they highlight the importance of generalising these strategies to all rooms in the building and ensuring their continuous operation. The results also show that, under current climatic conditions, different strategies can partly compensate for one another, for example through improved control or alternative combinations of measures. However, only the combined improvement of the technical characteristics of passive controls, including limited openness factor of solar shading, higher ventilative cooling air-change rates, and increased thermal mass, together with optimised operation, appears capable of effectively mitigating overheating risks under future high-emission scenarios. In this respect, the results corroborate the findings of De Pauw et al. [105].

Important note: At the time of initiating the work of Chapter V, the climate data from the ALARO Model [20] were the only publicly available. Lots of development have since been made and several sources of future weather datasets are now available to the building sector [19] [21, 22]. A preliminary comparative analysis of these datasets, presented in Appendix F, shows that the ALARO model produces the lowest temperatures under both historical conditions and future high-emission scenarios. Using other climate models for the study conducted in Chapter V would likely have strengthen the findings.

A.3. Conclusion

Part A of this research demonstrated that maintaining comfortable indoor thermal conditions during summer in newly built dwellings is already challenging in Wallonia, confirming concerns reported in other heating-dominated temperate regions. (see Section I.1.3).

Although low-energy dwellings are generally appreciated for their winter performance, the results illustrate their tendency to experience high indoor temperatures, making summer thermal discomfort the most frequently reported source of IEQ-related discomfort among occupants. In this respect, the results confirm that sleeping environments are particularly at risk and that climate change will inevitably exacerbate this situation.

The results of Chapter IV also indicate that perceived discomfort in living spaces is mainly associated with highest indoor temperatures. In sleeping environments, by contrast, even relatively small temperature deviations are associated with higher levels of discomfort and more frequent complaints. This difference may be explained by occupants' more limited opportunities for adaptation during the night and by the potential effects of even moderate heat exposure on sleep quality and recovery.

Nevertheless, the results also show that the diagnosis of overheating strongly depends on the comfort model applied, whether static or adaptive, particularly in the context of climate change. Consequently, the limitations of adaptive comfort model, as well as the conditions governing its applicability, should be carefully considered in residential contexts, especially in sleeping environments.

More generally, the results of Part A call for greater attention to the design strategies and comfort models used to support more effective summer thermal adaptation in residential buildings.

“The future depends on what you do today.”

Mahatma Gandhi

PART B. ON THE INTEGRATION AND USE OF PASSIVE CONTROLS

B.1. Scope and research objectives

Passive controls have consistently been identified as effective means of mitigating overheating risks and supporting the operation of free-running residential buildings in temperate climates (see Section 1.1.1.7). Previous studies often suggest that appropriate design, combined with the proper integration and operation of passive controls aimed at limiting solar gains and enhancing heat dissipation, could have prevented the overheating situations identified in Part A.

Also, in future conditions, passive control implementation will be crucial to limit the widespread and uncontrolled adoption of low temperature active cooling systems which would inevitably lead to increased energy consumption [118], greater environmental impacts [118], and, in urban contexts, an intensification of the Urban Heat Island effect [223]. Moreover, passive controls are recognised as enhancing building resilience in the event of power outages [224] and supporting human adaptation to heat [43].

Taken together, these considerations call for greater attention to the practical implementation of passive controls in contexts where their use is not culturally embedded. Consequently, Part B of this research, comprising Chapter VI and Chapter VII, focuses on current practices related to the integration and use of passive control strategies in dwellings.

More specifically, as illustrated by Figure B.1, Chapter VI addresses Research Objectives 5 and 7 by assessing current integration practices (RO5), as well as the effectiveness of their use by occupants (RO7). Chapter VII then examines the factors shaping these practices, thereby addressing Research Objectives 6 (RO6) and 8 (RO8).

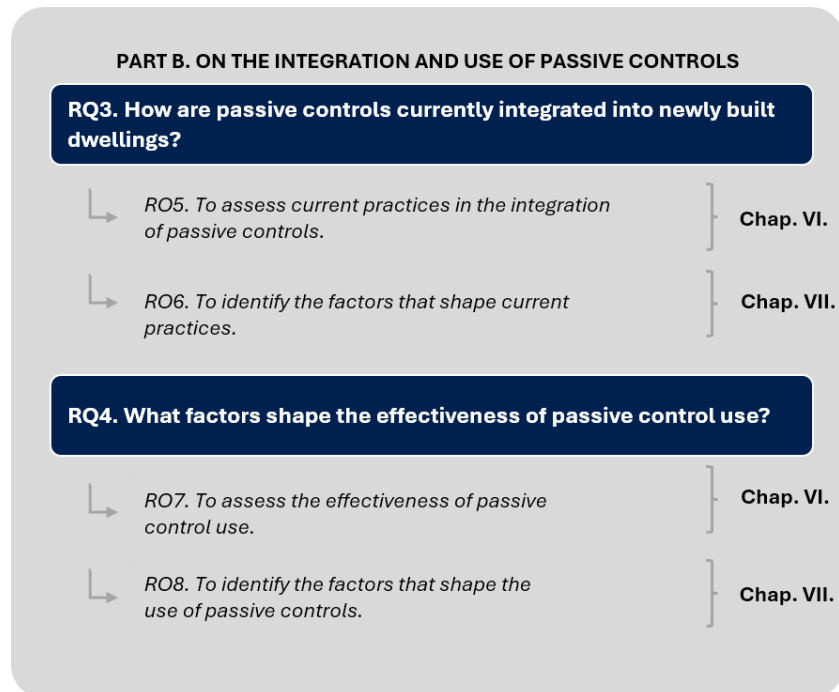


Figure B.1. Research sub-questions addressed in Part B. with their corresponding research objectives and chapters.

Chapter VI. On the effectiveness of passive controls for summer thermal comfort

This chapter is based on the following publication:

Title: *On the effectiveness of passive controls for summer thermal comfort in highly insulated dwellings.*

Journal: Building Research and Information.

Year: 2024.

Role of the thesis author: Lead author. Table VI.1 further details the author's contributions to this publication.

Table VI.1. Contributions of the thesis author to the paper constituting Chapter VI., according to the CRediT taxonomy [213].

Contribution Type	Chapter VI
Conceptualization	✓
Data curation	✓
Formal analysis	✓
Investigation	✓
Methodology	✓
Software	✓
Validation	✓
Visualization	✓
Writing – original draft	✓
Writing – review & editing	✓ ¹

¹: In collaboration with Erwin Mlecnik (TU Delft), Geoffrey van Moeseke, Gabrielle Masy and Sergio Altomonte (UCLouvain).

Citations: 8 citations according to Google Scholar (July 2026).

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RESEARCH ARTICLE



On the effectiveness of passive controls for summer thermal comfort in highly insulated dwellings

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ABSTRACT

Among environmental controls, solar shading and ventilative cooling are widely considered as key passive strategies for limiting the overheating risks in buildings. While their application is encouraged through Energy Performance of Buildings Directive regulations, several studies have shown that summer thermal comfort in heating-dominate temperate climates still requires deeper investigation, particularly in low-energy residential buildings. Based on qualitative and quantitative data collected through surveys and monitoring in 147 highly insulated houses in Wallonia (Belgium), this paper gives an overview of the implemented passive strategies and discusses their effectiveness. Statistical tests are conducted to evaluate their impact on both perceived and measured indoor conditions. In general, the results highlight a limited impact of the implemented strategies, questioning their proper operation. Operational modes for environmental controls thus appear crucial, and should better respond to occupants' needs, preferences and control opportunities. At a more general level, the study calls for a better understanding of the barriers inhibiting successful integration and operation of environmental controls, in order to effectively reduce overheating risks in residential buildings and limit future diffusion of active cooling systems with their induced environmental impacts.

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Solar shading; ventilative cooling; passive strategies; summer thermal comfort; overheating; highly insulated buildings

Introduction and background

The concern for summer thermal comfort in buildings has also increased for temperate climates over the recent years (Beizaee et al., 2013; Lomas & Kane, 2013; Pathan et al., 2017; Yannas & Rodríguez-Álvarez, 2020). While heatwaves are expected to become more intense and frequent (Ouzeau et al., 2016), it is recognized that excessive exposure to such conditions can negatively impact the comfort, well-being and health of people (World Health Organization, 2004). Various studies (Jones et al., 2016; Yannas & Rodríguez-Álvarez, 2020) have shown that highly insulated and airtight dwellings, which are increasingly encouraged by the general application of the nearly Zero Energy Buildings (nZEB) framework (European Parliament, 2018; European Commission, Directorate-General for Energy, 2021) in heating-dominated temperate climates, are particularly subject to overheating risks. In response, there is a need for the building sector to target achieving comfortable and healthy indoor thermal conditions during summers (Ortiz et al., 2020), yet also limiting the diffusion of active cooling systems (Yang et al., 2021) owing to their energy use and induced environmental impacts (Ademe & Coda-strategies, 2021).

For summer periods in temperate climates, the most effective combination of passive strategies – that is, strategies requiring none to very little energy for their operations (Chan et al., 2010) – is based on the use of solar shading and ventilative cooling (Encinas & De Herde, 2013; Porritt et al., 2012; van Hooff et al., 2015). Various studies have found these techniques capable of maintaining summer thermal comfort (Figueiredo et al., 2016; Tink et al., 2018; van Hooff et al., 2015; Yannas & Rodríguez-Álvarez, 2020).

By absorbing or reflecting solar radiation, solar shading devices can limit the portion of solar radiation that reaches interior spaces in buildings. According to the Technology Readiness Level (TRL) metric, a metric used for assessing the maturity of various technologies (European Commission, 2014), solar shading devices are proven in operational environments (TRL 9 [Zhang et al., 2021]). Different types of solar shadings are available in the market: interior or exterior, fixed or mobile, automated or manual, etc. In general, external solar protections are considered as one of the most effective means for preventing overheating (Mlakar & Štrancar, 2011; Porritt et al., 2012; van Hooff et al., 2015), and their usefulness is recognized in many

climates (Gamero-Salinas et al., 2020; Harkouss et al., 2018; Zhang et al., 2021). Internal solar shading devices, generally being less expensive than the external ones, are also less efficient in limiting solar radiations – since part of the heat transmitted through glazing remains trapped inside the room. However, the use of light colours or reflective material can improve their efficiency by increasing the reflection of solar radiation towards the outside (yet, without reaching the performance of an external protection). In the Belgian temperate climate, it has been shown that cooling needs could be reduced by 37% using internal light-coloured solar shading devices, and by 70% using external solar shading with low openness factor (Dartevelle et al., 2015).

Ventilative cooling is also considered as a very efficient passive strategy (Hamdy et al., 2017; Mlakar & Štrancar, 2011; van Hooff et al., 2015). Aiming to remove sensible heat from the inside (Zhang et al., 2021), ventilative cooling can be achieved naturally in residential buildings by simply opening windows when the outdoor temperature is lower than the indoor temperature. At TRL 9 (Zhang et al., 2021), it does not require any additional technology. The effectiveness of the technique will depend on the position, size and characteristics of the openings, the presence of wind, but also the difference between outdoor and indoor temperatures (Bernard et al., 2018). The efficiency of ventilative cooling increases with the difference between the outside and the inside temperature, outside being lower. Night time is therefore ideal for this type of ventilation, and is recommended in the literature (Heraclous & Michael, 2018; Weng, 2017).

The thermal mass (concrete, masonry, stone, etc.) of a building and its accessibility i.e. contact with the indoor environment, can also influence indoor summer thermal conditions (Kisilewicz, 2015; Mlakar & Štrancar, 2011). When in contact with the indoor environment, thermal mass can absorb, store and release thermal energy to regulate the indoor temperature on a cyclical basis (Zhang et al., 2021). It has been shown that accessible thermal mass does not lower indoor daily mean temperature compared to lightweight buildings, but has the capacity to limit indoor temperature extremes (Staepels et al., 2013). Consequentially, many authors recommend the use of high thermal mass in residential buildings (Kuczyński et al., 2021; Verbeke & Audenaert, 2018). However, the efficiency of this strategy depends on many other factors: climatic conditions, exposure to heat sources, characteristics of the envelope, time when it is desirable to limit the interior temperatures (depending on the presence of the occupants), ventilation schedule, etc. (McLeod et al., 2013; van Hooff et al., 2015). It is recognized that the potential

of thermal mass to prevent overheating is greater when combined with an effective ventilative strategy, such as night cooling (Kuczyński et al., 2021; Mhuireach et al., 2020; Pomfret & Hashemi, 2017; Yannas & Rodríguez-Álvarez, 2020).

Many authors have shown, based on simulation (Figueiredo et al., 2016; van Hooff et al., 2015; Zinzi et al., 2017) and/or monitoring studies (Tabatabaei Sameni et al., 2015; Tink et al., 2018; Yannas & Rodríguez-Álvarez, 2020), that it is often possible to reach acceptable indoor summer thermal conditions using passive strategies only, and without any active cooling system. For future climate scenarios, however, the debate is still open, with some authors warning that these measures could indeed be insufficient (Dodoo & Gustavsson, 2016; Ortiz et al., 2020). In any case, it is well ascertained that the implementation of passive techniques may limit the environmental impacts related to the use of air-conditioning by reducing buildings' cooling needs (Yang et al., 2021) and facilitating the adoption of low enthalpy systems (De Pauw & Jeroen., 2022).

Occupant behaviour could however be a key factor affecting the efficiency of these strategies, especially when manual interventions are required for their operation (i.e. for windows opening, solar shading closure) (Mavrogianni et al., 2017). As a consequence, the definition and simulation of occupant behaviour have gain of interest this last decade (Yan & Hong, 2018). In this way, it is recognized that occupants could play a considerable role in controlling summer thermal conditions (Mavrogianni et al., 2017; Ozarisoy & Elsharkawy, 2019). Authors have thus warned about the importance of properly disseminating information to the occupants (Mlakar & Štrancar, 2011; Tabatabaei Sameni et al., 2015) and have identified factors such as security, noise, pollution, etc. that could limit their actions (Tillson et al., 2013).

While the potential of these techniques is widely recognized, their practical efficiency needs to be questioned, especially in temperate climates without a tradition for implementing such techniques. In fact, while the application of these techniques is encouraged by building energy codes for new buildings, for example, the Energy Performance of Buildings Directive (EPBD) (European Parliament, 2018), it has been shown in heating-dominated regions such as Wallonia, Belgium, that overheating is still an important cause of discomfort in recently-built highly insulated houses (Jones et al., 2016; Ortiz et al., 2020; Rohdin et al., 2014; Toledo et al., 2016). This is also the case when renovations are conducted (Singh et al., 2014). The reasons behind this situation need to be explored. In this context, this paper gives an overview of implemented summer passive strategies in recently-built highly insulated houses, and discusses their practical

impact on the perceived and measured indoor thermal conditions. The main novelty of the paper is thus to question, evaluate and discuss the effectiveness of these passive controls in actual situations.

Method

Data regarding implemented passive summer strategies, and the perceived and measured summer thermal conditions for this study, were primarily extracted from previously conducted Post Occupancy Evaluations (POEs) (Dartevelle & Vanwelde, 2018). These POEs had collected data via survey and measurement campaigns in highly insulated houses in Wallonia between 2015 and 2018. On the extracted data, statistical tests were performed to evaluate how the implemented strategies effectively improved summer thermal conditions. The set-up of this method is illustrated in Figure 1.

The analysed buildings were part of a public action accompanying the first steps of the EPBD implementation (European Parliament, 2018). Their main characteristics (geometry, constructions characteristics and estimated energy performance according to EPBD calculation) were available in a dedicated database. All selected dwellings had been occupied for a minimum of 3 years in order to guarantee a sufficient living experience of the users (Li et al., 2018).

The methods used for the survey and measurement campaigns, described in the following subsections, were submitted for approval to the Belgian Data Protection Authority (number VT005055129) and, in this context, an informed consent was obtained from all participants.

Survey

Data regarding implemented passive summer strategies and perceived summer thermal conditions were derived from the results of the survey conducted on the initial sample of 453 houses by means of an online questionnaire using Limesurvey (Limesurvey GmbH, 2006–2023).

The questionnaire was launched at the end of 2015. It was compound of 59 questions and included three parts. The first part focused on occupants' appraisal of the Indoor Environmental Quality (IEQ) of the building (25 questions), the second aimed to verify and complete the known buildings' characteristics (10 questions) and the third was dedicated to ascertaining the profiles and the habits of the occupants (24 questions). The occupants were asked to give a general appreciation or description, not particularly relating to the moment when the questionnaire was completed. A total of 147 complete responses (one per house) were received, representing a response rate of 32.5% (incomplete or

judged unreliable data were first removed). In the following, this sample is defined as S1 ($n = 147$).

For the present study, the answers to the following questions were specifically analysed and discussed:

Q1. Do you experience overheating situations in your dwelling? In which room and season?

Q2. Do you use solar shading to protect against the heat of the sun? (Examples of solar shading were given, including both external and light-coloured reflective internal devices)

Q3. Were these solar shading devices present at the end of the construction stage?

Q4. Are they automatized? (automatic closing and opening)

Q5. Do you open the windows in order to cool down the rooms? In which room, season and moment of the day (day and/or sleeping time)?

After conducting a pilot test, which involved a focus group with an independent group, and considering that evaluating the frequency of discomfort episodes was the main objective of the measurements campaign (see next section), discrete answer options (i.e. yes or no) were preferred. This choice aimed to facilitate and speed-up questionnaire responses, as well as enhance user acceptability of the survey. The authors, however, acknowledge that using Likert scales would have allowed the introduction of 'quantitative' aspects and more nuanced analysis.

These questions were intended to give an overview of the implemented strategies. In order to get the full picture of their implementation by the occupants, capturing the moment, the frequency and duration of actions (opening/closure) and/or episodes of discomfort would have been necessary, which was out of the scope of the survey.

Measurements and on-site verifications

Data regarding measured summer thermal conditions were derived from measurements conducted just after the survey campaign, on a subsample of 23 buildings (S2, $n = 23$). This subsample was selected from the first sample (S1, $n = 147$) based on the agreement of the occupants and on the feedback received in terms of overheating complaints. The aim of this purposive sampling was to have a similar overheating complaints rate in subsample S2 compared to sample S1. Key indicators of Indoor Environmental Quality (air temperature, relative humidity, CO₂, sound level) were measured during one entire year with a 10 min time step. Two initially participating houses had to be removed since the participants dropped out, and have thus not been included in S2.

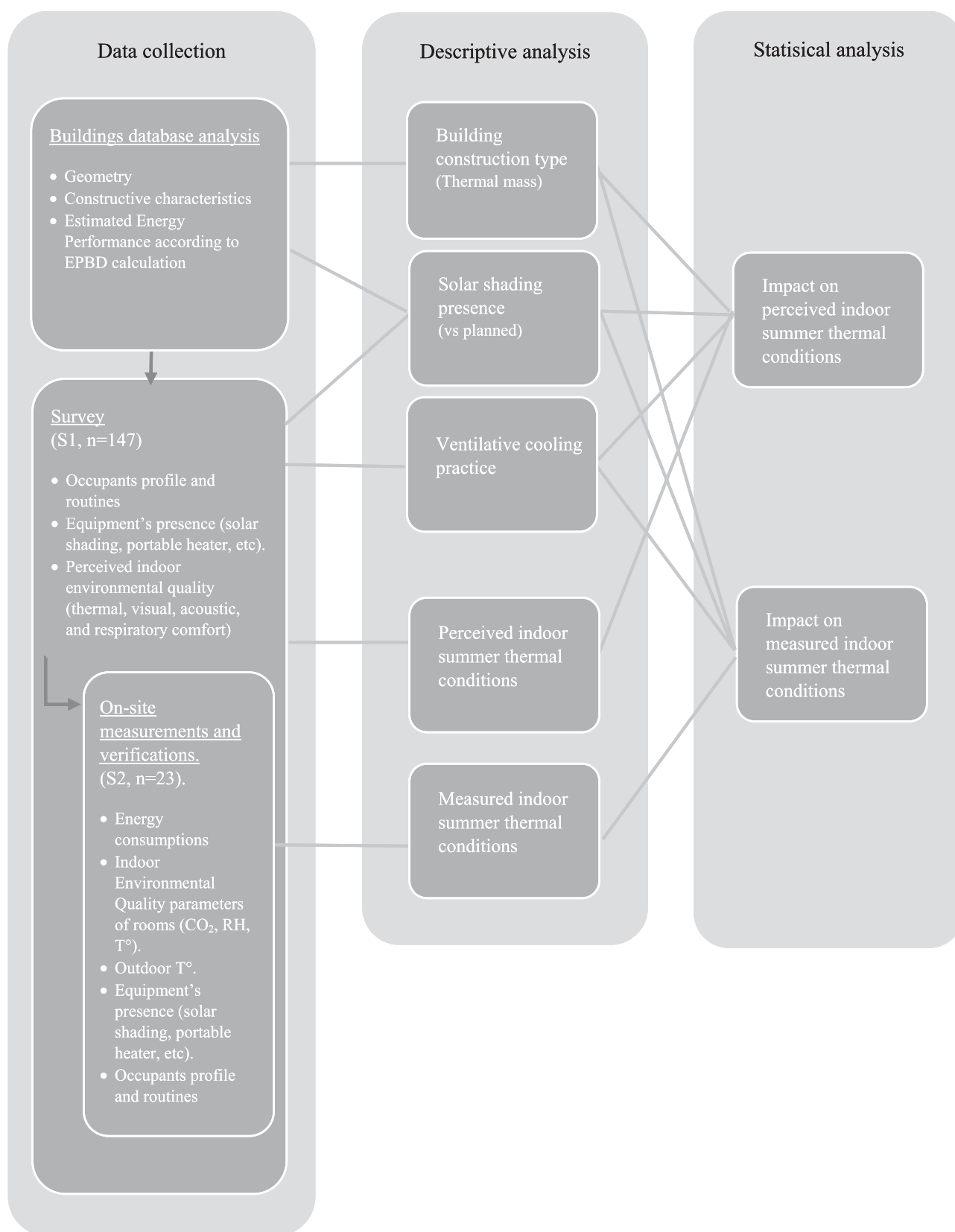


Figure 1. Workflow of the study.

The campaign took place in 2016, a year that can be considered broadly an average of the last 30 years for solar radiation and temperature (Royal Meteorological Institute of Belgium, 2017). Six days exceeded the maximum temperature of 30°C, 25 days exceeded 25°C and 97 days exceeded 20°C.

The measuring devices (Netatmo sensors with verified tolerance of $\pm 0.3^\circ\text{C}$) were all calibrated by the Belgian Building Research Institute (BBRI) before the measurement campaign. Sensors were placed on top of existing furniture at a minimal height of 80 cm by the research team, and were placed away from other internal heat sources and windows to avoid direct solar radiation.

For the present analysis, the percentage of occupancy time when indoor air temperature exceeded 25°C was used to describe indoor summer thermal conditions.

This indicator differs from common overheating criteria since it is based on air temperature and not operative temperature; although these two values are frequently considered equivalent in highly insulated building (Fletcher et al., 2017; Gamero-Salinas et al., 2020). As most common time-integrated indices used to describe overheating in buildings (Rahif et al., 2021) the other environmental parameters such as air velocity and relative humidity, and personal factors such as clothing factor and metabolic rate, which affect thermal comfort, are neglected. It is also acknowledged that a criterion exclusively based on the percentage of time exceeding a specific indoor air temperature, might not be directly representative of thermal comfort – as it does not consider the adaptive capacity that occupants could have in certain rooms (de Dear et al., 2020; NBN, 2019). There is still however discussion on the applicability of this adaptive capacity in residential contexts, especially in sleeping area where the adaptive capacity of occupants may be reduced (Peeters et al., 2009). Some authors have thus proposed new limits, specifically dedicated to residential buildings (de Dear et al., 2018; Peeters et al., 2009). As the focus of this study was to illustrate the impact of summer passive strategies on indoor conditions, rather than their implication on thermal comfort, a static threshold based on air temperature was preferred. This criterion has the advantage of offering a shared basis for the description of indoor conditions (Fletcher et al., 2017; Fokaides et al., 2016; Lomas & Kane, 2013; McLeod & Swainson, 2017). This can facilitate the comparison between different rooms and buildings, which were all exposed to the same climate. Also, using a relatively low threshold, such as 25°C, gave a specific value for all rooms of all buildings, differing from 0 and improving the statistical power of the conducted analysis.

As room occupancy was found to considerably vary across days and houses, and in the absence of

continuous high-resolution spatio-temporal models of occupants' location, realistic assumptions had to be made. Based on feedback from households, and in line with similar studies (Adekunle & Nikolopoulou, 2016; Fletcher et al., 2017; Lomas & Kane, 2013), assumptions were made for general occupancy. For living room, general occupancy was assumed between 7 am and 10 pm, and for bedrooms between 10 pm and 7 am, for cases that were occupied during working hours ($n = 7$). Conversely, for houses that were unoccupied during the day ($n = 16$), occupancy of the living room was considered only from 7 am to 9 am and from 5 pm to 10 pm on business days. Known periods of prolonged absence (e.g. vacations) were excluded from the analysis, in order to limit bias that could be induced by uncontrolled situations (i.e. no action undertaken by the occupants to control solar radiation or to dissipate the heat accumulated in the building).

While installing the measuring devices, the research team visited the houses and conducted semi-structured interviews with occupants in order to verify the data collected by means of the survey, e.g. routines, satisfaction and buildings characteristics. No substantial discrepancies were found especially in the reported actions. Nevertheless, some informal discussion with the occupants regarding their ventilative cooling practice suggested that improvements were possible, especially regarding the duration and moment of openings. Additionally, a grey coloured internal solar shading device, which did not demonstrate high reflective properties, was not considered in the analysis.

In a few cases, discrepancies were also found between perceived discomfort reported during the initial survey and measured data. Despite this subject being relevant in thermal comfort domain, the analysis was out of the scope of the present paper aimed at questioning the effectiveness of passive controls. It was thus not analysed in this paper, since this would necessitate specific approaches such as considering perceived comfort directly related to the measured period.

Statistical analysis

Statistical analysis has been carried out to evaluate whether the presence of solar shading (external or light-coloured/reflective internal devices), ventilative cooling practice and/or high thermal mass of the building significantly reduced the frequency of overheating discomfort reported by occupants (survey data) and the time when temperature exceeded 25°C (measurements).

The influence on perceived discomfort was studied through a chi-squared analysis (Fisher, 1922; Pearson,

1900) to compare the observed frequencies with those expected by-chance in various categories.

Since the data distributions were significantly different from normal (p -value of Kolmogorov–Smirnov test $< .001$ (Kolmogorov, 1933; Smirnov, 1939)), a Wilcoxon non-parametric test was used to analyse the influence on temperature exceeding 25°C (Wilcoxon, 1945). This test, based on ranked values, estimates the probability of having the same difference of medians between two samples, if these were part of the same population.

Due to the limited size of the sample, to counteract the risk of not detecting an effect that actually exists (Type II error), the analysis calculated, for each test, both the statistical significance (p -value at the alpha level of .05) and the effect size of the detected differences. The effect size offers a standardized method to estimate the magnitude and the substantive relevance of the differences or deviations between groups of data (Field et al., 2012), without being subjected to some of the limitations of null hypothesis significance testing (NHST). Pearson r effect sizes were estimated based on Rosenthal (Rosenthal, 1991). The Cohen interpretation of effect size values was used for this study: $r > 0.1$ small; $r > 0.3$ medium; $r > 0.5$ large (Cohen, 1992).

Building characteristics and occupant profiles

The dwellings that were selected to be part of the samples were mainly energy efficient detached single-family houses, which composed about 90% of the entire sample. This building type represents 79.7% of the Belgian housing stock (Anfrie et al., 2017).

The houses are all located in Wallonia, in the southern part of Belgium, and correspond to a latitude of around 50° North. This falls in a Cfb climatic zone, which is a temperate oceanic climate according to the Köppen–Geiger climate classification system (Peel et al., 2007). The monitored houses of subsample S2 are all located in semi-rural to rural settings, and have little-to-none surrounding obstructions, which potentially allows an optimal facade orientation.

Quantitative and qualitative characteristics of the buildings featured in sample S1 and subsample S2 are presented in Figures 2 and 3. These data were collected from the available Belgian EPBD calculations database (Gouvernement wallon, 2008) and from the conducted survey and on-site measurements/verifications. In Figure 2, quantitative characteristics are presented using boxplots to illustrate the range and distribution of variables: minimum, 25th percentile, median, 75th percentile, maximum. Mean values are also indicated by a circular dot to enhance readability. It must be

noted that the presented characteristics of S1 also include the characteristics of its subsample S2.

In general, the buildings present the following characteristics: heated floor area close to 220 m^2 , mean U -value of $0.22\text{ W/m}^2\text{ K}$ (ranging from 0.09 to $0.4\text{ W/m}^2\text{ K}$) for walls, mean U -value of $0.16\text{ W/m}^2\text{ K}$ (ranging from 0.09 to $0.38\text{ W/m}^2\text{ K}$) for roof, mean U -value of around $1.5\text{ W/m}^2\text{ K}$ (ranging from 0.71 to $1.9\text{ W/m}^2\text{ K}$) for windows, and mechanical ventilation with heat recovery (95% of the cases for S1 and 100% for S2) resulting in a mean heating need close to $40\text{ kWh/m}^2\text{ year}$ (ranging from 0 to $105\text{ kWh/m}^2\text{ year}$). Around 75% of these houses are constructed using traditional masonry, that is, cavity walls. Following a simplification of the Belgian EPBD classification based on the thermal capacity of building elements, these houses are considered as heavy constructions, even in case of wood structure for the roof. Conversely, the buildings that do not reach 50% of horizontal and vertical elements presenting at least an accessible mass of 100 kg/m^2 are considered as light constructions. In practice, the houses presenting this condition (1 out of 5 in S1, and 1 out of 4 in S2) were found to have a timber frame.

Overall, all these highly insulated dwellings – built with a focus on the reducing heating energy demands – can be considered as at least ‘low-energy houses’. In fact, 11% of the cases present characteristics close to the ‘passive standard’ (Plate-forme Maison Passive, 2020). By extension, they can be considered as representative of current building practices in Wallonia in terms of envelope performance.

The households size varied between 1 and 7 people, mostly families with children (mean of 3.5 people), and all the dwellings were owner-occupied. In terms of occupancy schedule, dwellings are mainly occupied at the end of the day and at weekends (cf. Figure 3). In 30% to 36% of the dwellings, respectively for subsample S2 and sample S1, occupants were usually present during the day. The respondent to the survey (one per household), was a male with average age of 44 years, in 80% of the cases. Almost all respondents (92% for S1 and 100% in S2) have high education qualification, and only 1% of S1 was unemployed. 92% and 95% of respondents formulate to understand or to master the technical principles of their house. This profile of educated, informed and aware respondents is likely to enhance the quality of the collected data, but cannot be considered as representative of the general population.

Results

The following section presents the data collected on the implemented summer design strategies, that is, presence of solar shading devices and the practice of ventilative cooling by windows opening. Further, the

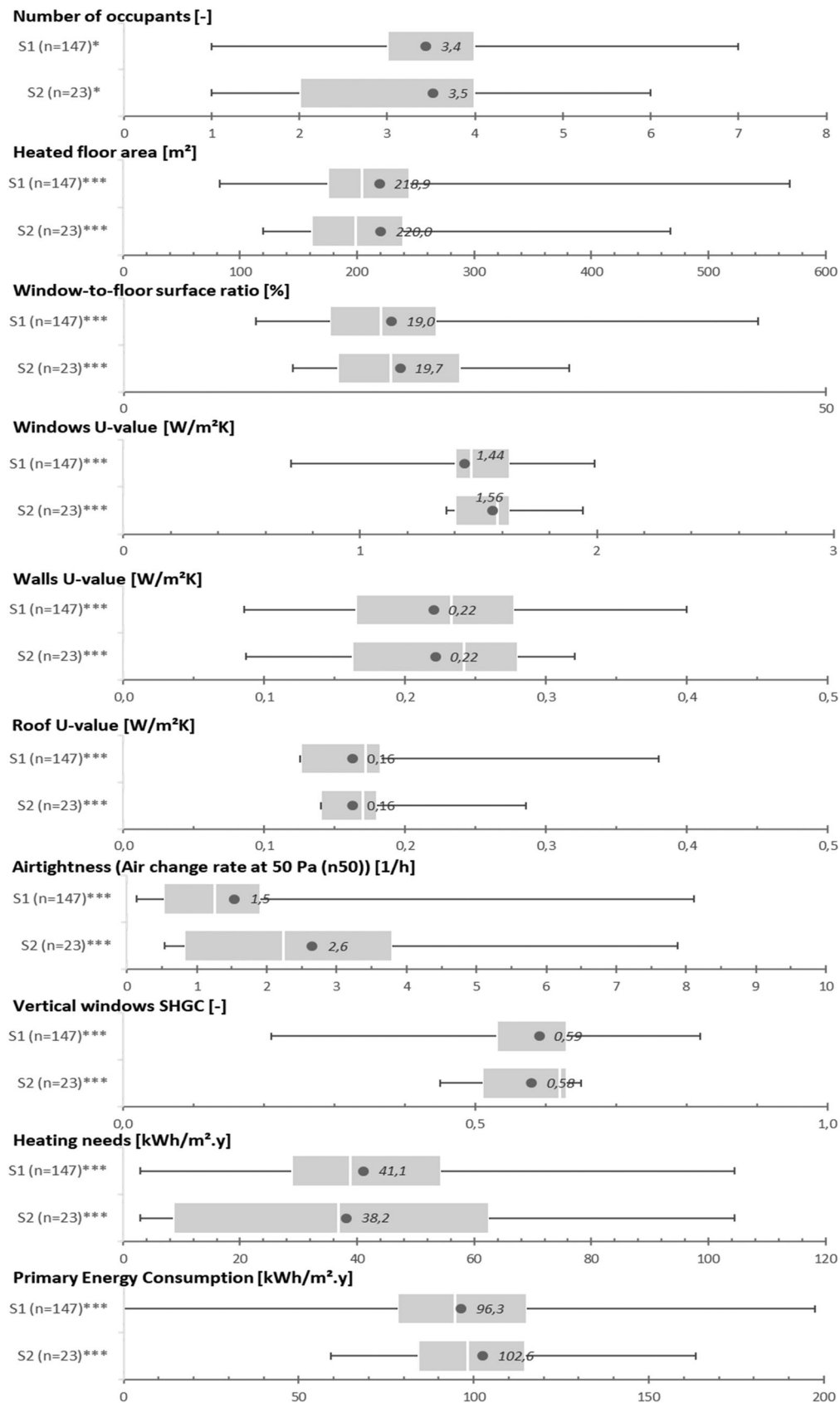


Figure 2. Quantitative characteristics of the buildings featured in sample S1 and subsample S2. Source of data: *On-site verification; *** Belgian EPBD calculation.

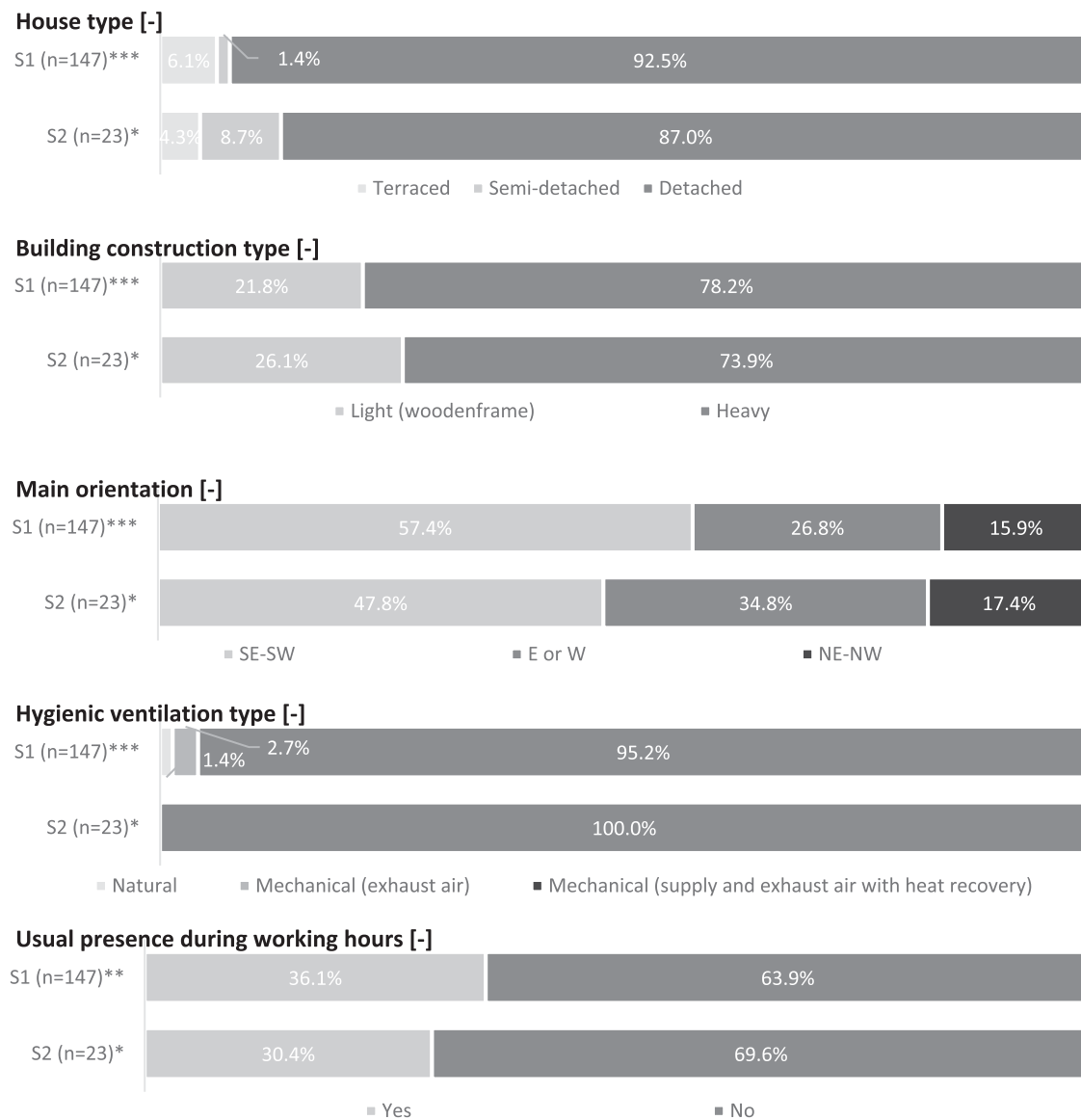


Figure 3. Qualitative characteristics of the buildings featured in sample S1 and subsample S2. Source of data: *On-site verification; ** Survey; *** Belgian EPBD calculation.

results of the statistical analysis are presented, which evaluated how effectively these strategies improved the perceived and measured indoor conditions. The results of each test, indicated on the upper part of each corresponding figure, are analysed using statistical significance and effect size of the detected differences.

Solar shading presence, position and control type

The following figures describe the presence, position (Figure 4) and control type (Figure 5) of solar shading in sample S1 and subsample S2. These data were collected by means of the questionnaire (questions Q2, Q3, Q4) for sample S1 and were discussed with the occupants for subsample S2.

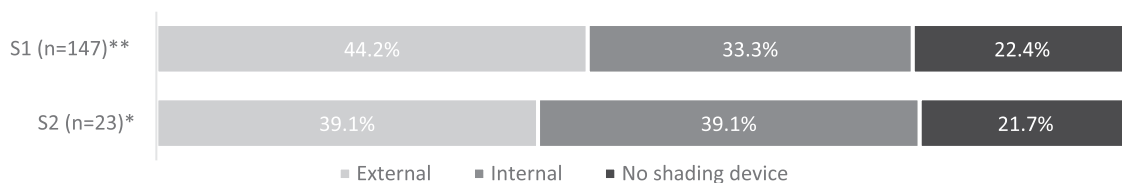


Figure 4. Solar shading presence and position encountered in sample S1 (top) and subsample S2 (bottom). Source of data: *On-site verification; ** Survey.



Figure 5. Solar shading device control types encountered in sample S1 (top) and subsample S2 (bottom). *Source of data: *On-site verification; ** Survey.*



Figure 6. Percentage of shading devices present at the end of the construction stage in sample S1 (top) and subsample S2 (bottom). *Source of data: *On-site verification; ** Survey.*

Figure 4 shows that around 40% of the houses were equipped, at least partially, with external devices. Also, more than a third of the sampled houses had a light-coloured or reflective internal shading. Around a fifth of the cases did not have any solar shading device. Figure 5 shows that very few were equipped with automatic control (17.5% in S1 and none in S2). Figure 6 illustrates that only between 16% (subsample S2) and 33% (sample S1) of these shading devices were placed at construction stage.

Detailed characteristics of shading devices, such as fixed or mobile, device materials, whether parallel to the glazing, etc. have not been collected in detail through the survey. Nevertheless, open commentaries suggest that shading devices parallel to the glazing, such as screens and venetian blinds, are the most common external systems, and that internal protections often were light-coloured internal curtains. On-site verifications confirmed these observations for subsample S2 ($n = 23$). No automatized system was encountered in subsample S2, but open commentaries of the conducted survey suggests that they were mainly based on incident solar radiation in Sample S1.

Ventilative cooling practice

Figures 7 and 8 illustrate the ventilative cooling habits of the occupants in sample S1 ($n = 147$) and subsample S2

($n = 23$). These data were collected by means of the questionnaire (question Q5) for sample S1 and were discussed with the occupants for subsample S2.

The data show that ventilative cooling by windows opening was practiced between 50% of the cases (S2) in the living room and more than 70% in other rooms (S1 and S2). Night ventilative cooling seems easier to practice in the bedrooms (Figure 8) than in the living rooms (Figure 7) (45.6% of the cases versus 11.6% in sample S1). Results for the living room of subsample S2 (Figure 7) differ considerably, showing more night opening practice (43.5%) but also more cases where no ventilative cooling was practiced in the living room (47.8%). As a consequence, results of subsample S2 regarding night ventilative cooling practice could not be considered as representative of the habits of the larger sample.

Characteristics of windows type and opening mechanisms have not been collected in detail through the survey. Nevertheless, on-site verifications confirmed typical trends of the Belgian housing market: sliding and 'tilt and turn' were the main encountered types of windows in the living rooms while 'tilt and turn' and openable roof windows were mostly encountered in bedrooms. There is thus no doubt about the fact that the aperture areas of these opening systems have the capacity to contribute to effective ventilative cooling.

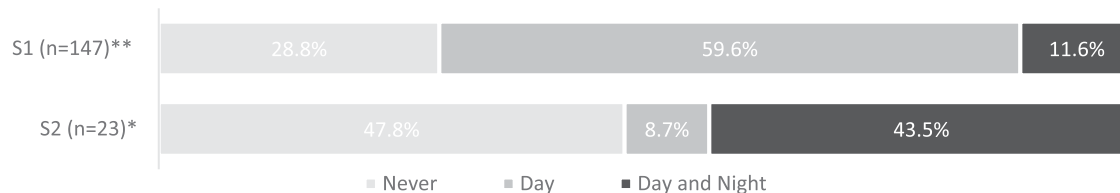


Figure 7. Percentage of cases where there is a ventilative cooling practice in the living rooms for sample S1 (top) and subsample S2 (bottom). *Source of data: *On-site verification; ** Survey.*

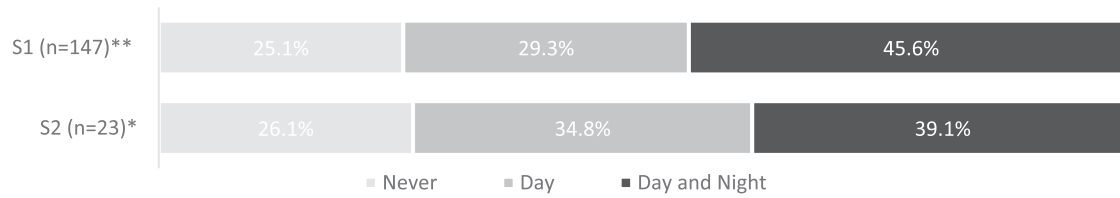


Figure 8. Percentage of cases where there is a ventilative cooling practice in the bedrooms for sample S1 (top) and subsample S2 (bottom). Source of data: *On-site verification; ** Survey.

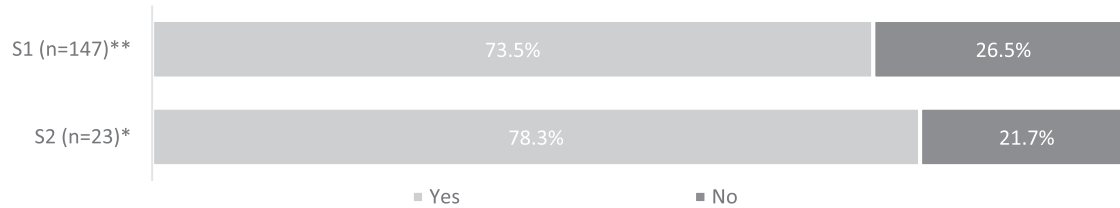


Figure 9. Percentage of cases where an overheating discomfort is encountered in sample S1 (above) and subsample S2 (below). Source of data: *On-site verification; ** Survey.

Impact on perceived discomfort

The distributions of responses illustrated in Figures 9 and 10 correspond to the following question:

Q1. Do you experience overheating situations in your dwelling? In which room and season?

The figures show that the percentage of cases where overheating discomfort was reported by the occupants reaches 73% for sample S1 and 78% for subsample S2 (Figure 9). As illustrated by Figure 10, these occurrences of discomfort were reported mainly during the summer in the living areas, such as living rooms, bedrooms and kitchens. The definition of summer was not detailed in the survey. However, meteorological summer is considered from the beginning of June to the end of August in Belgium. During the other seasons, the percentage of reported discomforts is almost non-existent. Only a few percentage (maximum 5%) of respondents reported a discomfort during the spring season. The following illustrates, for sample S1 ($n = 147$), the influence of the presence of passive strategies on the frequency of overheating complaints reported by occupants. Results of the chi-squared tests conducted on these data are presented above each graph.

Figure 11 illustrates this for cases with solar shading absence/presence (left) and according to the position of solar shading (right). The analysis shows that, for the sample studied, the frequency of reported complaints does not differ significantly in case of solar shading presence, and stays around 70%. In fact, the statistical tests did not detect any significant difference ($\chi^2 = 0.68$, n.s.) with the Pearson effect size being <0.1 ($r = 0.02$). Similarly, an external position of the shading device

did not lower the frequency of complaints compared to internal shading ($\chi^2 = 0.12$, n.s., $r = 0.01$). It is also interesting to note that 28% of the cases without solar shading did not encounter overheating discomfort (=9% of the sample). This should result from a combination of influencing factors: reduced glazing surfaces, orientation, lower SHGC, environmental shadings, etc.

Figure 12 illustrates the frequency of overheating complaints reported by the occupants of sample S1 ($n = 147$) for the cases with and without ventilative cooling practice by windows opening (left). The figure shows that window opening is more often exerted when overheating is encountered. This effect is small ($r = 0.20$) but statistically significant ($\chi^2 = 5.92$, $p < .05$). Conversely, the graphs on the right shows that, for the studied sample, the frequency of reported complaints does not

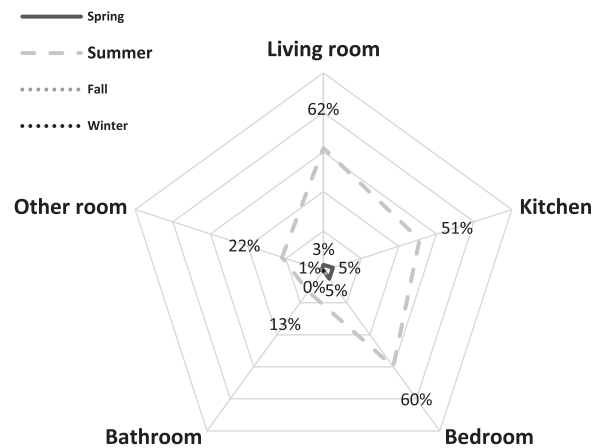


Figure 10. Localization and moments of overheating discomfort in sample S1. Source of data: Survey.

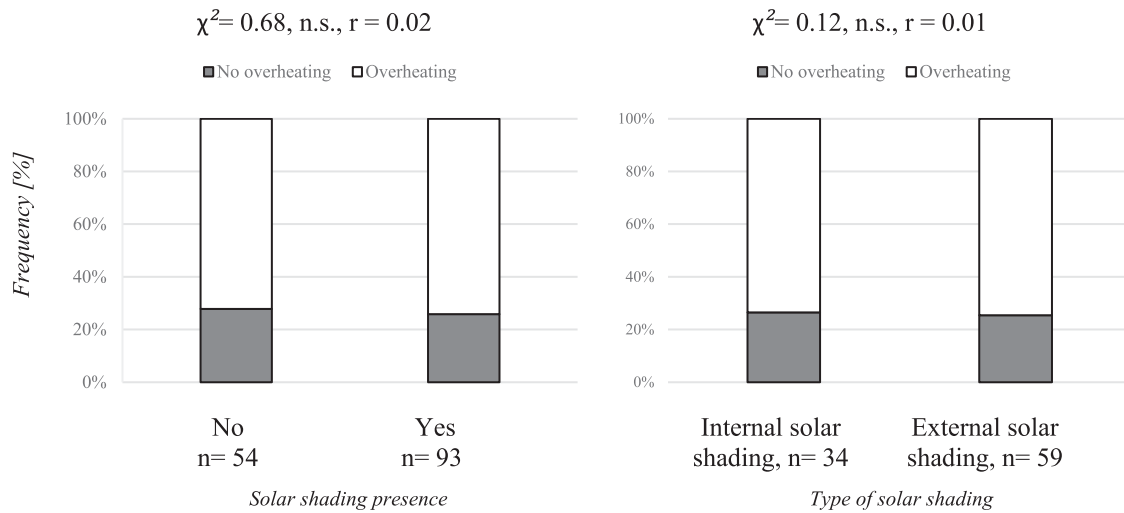


Figure 11. Impact of solar shading presence (left) and position (right) on reported overheating situations

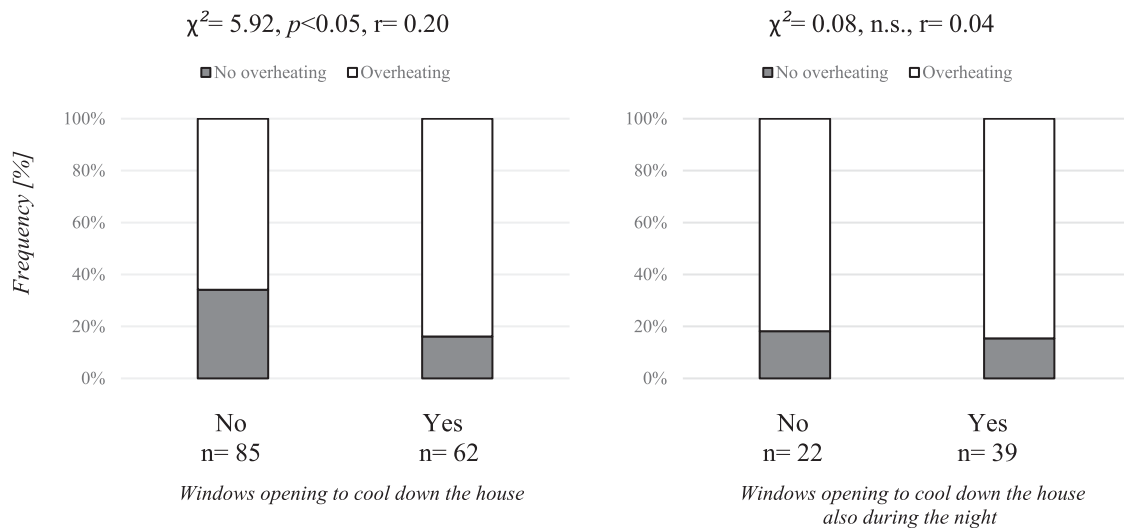


Figure 12. Impact of ventilative cooling practice (left) and moment (right) on encountered overheating situations.

show any significant ($\chi^2 = 0.08$, n.s.) and practically substantive ($r = 0.04$) differences for the cases that declare practicing ventilative cooling by windows opening also during the night.

Figure 13 illustrates the impact of the construction type, that is, the access to thermal mass, on the frequency of overheating complaints reported by the occupants of sample S1 ($n = 147$). The figure shows that, in lightweight buildings, the frequency of complaints is statistically and practically significant and slightly higher ($\chi^2 = 4.13$, $p < .05$, $r = 0.17$) than in other buildings.

Figure 14 illustrates the impact of the combination of solar shading presence, windows opening practice in non-wood frame (masonry) buildings on the frequency of encountered overheating situations. The statistical test did not show any significant and practically relevant differences with this combination ($\chi^2 = 0.19$, n.s., $r = 0.04$).

Since environmental controls, such as deployment of movable solar shading and windows opening, were mostly manually operated in the studied sample (cf. Figure 5), the impact of the presence of the occupant during the day has also been tested. The results illustrated in Figure 15 do not show a significant difference in the frequency of overheating complaints between buildings that were occupied during the day and those that were not ($\chi^2 = 0.01$, n.s., $r = 0.01$).

Impact on measured thermal conditions

Figure 16 presents the distribution of occupancy time exceeding 25°C in subsample S2 ($n = 23$) by means of boxplots (minimum, 25th percentile, median, 75th percentile, maximum). Numerical median values are also indicated to increase the readability of the graphs. The

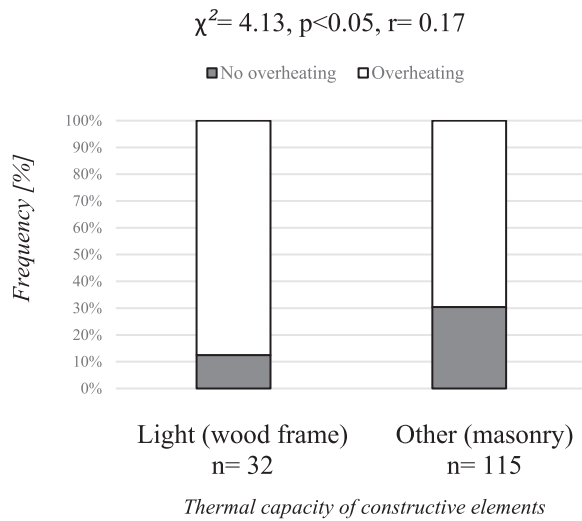


Figure 13. Impact of the construction type on reported overheating situations.

boxplots show that the distribution is quite similar for each room ranging from 1% to more than 30% of the occupancy time over 25°C with a median value of 6.4% (the Belgian Passive House Plateforme recommend not to exceed 5% (Plate-forme Maison Passive, 2020)).

Figures 17–23 illustrate by means of boxplots, for subsample S2 ($n = 23$), the influence of the implemented passive strategies on the distribution of occupancy time exceeding 25°C in the living room (left), and in the main bedroom (right). Results of the Wilcoxon tests are presented above each graph and median values are reported below.

Figure 17 presents the impact of the presence of solar shading on the percentage of occupancy time exceeding 25°C. The figure shows that, for the studied sample, the

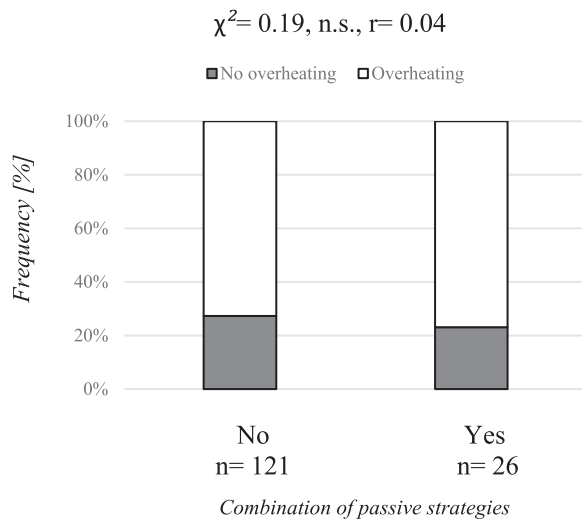


Figure 14. Impact of the combination of solar shading presence, ventilative cooling practice on reported overheating situations in masonry buildings.

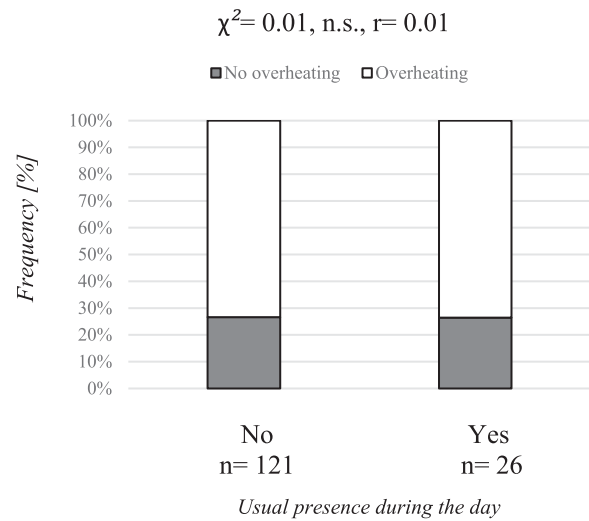


Figure 15. Impact of daytime presence of the occupant on reported overheating situations.

presence of solar shading did not lead to detect significant differences (living rooms, $W = 185$, n.s.; main bedrooms, $W = 135.5$, n.s.), although the small but practically relevant effect sizes show a tendency towards a decreased frequency of temperatures over 25°C with the presence of shading devices ($r = -0.28$ and $r = -0.27$, respectively). It should be considered here that the size of the sample might have had an impact on the detected significance of the statistical tests.

The cases with external shading devices were also compared to those equipped with internal shading (Figure 18). Although the analysis did not detect statistically significant differences (living rooms, $W = 53.5$, n.s.; main bedrooms, $W = 30$, n.s.), for the living rooms the small estimated effect size ($r = 0.21$) lead to infer a tendency for a higher percentage of time of occupancy exceeding 25°C with external shading. It should be remembered here that all shading devices in subsample S2 ($n = 23$) were manually operated. Also, the window-to-floor ratio was slightly higher in presence of external shading for the subsample S2 compared with the other cases (median of 18.5% compared to 16.5%, $W = 875$; n.s.; $r = 0.16$). The influence of the main orientation, which corresponds to the largest glazing area of the house, was also questioned; but the analysis did not highlight a clear tendency. The explanation is that all houses have various orientations: four orientations for the 20 detached houses; three for the 2 semi-detached houses and two for the terraced house, that could contribute to solar heat gains and increase the overheating risk of the building.

Figure 19 presents the impact of ventilative cooling practice on the percentage of occupancy time exceeding 25°C for the living rooms (left) and the main bedrooms

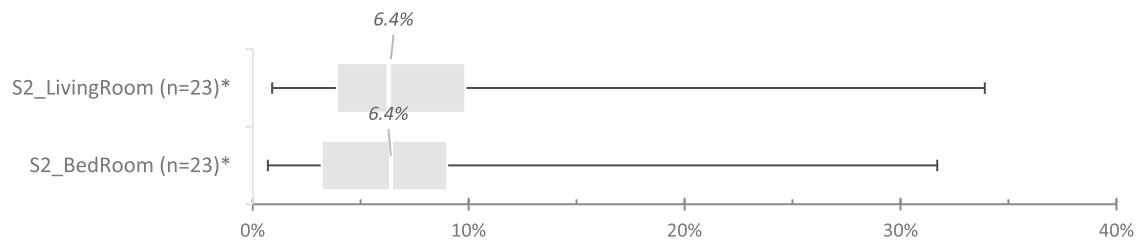


Figure 16. Distribution of occupancy time exceeding 25°C in the living rooms (top) and in the main bedrooms (bottom) of subsample S2. Source of data: *On-site verification/measurements.

(right) of subsample S2 ($n = 23$). While no significant and practically relevant difference could be detected in the main bedrooms ($W = 201$, n.s., $r = -0.04$), a small but practically relevant effect size ($W = 161.5$, n.s., $r = 0.23$) indicates, for the living rooms, a tendency for a higher percentage of occupancy time exceeding 25°C when ventilative cooling is practiced.

Figure 20 illustrates the impact of ventilative cooling practice when this strategy is also practiced at night. Compared to the cases practicing windows opening during the day only, the cases with night opening present lower percentages of occupancy time exceeding 25°C. The estimated magnitude of the effect was found to be large in the living rooms ($W = 46$, $p < .05$, $r = -0.61$) and moderate in the main bedrooms ($r = -0.32$), although for the latter case the test was not statistically significant ($W = 67.5$, n.s.).

Figure 21 shows the impact of the construction type on measured thermal conditions. No significant and practically relevant difference could be detected for the living rooms ($W = 72.5$, n.s., $r = 0.01$), while for the bedrooms the analysis did not detect statistical significance, but an effect of small size ($W = 87.5$, n.s., $r = 0.23$).

Figure 22 compares the percentage of occupancy time exceeding 25°C for the cases presenting a combination of solar shading, windows opening practice and heavy weight construction with the other cases. The differences detected were all not statistically significant (living rooms, $W = 74.5$, n.s.; main bedrooms, $W = 66.5$, n.s.), although an effect of small but practically relevant magnitude ($r = -0.24$) could be estimated for the bedrooms. Similar results (not illustrated here) were found for the cases presenting this combination of strategies but where the windows opening was also practiced during the night.

Since some environmental controls, such as adjustment of solar shading and windows opening, were manually operated in the studied subsample S2 ($n = 23$), the impact of the presence of the occupant during the day was also tested. This is illustrated in Figure 23, showing that the percentage of occupancy time exceeding 25°C was lower when the occupant is at home during the day for both the living room ($W = 51.5$, $p < .05$) and the main bedrooms ($W = 44.5$, $p < .05$), with estimated magnitude of effects ranging from medium ($r = -0.45$) to large ($r = -0.55$), respectively. It was

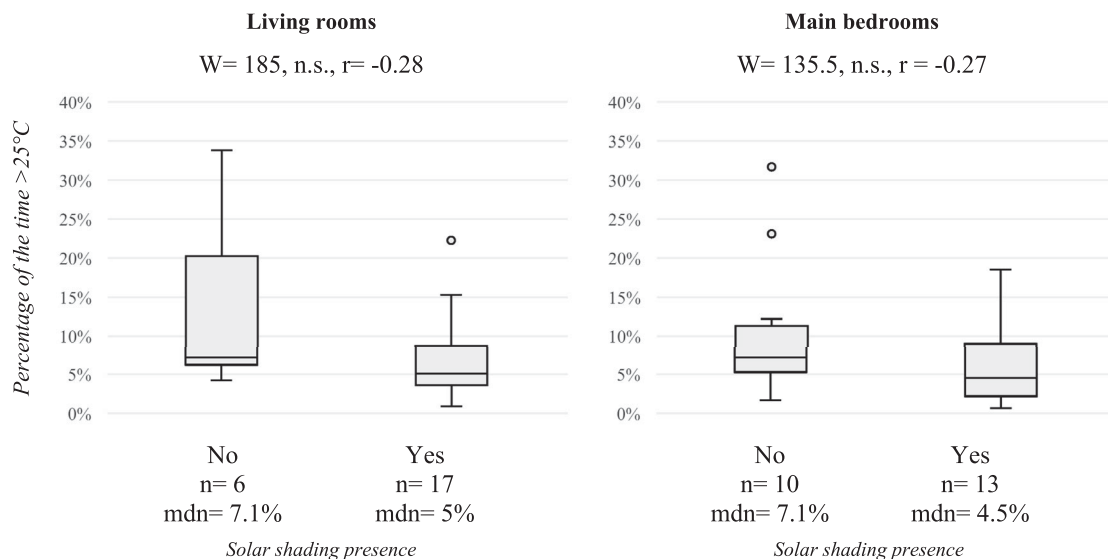


Figure 17. Impact of solar shading presence on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

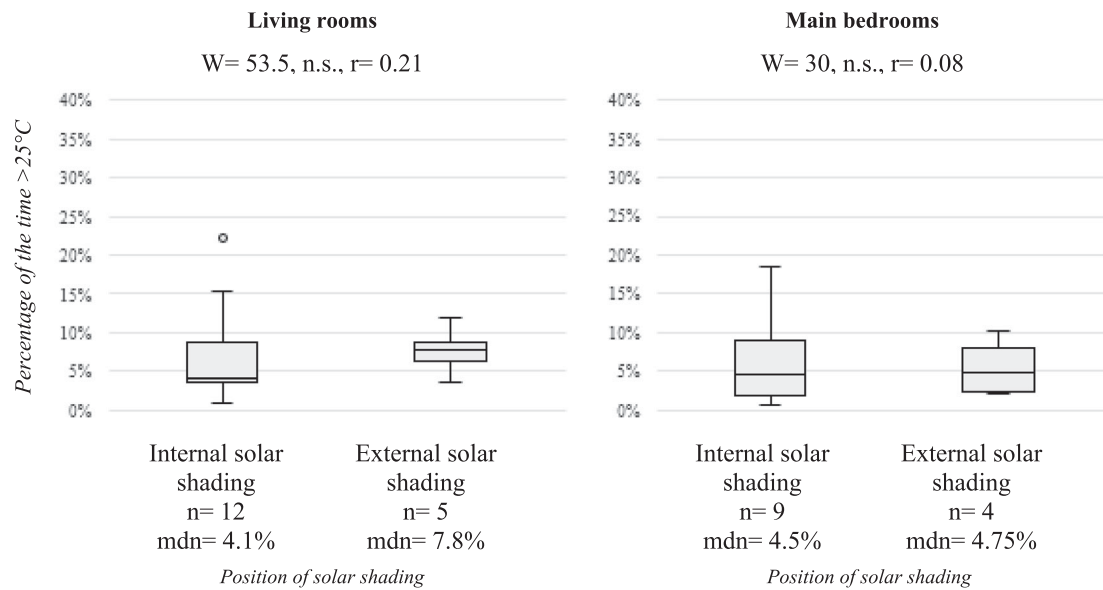


Figure 18. Impact of solar shading position on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

also noticed that more appropriate environmental controls were available in the buildings occupied during the day. In fact, all were equipped with solar shading, at least in the living rooms, and all occupants declared to practice window opening to cool down the rooms in these cases.

Discussion

As a primary consideration, it is important to highlight the high frequency of overheating discomfort reported by the occupants, which accounted for more than 70% of the sampled cases. This is substantiated by the results

of the monitoring campaign, which shows that around 60% of the cases (S2) exceeded the threshold recommended by the Belgian Passive House Institute (5% of occupancy time over 25°C in a year consistent with seasonal norms (Plate-forme Maison Passive, 2020)). These results are quite alarming, since other types of housing, such as apartments in cities are considerably more exposed to overheating risks than those analysed in this study: single-family houses located in rural or semi-rural areas (Lomas & Kane, 2013; Sharifi et al., 2019). Owing to global warming, this risk will clearly increase in future climate scenarios (Attia & Gobin, 2020; Hamdy et al., 2017; McLeod et al., 2013; Rahif

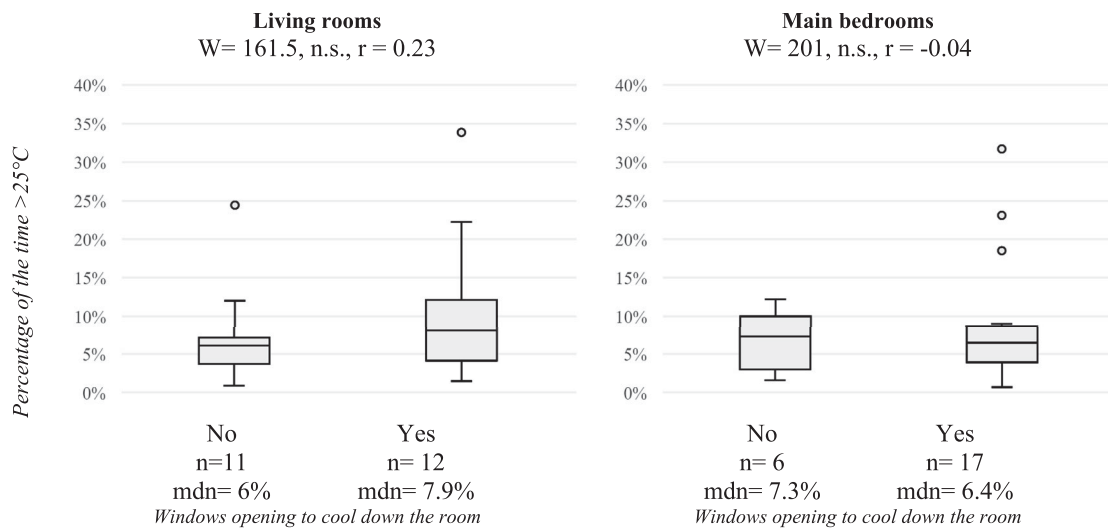


Figure 19. Impact of ventilative cooling practice on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

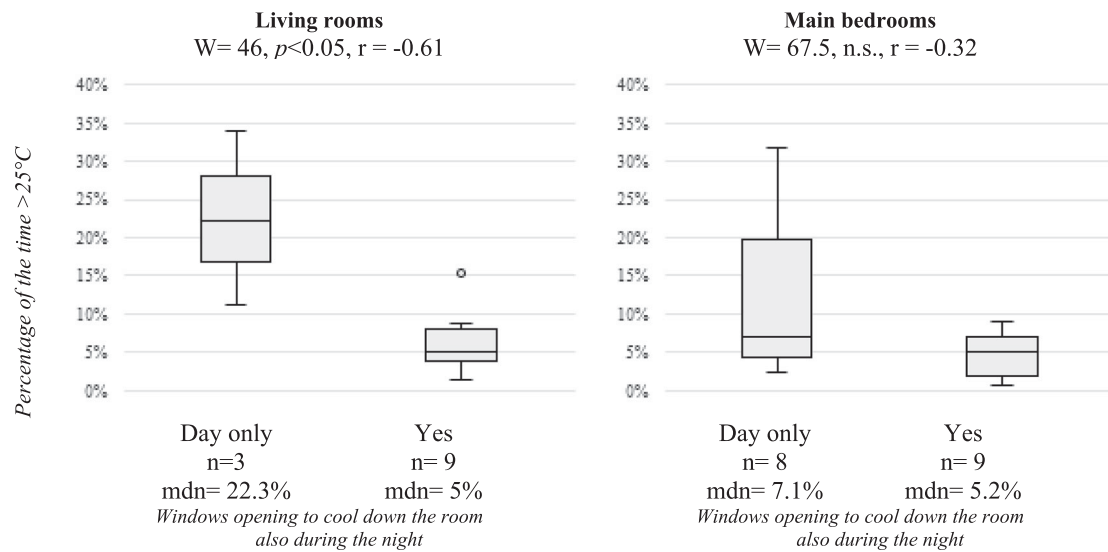


Figure 20. Impact of ventilative cooling practice at night on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

et al., 2022). Consequently, these findings confirm that summer thermal comfort in residential buildings should also become a priority in temperate climates (Tabatabaei Sameni et al., 2015; Toledo et al., 2016).

The results also illustrate that practitioners have not yet embraced the practice to implement passive strategies, in order to improve summer thermal comfort. While over 70% of the studied buildings were equipped with solar shading after some years of occupation (Figure 4), only 40% of these devices were external and a large majority was not present at the end of the construction stage (around 70% in sample S1, and more than 80% in subsample S2) (Figure 6). Only few solar shading systems were effectively present at the end of

the construction stage. This supports similar findings in other contexts (Ozarisoy & Elsharkawy, 2019; Rohdin et al., 2014) and leads to question the reasons behind the difficulty to properly integrate building summer passive strategies in countries that have no such tradition. According to Social Practices Theory (Reckwitz, 2002; Schatzki, 1996), a practice such as the use of solar shading to increase summer thermal comfort, is supported by linked components. These components are related to *competences*: which include know-how, habits, institutionalized knowledge and explicit rules, etc., *meanings*: which are associated with beliefs, emotions, moods, etc. and *materials*: which include available technologies and products, etc. (Shove et al., 2012). As highlighted

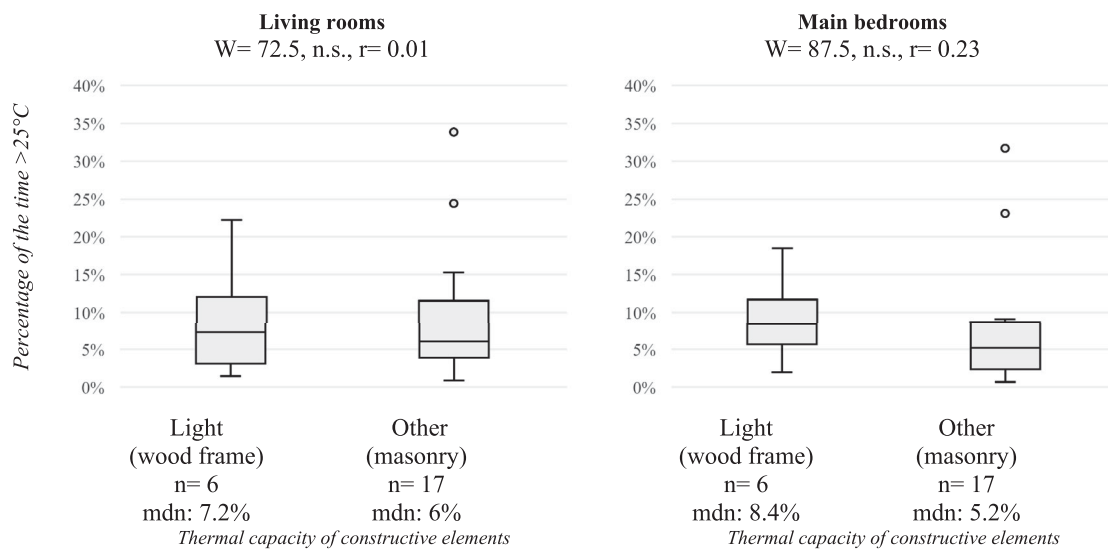


Figure 21. Impact of construction type on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

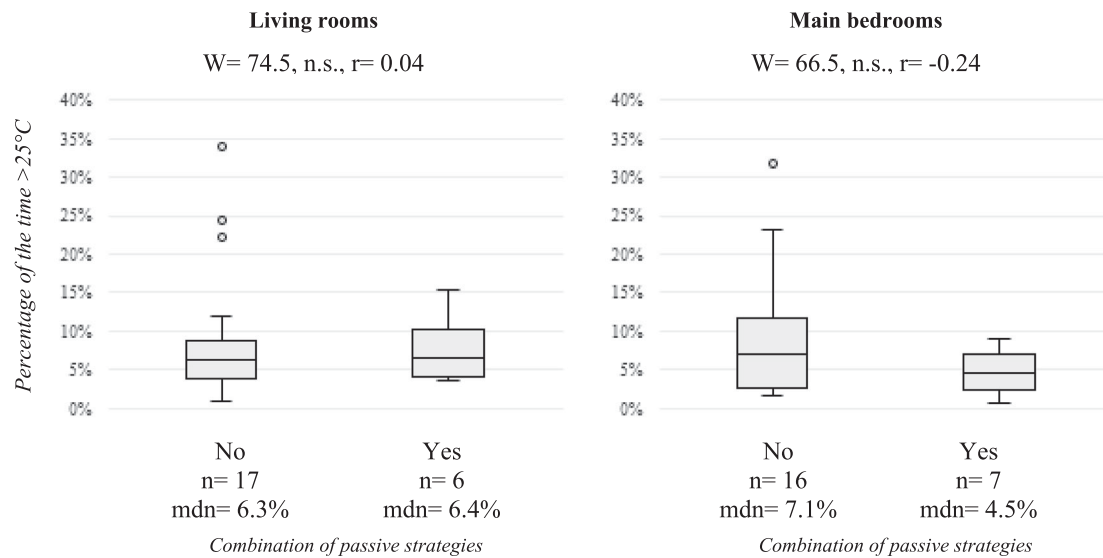


Figure 22. Impact of combination of solar shading presence, ventilative cooling practice and heavy construction type on the percentage of occupancy time exceeding 25°C in the living room (left) and in the main bedroom (right).

by Shove (2003), these components must co-evolve to generate new practices, or to change existing ones. If, as in this case, the technology is mature, such as TRL 9 (Zhang et al., 2021), the reasons of its scarce implementation may probably be searched among *competences* and *meanings* components of social practices, and should probably be derived according to the type of solar shadings. It is also recognized that different actors interfere in the introduction, adoption and diffusion of innovations (Rogers, 2003). These include: the supply (enterprises) and demand (end users) sides, as well as the steering environment (policymakers). Consequently, the practices of occupants but also of all practitioners intervening in the building process (architects,

engineers, builders, etc.) need to be specifically studied in order to properly identify levers and barriers to the implementation of such techniques.

The effectiveness of the implemented passive strategies should also be questioned. In the analysed sample, the presence of solar shading shows that indoor thermal conditions only marginally improved (Figure 17), yet did not substantially impact the rates of overheating complaints from the occupants (Figure 11). Conversely, when external shading devices were present, an even higher percentage of occupancy time over 25°C could be inferred (Figure 18). This might partly be due to the fact that external shading devices were placed mostly in critical cases (e.g. large glazing surfaces, challenging

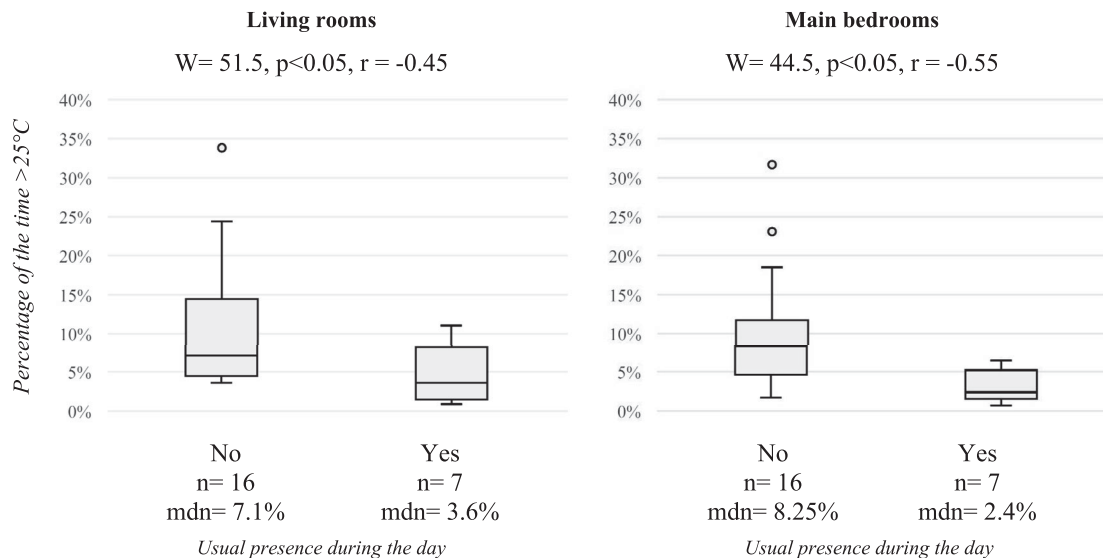


Figure 23. Impact of daytime presence of the occupant on percentage of time exceeding 25°C.

orientations, etc.), hence suggesting some design considerations that might go beyond the unique installation of protection systems. Ventilative cooling by windows opening is frequently practiced by occupants (Figures 7 and 8) and was evident in around 70% of cases. This strategy appears, however, as a reactive response to perceived discomfort and not as a measure to prevent it. Figure 12 shows, in fact, a statistically significant higher rate of overheating complaints when ventilative cooling is practiced. Figure 19 confirms that cases where windows opening is practiced in the living room present a slightly higher percentage of time over 25°C than the other cases. Night windows opening seems generally less practiced in the living rooms (only 11% of the cases for living rooms of sample S1 compared to 40% for the bedrooms). The reasons behind these differences, possibly those such as protection against insects, noise, security, lack of knowledge about the efficiency, etc. (Tillson et al., 2013), have not been specifically questioned in this study, and should be explored more in depth in further studies. Again, this must take into account the linked components of social practices: competences, meanings and materials (Shove et al., 2012). Nevertheless, the positive impact of this strategy, which is taking advantage of low outdoor temperature at night to improve the efficiency of ventilative cooling, could be illustrated by Figure 20. In fact, the data collected shows that temperature during the occupancy time was moderately to largely impacted for the cases applying night ventilative cooling ($r = -0.32$ for bedrooms; $r = -0.61$ for the living rooms).

The effect of higher thermal mass was also analysed. More complaints about overheating were noticed in lightweight buildings than in the other cases (small effect, statistically significant) but the effect on temperature exceeding 25°C for subsample S2 was not so evident (Figure 21). This observation could be explained by the thermal behaviour of lightweight buildings (e.g. wood frame), which are known to increase/decrease more rapidly their indoor temperature due to their lower thermal capacity (Staepels et al., 2013). The impact of higher thermal mass depends, in fact, on several other dynamic parameters, such as, accessibility of thermal mass, presence of furniture (Johra et al., 2017), ventilation schedule (van Hooft et al., 2015), occupancy schedule, etc. Based on literature, the effectiveness of thermal mass in maintaining acceptable summer thermal conditions in residential buildings, can also substantially vary, depending upon climate patterns (Verbeke & Audenaert, 2018).

Nevertheless, it is commonly recognized that the combination of a higher thermal mass with other passive strategies, especially ventilative cooling, can considerably improve summer thermal comfort (Sorgato et al., 2016).

This could not be detected in the studied samples, as the combination of strategies such as solar shading presence, practice of ventilative cooling and masonry construction type, etc. only provided a small decrease of temperature. This decrease was statistically non-significant for the bedrooms of subsample S2 (Figure 22) and did not lead to a lower rate of reported discomfort (Figure 14). The simple provision of environmental controls, even if increasing the occupant's adaptive capacity (Adekunle & Nikolopoulou, 2016), was not found sufficient to guarantee summer thermal comfort.

These findings lead to question the operation of passive control strategies by occupants. Even if occupants declare practicing ventilative cooling, do they open the windows adequately to provide effective ventilation that allows for the discharge of accumulated heat in the buildings? Do they open the windows when outside temperatures are lower than inside? Do they effectively close the windows when outdoor temperatures exceed indoor temperatures? Results of Figures 7 and 12 – respectively showing that windows opening in living room is practiced only mainly during the day of sample S1 (Figure 7), and that the opening is often practiced in response to a perceived discomfort (Figure 12) – suggest the contrary. Similar questions could be asked regarding the use of solar shading, such as whether the solar shadings were placed adequately for each glazing or whether they were preventively operated each time the sun hit the building façade. The small proportion of external shading devices installed (Figure 4) and the availability of automated controls (Figure 5), again, suggest the contrary. This reinforces the conclusions of previous studies showing that occupants' actions are key factors to avoid overheating (Ozarisoy & Elsharkawy, 2019), although occupants might not always make proper use of passive strategies in dwellings (Kuczyński et al., 2021).

Modes of operation appear, therefore, to be as important as the technical characteristics of the devices themselves. Figure 23 shows that the presence of the occupant during the day can limit the percentage of time when temperature exceeds 25°C. For all these cases, at least the living rooms were equipped with solar shading, and all the occupants declared practicing ventilative cooling. This suggests that these environmental controls should be operated continuously, or in a preventive way, in the absence of the occupants during the day, to avoid the accumulation of heat inside these highly insulated buildings. However, the presence of the occupant during the day does not lower the frequency of overheating complaints (Figure 15), this, reinforcing the finding that environmental controls are more often operated when the discomfort is already perceived (Figure 12) as previously suggested. This

phenomenon has recently been described, where the ‘time lag’ of behaviour occurrence regarding the operation of solar shading in office buildings was introduced and quantified (Li et al., 2022). Things could be more complex in the context of residential buildings, where the occupant could be away for part of the day, not occupying the specific room where an operation: such as closing a solar shading, could be beneficial. Alternatively, the occupant could simply not be able to operate the environmental control, such as, in the case of elderly people (Kuczyński et al., 2021). More research on how environmental controls are operated in residential buildings is thus needed. That would imply the collection in much higher detail, of the habits of the occupants regarding the moment, frequency and duration of opening/closure that was done in the present study.

In the context of generalized development of smart buildings (European Parliament, 2018), the integration of Internet Of Things (IOT) in buildings (Kumar et al., 2021) has certainly the potential to help the occupant in properly acting on environmental controls, or to improve and optimize their operation. Connected devices could sense the correct parameters at the right time and place and, on this basis, actuate the right response. Alternatively, these devices could adequately inform the occupant to manually intervene in a preventive manner. However, only a small proportion of automatized systems were found in this study (Figure 5). Understanding the barriers inhibiting a better implementation of automatized systems seems necessary. Again, this needs to integrate all the components: competences, materials and meanings, that influence the related social practices. This must also consider all the actors intervening in the decision-making process, such as: end users, designers, contractors, manufacturers, regulators, etc. Also, selecting the adequate mode of operation of environmental controls, such as, manual, automatized, fixed, etc. requires a more thorough characterization of the occupants’ profiles, needs and preferences. This as a key determinant to prevent overheating risk in residential buildings and should be included in energy standards (European Parliament, 2018).

Conclusions

In temperate climates, a combination of solar shading devices with ventilative cooling via windows opening, are key passive strategies for ensuring summer thermal comfort in residential buildings. Their combined effect towards controlling solar gains and dissipating the heat accumulated in the building, has been demonstrated to prevent overheating risks (van Hooff et al.,

2015), to limit the need of active cooling (Yang et al., 2021) and to facilitate the use of more sustainable cooling systems based on low enthalpy (BBRI, 2022).

Based on a cross analysis of qualitative (survey) and quantitative (measurements) data collected in a sample of 147 highly insulated houses, this study has shown that the implementation of these techniques is not yet sufficient to reduce the risks of summer thermal discomfort in highly insulated residential buildings in Wallonia, Belgium. It is therefore crucial to understand barriers that inhibit a more effective integration of these environmental controls. The study also questioned the proper operation of these strategies that, in highly insulated buildings, is probably as important as the characteristics of the devices themselves. Proper control of passive strategies should anticipate the occurrence of discomfort, rather than being motivated by it. In a context of Internet Of Things and smart buildings development (Kumar et al., 2021), automatized systems could probably be part of the response to this challenge. If barriers for implementing smart and active technologies need further investigation, this study suggests that the choice of an appropriate operation system must be occupant-centred (O’Brien & Tahmasebi, 2023). That is, operational choices such as fixed, automatized or manual mode must correspond to the effective needs and possibilities, and should be based on the accurate characterization of the occupant’s needs, preferences and profile: such as, absence during the day. This should go alongside a more thorough understanding of the components (competences, meanings, materials) upon which social practices rely for each group of actors intervening in the decision-making process: end users, designers, contractors, manufacturers, regulators. Also, in temperate climates, these are key determinants for reducing the overheating risks in residential buildings and limit, in the future, the diffusion of active cooling with their induced environmental impacts.

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Chapter VII. On the practical implementation of passive controls

This chapter has been written in the form of a journal article but had not yet been submitted for publication at the time of writing this thesis. Together with selected elements discussed in Chapter IX (Research Implications), this analysis is intended to form the basis of a future journal publication.

Provisional title: *On the Practical Implementation of Passive Controls for Summer Thermal Comfort in Residential Buildings: Insights from a Social Practice Study.*

Role of the thesis author: Lead author. Table VII.1 further details the author's contributions to this chapter.

Table VII.1. Contributions of the thesis author to Chapter VII, according to the CRediT taxonomy [213].

Contribution Type	Chapter VII
Conceptualization	✓ ¹
Data curation	✓ ¹
Formal analysis	✓
Investigation	✓ ¹
Methodology	✓
Software	✓ ¹
Validation	✓
Visualization	✓
Writing – original draft	✓
Writing – review & editing	✓ ^{1,2}

1: In collaboration with Julie Castreman (Research Assistant - UCLouvain).

2: In collaboration with Erwin Mlecnik (TU Delft), Geoffrey van Moeseke, Gabrielle Masy and Sergio Altomonte (UCLouvain).

On the practical implementation of passive controls for summer thermal comfort in residential buildings: Insights from a Social Practices study.

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Abstract

Newly built dwellings often fail to meet occupant expectations regarding summer thermal comfort in heating-dominated climates, suggesting a need to reassess current design standards and practices. This study examines the challenges of implementing passive cooling strategies, such as solar shading and ventilative cooling, in residential buildings in the context of Belgium – a country with a temperate maritime climate in Western Europe. A large qualitative assessment, focusing on the practices of stakeholders involved in the building design process (enterprises, policy makers, end-users) and featuring more than 200 participants, was conducted through interviews, surveys and focus groups. The results show that the current implementation of passive control strategies for summer thermal comfort corresponds more closely to a form of behavioural adaptation than to a socially shared practice, highlighting that the mitigation of overheating has not yet been considered as a primary design challenge in residential buildings. Using Social Practices Theory as theoretical framework, the study identifies and analyses the key elements underpinning these practices, including material arrangements, know-how and routines, institutional procedures and teleoaffective structures.

Keywords: Solar Shading; Ventilative Cooling; Summer Thermal Comfort; Passive Control, Overheating, Social Practice Theory.

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INTRODUCTION

1.1. Background

In temperate climates, overheating has historically not been a central priority in building design, where the emphasis was traditionally placed on reducing heat loss during winter (Chen, 2019). However, summer thermal comfort is increasingly recognized as an emerging challenge (Lomas, 2021), with significant implications for occupants' comfort, wellbeing and health (World Health Organization, 2004). The building sector is increasingly called upon to ensure acceptable indoor conditions during hot periods (Taylor et al., 2023), while simultaneously avoiding the widespread adoption of energy-intensive active cooling systems with their environmental impacts (Ademe & Coda-strategies, 2021; European Parliament, 2024).

The use of passive control strategies, which require little or no operational energy (Chan et al., 2010) such as solar shading and ventilative cooling, has consistently been identified as an effective approach to mitigating overheating risks in residential buildings (van Hooff et al., 2015). Solar shading limits heat gains before they enter the building, while ventilative cooling enhances air movement to remove excess heat (Zhang et al., 2021). In temperate climates, when adequately implemented and ideally combined with thermal mass, these measures can allow to achieve acceptable summer thermal conditions without resorting to active cooling (Bugenings et al., 2025; Figueiredo et al., 2016; Tink et al., 2018; van Hooff et al., 2015; Yannas & Rodríguez-Álvarez, 2020). If passive measures alone might not suffice under the worst future climate scenarios (Attia & Gobin, 2020; Rahif et al., 2023; Velashjerdi Farahani et al., 2024), evidence shows that their systematic integration can significantly reduce cooling energy demand (Yang et al., 2021) and allow the adoption of more sustainable high-temperature cooling systems (De Pauw M. & J., 2022).

Energy codes such as the European EPBD (Energy Performance of Buildings Directive) explicitly encourage the use of passive control strategies in new constructions (European Parliament, 2024). However, recent research has highlighted that their implementation remains still insufficient to avoid recurrent overheating situations in newly built highly insulated dwellings in temperate climates (Dartevelle et al., 2023; McLeod & Swainson, 2017; Toledo et al., 2024). While heatwaves are expected to increase in frequency and intensity (Ouzeau et al., 2016), it is therefore becoming urgent to embed summer passive design strategies more systematically into design and building practice.

1.2. Research gap and aim of the study

Passive cooling strategies have been the subject of extensive research over the past decades, approached through different disciplinary lenses.

From a building physics perspective, studies have primarily investigated the impact of these strategies on indoor thermal comfort (Encinas Pino, 2012), and energy demand (Harkouss et al., 2018). While results highlight their potential to significantly improve thermal comfort and reduce cooling needs (De Pauw M. & J., 2022), the effectiveness of passive cooling strategies depends strongly on how occupants operate and control them (Kermeci, 2017; Mavrogianni et al., 2016), this resulting in recurrent performance gaps (Wingrove et al., 2024).

From a behavioural and psychological perspective, research has explored the role of occupants' perceptions, habits, and decision-making processes in the use of passive cooling solutions (Heydarian et al., 2020). These studies underline that user comfort expectations, environmental conditions, adaptive opportunities, and cultural factors significantly mediate the success of passive controls in practice (Hong et al., 2017; Pereira & Ramos, 2019).

Together, these two perspectives highlight the need for an integrated approach to better capture the complexity of passive cooling performance in real-life contexts, bridging building physics with user-centred insights (Nagy et al., 2023).

While both building physics and psychological/behavioural perspectives have generated important insights, they also reveal certain limitations. The building physics approach tends to conceptualize occupants mainly as boundary conditions or sources of uncertainty in simulation models, reducing complex patterns of everyday life to simplified assumptions (Hu et al., 2020). Conversely, the psychological and behavioural lens often isolates individual decision-making processes or attitudes, which risks overlooking the collective routine and socially embedded nature of building design and use (Behar, 2016).

Social Practice Theory (SPT) has emerged as an alternative methodological approach shifting the focus from individual behaviours to socially shared practices (Schatzki, 1996). Traditionally, SPT considers practices as shaped by the interplay of elements linked with materials, competences, and meanings (Shove et al., 2012). It aims to capture the broader social and cultural contexts in which these practices are adopted, offering a complementary understanding of why performance gaps could persist and how more sustainable practices might be fostered (Kuijter, 2014).

Social Practice Theory (SPT) has been applied to various domains, exploring for example energy use (Shove & Walker, 2014) and sustainable practices (Behar, 2016; Breadsell & Morrison, 2020), often with the aim of providing insights for policymakers (Strengers, 2012). It was identified as particularly useful in sustainability transitions studies (Laakso et al., 2024).

Existing SPT research on summer thermal comfort has particularly focused on practices around the use of cooling systems (Shove et al., 2013; Strengers & Maller, 2011). While these studies acknowledge the effectiveness of passive cooling strategies – such as solar shading and ventilative cooling – in reducing energy demand, research specifically addressing their implementation remains limited (Heydarian et al., 2020).

Adopting an SPT lens, this study aims to generate new insights into the effective implementation of passive cooling strategies in residential buildings based on a the qualitative assessment of current practices in recently built dwellings in the temperate maritime climate of Belgium. To the authors' knowledge, this represents one the first explicit application of SPT to the study of passive controls implementation. By extending the application of SPT to underrepresented areas of inquiry and to new geographical contexts this study responds to two of five recent propositions for advancing SPT in technology-related research (Mesenhöller, 2025).

2. METHOD

The present study employed an exploratory mixed-methods approach, with data collection and analysis explicitly informed by Social Practice Theory (SPT). It involved semi-structured interviews, online surveys and focus groups (Figure 1). The data were collected in 2022 and 2024 as part of the *SOFTSummer* project activities (*Smart Operation For Thermal Summer comfort in residential buildings*) funded by the Walloon region in Belgium (Buildwise, 2022). Details of the sample are reported in section ‘2.2. Target Groups.

The elements constituting current practices were identified through an iterative process combining semi-structured interviews with end-users, enterprises, and policymakers. This phase, which lasted about one year, was followed by an online survey targeting enterprises more broadly. Owing to the interdisciplinary nature of the study, each step was conducted collaboratively by researchers from sociological and technical disciplines.

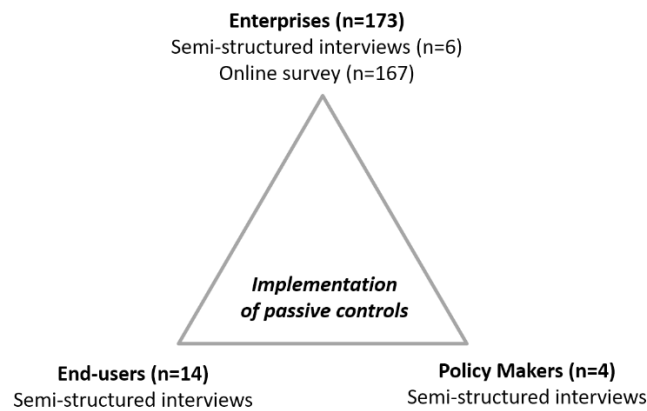


Figure 1. Methodological overview of the study.

The research project was realised in collaboration with Buildwise (formerly the Belgian Building Research Institute) and accompanied by the public administration responsible for research and for implementing building energy performance policies in Wallonia, as well as by several professional organisations, including the Union Wallonne des Architectes, Cap Construction, and the Fédération de la Construction (Embuild). Together, these organisations formed the project steering committee, providing practical support and helping to disseminate key information about the projects, notably by diffusion of the surveys.

2.1. Theoretical framework

Social Practice Theories (SPT) conceptualize individuals as carriers of socially shared practices (Reckwitz, 2002; T. Schatzki, 1996). These practices emerge from interconnected elements – each essential for their occurrence – commonly categorized as *materials*, *competences*, and *meanings* (Shove et al., 2012).

Materials – also referred to as material arrangements (Schatzki, 2010) – comprise the artifacts and physical entities that enable or constrain the performance of a practice. They include objects, technologies, infrastructures, products, tools, equipment and the body itself (Shove et al., 2012).

Competences refer to incorporated knowledge – that is, the competences and skills required to enact a practice – as well as the habits and routine inherent to it. Repeated performance of these activities tends to routinize them, particularly relevant in domestic contexts (Dubuisson-Quellier & Plessz, 2013). Routinization of daily activities suspends part of the reflexivity without preventing their potential transformation over time. Competences also include *institutionalized procedures*, encompassing explicit rules, principles, and instructions that guide how practices are performed (T. Schatzki, 1996). In the context of energy use in buildings, these procedures are especially important because they are shaped by specific standards, such as the EPBD. In the present study, and in line with previous research (Bartiaux et al., 2014), institutionalized procedures are analysed separately.

Meanings – also referred to as *teleoaffective* structures– are defined as “*hierarchical orders of ends, projects, tasks, actions, beliefs, and emotions within a range of acceptable orders*” (T. Schatzki, 1996). They represent the goals, values, purposes, and emotions that practitioners consider legitimate and desirable.

Understanding these interlinked elements can help to explain both, social reproduction and change of practices (Warde, 2005).

2.2. Target groups and samples

Whereas previous research has focused primarily on households and their everyday practices (Breadsell & Morrison, 2020), this study adopts a broader perspective by considering the implementation process as the result of shared practices among multiple stakeholders engaged in the design, construction, and use phases of residential buildings. These include both the supply side (enterprises (industry)) and the demand side (owners and occupants (end-users)), as well as the steering body (policymakers) (Mlecnik, 2013).

a) End-Users (Occupants)

Fourteen households were interviewed regarding their summer thermal experiences and their practices related to the use of solar shading devices and ventilative cooling. The dwellings were selected based on opportunities and recommendations from the steering committee, using the following criteria: a) recently built or deeply renovated within the past 10 years; b) occupied for more than 2 years; c) compliant with, or close to meet, nZEB requirements (Gouvernement wallon, 2019) ; and (d) the independence of the selected participants from any economic interests related to the subject of the study. All selected houses were low-energy houses equipped with a Mechanical Ventilation with Heat Recovery (MVHR) system featuring a summer bypass. They were owner-occupied houses located in

Table 1. Main characteristics of the sampled dwellings (results from on-site interviews (n= 14)).

ID	Building description				Household characteristics				Used solar controls				Ventilative cooling practices			Other
	Construction type	EPBD Label	Overheating indicator	Dwelling type	Size	Involved in the design?	Informed?	Usual Day Presence	Type	Localisation	Construction phase realisation?	Operation type	Used devices	Localisation	Moment	
1	Newly-build	B	Orange	Semi-detached	3 <12 y/o: 1	No	Yes	No	External screens	Roof windows	No	Seasonal	(Roof) Windows	Bedroom + One downstairs	Night	Mosquito nets
2	Newly-build	B	Orange	Detached	2 <24 y/o: 1	No	Yes	Yes	External screens	Roof windows	No	Seasonal	(Roof) Windows	Upstairs +Kitchen	Night (upstairs) Morning (downstairs)	Mosquito nets
3	Newly-build	B	Orange	Detached	2	No	No	Yes	Curtains	Living room	No	Manual	Windows	All (tilt-position)	Day and Night	Fan
4	Newly-build	B	Orange	Semi-detached	3 <12 y/o: 1	No	No	No	Curtains	Living room	No	Manual	Windows	Entrance door + 1 roof window (attic)	Evening	Portable air conditioner
5	Newly-build	B	Orange	Detached	1 >65 y/o	No	No	No	Reflective film	Living room	No	Fixed	(Roof) Windows + MVHR	Upstairs	Night	/
6	Newly-build	B	Orange	Detached	2	No	No	No	External screens	Living room Roof window	No	Automated Seasonal	Windows	All	Morning	MVHR off (summer)
7	Newly-build	B	Orange	Semi-detached	4 <12 y/o: 2	No	No	No	External screens Curtains	Roof windows Ground floor	No	Manual	(Roof) Windows	Upstairs	Night	Portable air conditioner
8	Newly-build	B	Orange	Detached	3 <24 y/o: 1	No	No	No	Curtains	Living room + roof windows	No	Manual	(Roof) Windows + MVHR	Upstairs	Night (mechanical) and Evening	Fan
9	Newly-build	B	Orange	Detached	4 <12 y/o: 2	No	No	No	External shutter + Reflective film	Ground floor and Roof windows	No	Manual	(Roof) Windows	Upstairs	Evening and morning	MVHR off (summer)
10	Newly-build*	A	Orange	Detached	2	Yes	Yes	No	External screens	South and West Roof window	Yes	Manual Seasonal	(Roof) Windows	Upstairs + One downstairs (hall)	Night	/
11	Renovation	N/A**	N/A	Detached	3 <12 y/o: 1	No	Yes	No	External screen Selective Glazing Awing	Roof windows Large glazing (living room)	No	Automated Fixed Seasonal	(Roof) Windows	Upstairs (+ one small downstairs during heatwave)	Day and Night (Only when hot days)	Active cooling (main bedroom) + Automated opening of roof windows + Mosquito nets
12	Renovation	A++	Green	Detached	4 <24 y/o: 2	Yes	Yes	No	Architectural overhangs Screens	South facade West	Yes	Fixed Automated	Roof Windows + Louvers	Bedrooms + Entrance door	Day and Night	Mosquito nets
13	Newly-build	A	Orange	Detached	4 <24 y/o: 2	No	Yes	Yes	External screens	Northwest and Southeast	No	Automated	Windows	Upstairs	Night	/
14	Renovation*	A	N/A	Attached	5 <12 y/o: 3	No	Yes	No	Curtains	South façade	No	Manual	Windows + MVHR	Upstairs	Night	Mosquito nets

* Light Weight building; ** N/A= Not Available.

suburban areas in the south of Belgium, with only one situated in an urban context. Table 1 details the characteristics of the buildings and households, as well as the reported use of solar controls and ventilative cooling practices. The first nine dwellings belonged to the same building project, sharing similarities in construction techniques (e.g., materials) while differing in geometry and orientation. Households reported experiencing overheating to varying degrees of severity, which appeared largely associated with the extent of solar gains and control – from situations with no control measures applied (case 14) to those with nearly complete control (case 11).

b) Entreprises

Enterprises represent the supply side of the building process, from design through to the completion of construction. They include manufacturers, designers, and building trades. In relation to the implementation of passive strategies, these actors are responsible for advising, supplying, manufacturing and installing appropriate passive controls in dwellings. In total, six manufacturers – two producing solar shading systems (A and B), two producing devices related to ventilative cooling (C and D), and two active in both areas (E and F) – along with 136 designers and 31 building trade professionals participated in this study. All participants were recruited on a voluntary basis through the steering committee's contacts and dissemination channels.

c) Policy makers

Recent studies have highlighted the role of regulations in addressing the growing risks of overheating (Siu et al., 2025). In addition to the analysis of the local standards, four individuals, responsible for the regional implementation of the EPBD, were interviewed to assess how regulations shape current practices. These individuals were recruited on a voluntary basis following a request addressed to the public administration responsible for EPBD implementation.

2.3. Data collection and analysis

The data collection methods used in this study involved mainly semi-structured interviews and survey. The research was approved by the Belgian Data Protection Authority, and informed consent was obtained from all participants. Appropriate data-management procedures were implemented to ensure the secure handling, storage, and use of the collected data, and no personal or identifiable data were disclosed.

a) Semi-structured interviews

Semi-structured interviews were conducted with end-users, enterprises, and policymakers using mixed modes: on-site face-to-face or remote interviews (for some enterprises and policymakers), each lasting between one and two hours.

For end-users, the interview guide comprised 42 questions organized into several parts: perceived summer thermal comfort; everyday habits for mitigating heat in summer and during heatwaves; and, barriers and opportunities for the effective implementation of passive controls, such as the placement and use of solar shading and ventilative cooling. This final part, structured around the identified elements of practices, also informed the interview guides for enterprises and policymakers. Qualitative Data Analysis (QDA) of manually transcribed interviews was conducted using NVivo (Lumivero, 2023). Appendix D of this manuscript provides an example of the realised interview guide.

b) Online-survey

An online survey was specifically addressed to enterprises involved in the design and construction of dwellings. The survey, administered through LimeSurvey (LimeSurvey GmbH, n.d.), comprised 39 questions organized into different sections aimed at capturing the enterprise's activities, practical experience, and perceptions of summer thermal comfort, solar shading, and ventilative cooling. The dissemination of the survey was facilitated by professional associations from members of the steering committee, through mailing lists and social media channels, with participation on a voluntary basis. A total of 167 responses were received (136 designers and 31 building trades), and the results were analysed through frequency analysis.

3. RESULTS AND DISCUSSION

The following sections presents the elements of practices that have been iteratively identified throughout the iterative process of the study. The elements are classified into four categories – Institutionalised Procedures, Know-how and Routines, Teleoffective Structures and Material Arrangements – according to the theoretical framework presented in Section 2.1.

Table 2 offers a comprehensive view of these elements, identified throughout this study, as shaping existing practices, underscoring the central role of routinised practices.

Each of these identified elements is further discussed in the following based on selected results from interviews and survey. Figure 9 to Figure 8 presents for example the collected data through a selection of questions from the survey helping for the conducted discussions. The complete survey and the corresponding collected data are further detailed in Appendix E of this manuscript.

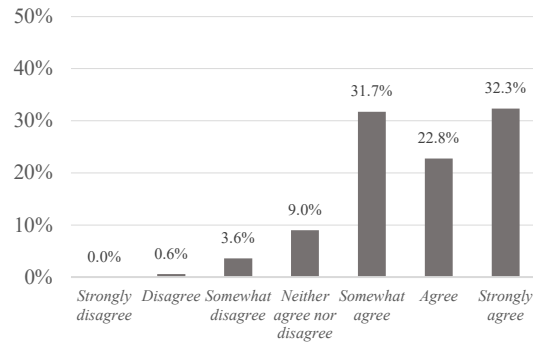
Table 2. Summary of identified elements of practices.

Institutionalised Procedures	Material Arrangements
<i>Standards and Regulations</i> - Explicit legal requirements - Recognition in Energy Performance Certificates (EPCs) - Consistency with other regulatory frameworks <i>Incentives</i> - Financial incentives - Recognition by environmental labels	<i>Availability and Visibility</i> - Degree of adoption - Availability <i>Technical feasibility</i> - Ease of integration - Extensibility and upgradability - Latency of technical potential <i>Implications of use</i>
Teleoffective Structures	Know-how and Routines
<i>Perceived necessity</i> <i>Perceived efficiency</i> <i>Perceived economic value</i> - Absolute/additional cost - Cost-benefice ratio <i>Aesthetics</i> <i>Perception of Alternative solutions</i> <i>Client/Occupant Values and Preferences</i> - Sustainability-conscious - Tolerance of discomfort - Need for quantification - Need for control vs. autonomous systems - Openness to (smart) technology	<i>Awareness, Skills and Capacities</i> - Client awareness and understanding - Client demand and expectations - Designer awareness and expertise - Professional know-how and technical competence - Occupant awareness and involvement <i>Professional Routines</i> - Consideration of summer thermal comfort - Time and/or resources available to: <i>Guide and inform the client/occupant.</i> <i>Assess the relevance of the solution.</i> <i>Coordinate with specific building trades.</i> <i>Occupant Routines and Habits</i> - Compatibility with lifestyle and daily routines - Compatibility with each occupant - Compatibility with pets

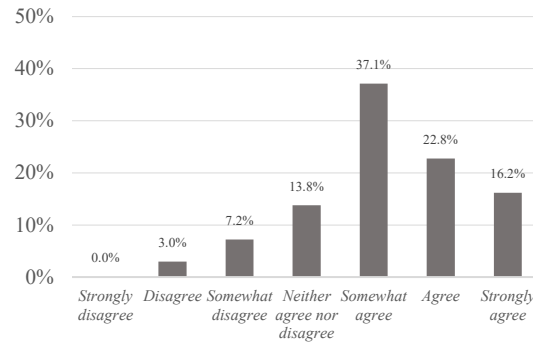
Q32. To what extent do you agree with these statements?

Summer thermal comfort ...

... should be a priority in newly built residential buildings.



... is already an issue in recently built dwellings.



... could become a growing issue in a few decades.

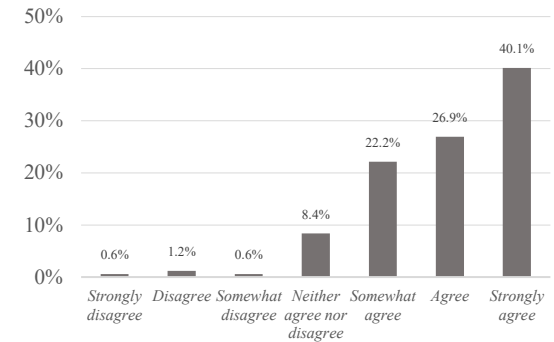
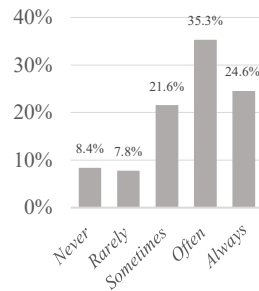


Figure 2. Perception of summer thermal comfort in dwellings by Enterprises (results of the online survey for Q32 (n= 167)).

Q10. In your residential projects over the past two years, did you consider the following techniques?

Solar Shading



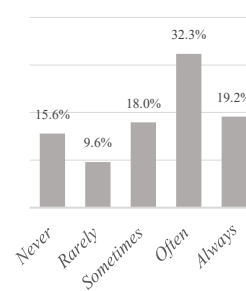
Reflective or Selective glazing



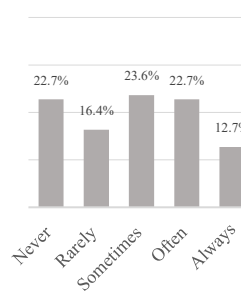
Limitation of glazed surfaces



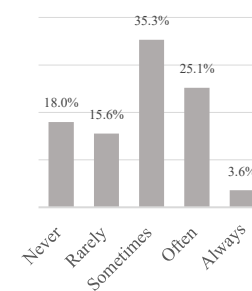
Ventilative Cooling



Reinforcement of Thermal Mass



Reversible heat pump (heating and cooling)



Air conditioning (localized or not)

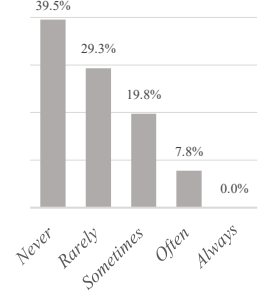


Figure 3. Cooling Techniques considered by Enterprises (results of the online survey for Q10 expressed in % (n=167)).

*Q11. When you recommend Solar Shading, what type do you usually consider?
(several answers possible)*

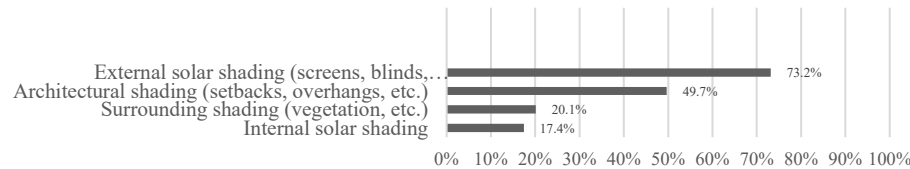


Figure 4. Type of solar shading usually considered by Enterprises (results of the online survey for Q11 expressed in % (n=149)).

*Q21. When you recommend Ventilative Cooling, what type do you usually consider?
(several answers possible).*

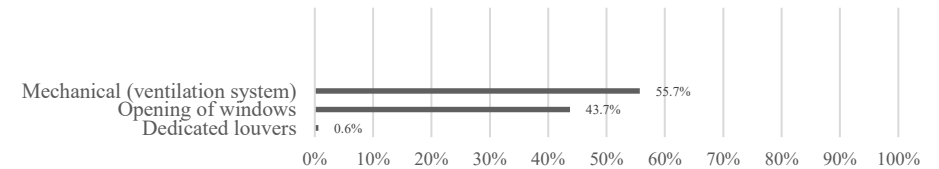


Figure 5. Type of ventilative cooling usually considered by Enterprises (results of the online survey for Q21 expressed in % (n=132)).

Q15. When you recommend these strategies, do you usually consider automated operation?

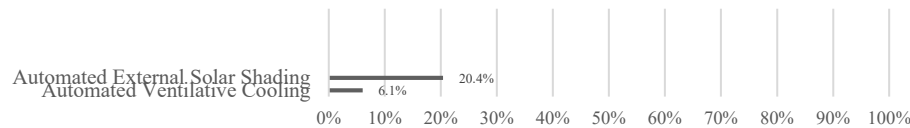


Figure 6. Portion of Enterprises usually considering Automated Operation (results of the online survey for Q15 expressed in % (n= 147 (solar shading), 99 (ventilative cooling))).

Q22. When you recommend these strategies, are they usually realised during the construction stage?

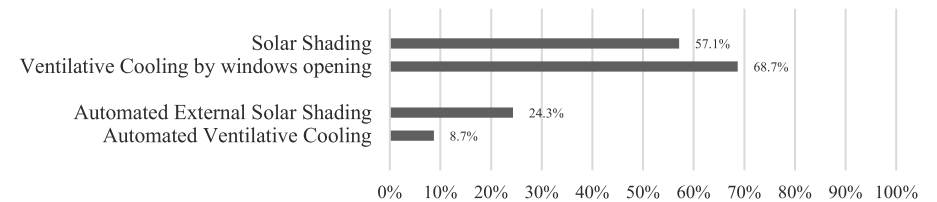
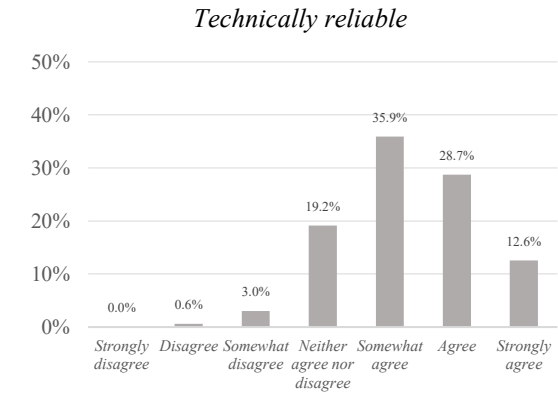
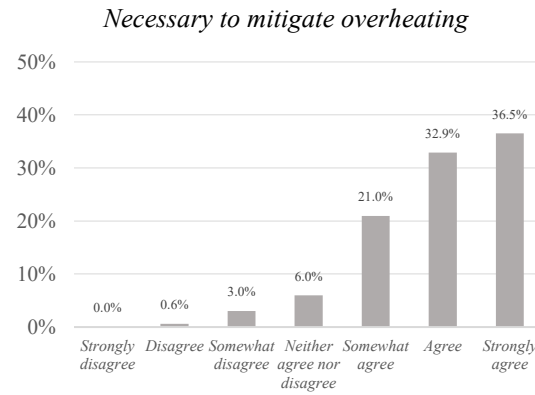
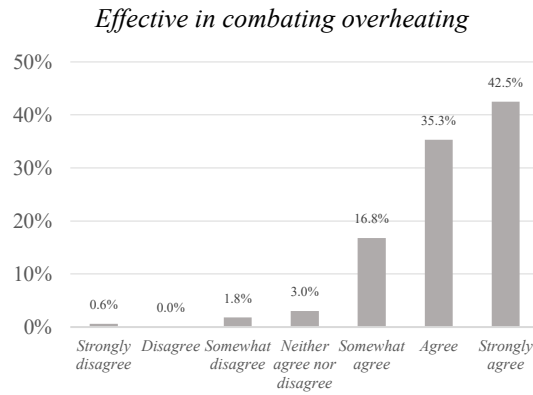


Figure 7. Portion of Enterprises considering that planned techniques are usually integrated during the construction stage (results of the online survey for Q22 expressed in % of n= 147 (Solar Shading), 99 (Ventilative Cooling)).,

To what extent do you agree with these statements?

Q18. External solar shading in dwellings is...



Q26. Ventilative cooling in dwellings is...

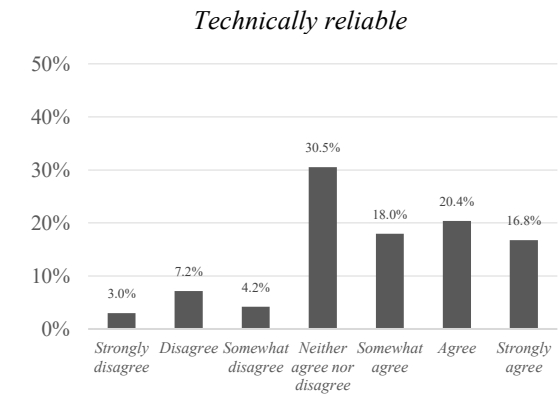
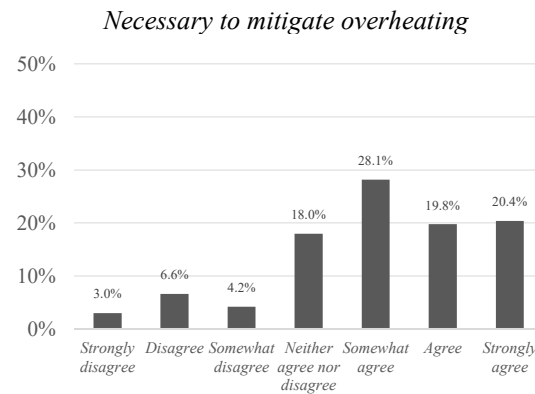
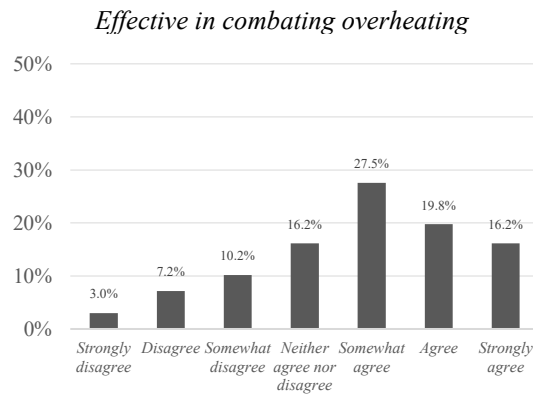


Figure 8. Perceived efficiency (left), necessity (middle) and reliability (right) of Solar Shading (up) and Ventilative Cooling (down) by Enterprises (results of the online survey for Q18 and Q26 (n= 167

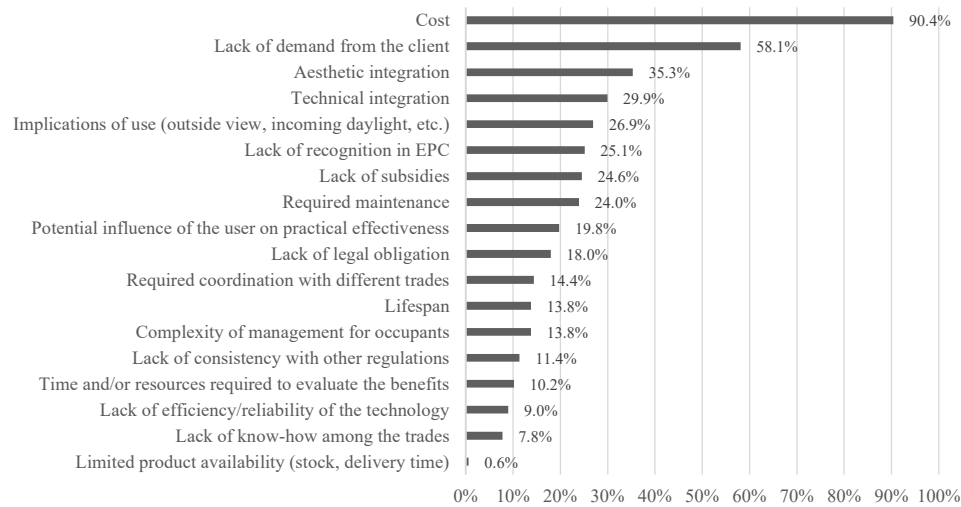


Figure 9. Main barriers to solar shading implementation according to Enterprises (results of the online survey for Q19 (n= 167)).

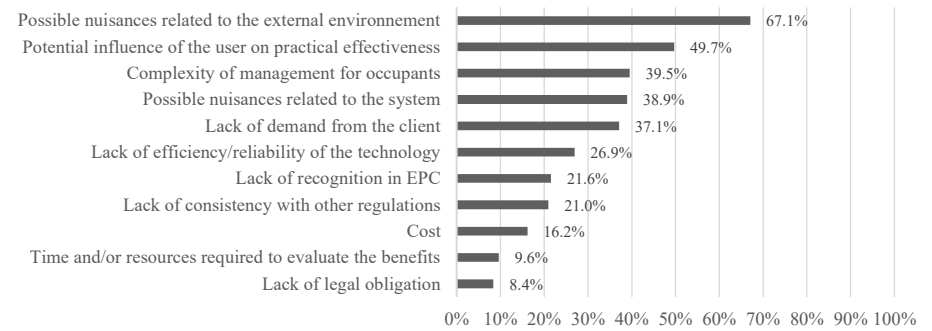


Figure 10. Main barriers to ventilative cooling practice according to Enterprises (results of the online survey for Q27 (n= 167)).

3.1. Institutionalised Procedures

Standards and Regulations

Building codes are recognised to play an important role in protecting occupants from overheating (Siu et al., 2025). In Europe, mitigating the risk of overheating in buildings is clearly identified as an aim of EPBD regulations (European Parliament, 2024). Various overheating calculation methods exist, differing in whether they are: time-integrated or instantaneous; single- or multi-zone; based on static or adaptive thermal comfort models; short- or long-term; stochastic or deterministic in occupant representations; normalised or not to occupied hours; climate-zone-specific or generic (Attia et al., 2023).

In Belgium, the EPBD overheating assessment relies on a time-integrated indicator derived from a monthly energy-balance method applied at the dwelling scale (Gouvernement wallon, 2019). This approach has been criticized for averaging solar and internal heat gains over both time and space (International Energy Agency, 2018a). Nevertheless, it indirectly values passive measures such as solar shading and ventilative cooling and their type of control (fixed, manual or automated). The method yields a probability of overheating represented by a coloured label, ranging from green (0%) to red (100%), with orange in between.

Nevertheless, this calculation applies only to new dwellings. For existing buildings, the Energy Performance Certificate (EPC) does not include this indicator, thereby overlooking passive cooling solutions. Interviews with policymakers highlighted several limitations. One noted that *“the most common label is orange, corresponding to an overheating probability between 1% and 99%”*, which is consistent with the sampled dwellings, where only one case fell into the green category (Table 1). The implications of this orange label are limited: *“It only results in additional cooling needs affecting the energy consumption on which the building label is established (F to A++). It is probably not dissuasive enough and can easily be offset through better insulation or photovoltaic panels”* (Policymaker B). Similarly, some manufacturers observed that the financial penalties linked to the red label *“are relatively low and may even be cheaper than investing in passive solutions”* (Manufacturer E).

Household interviews further revealed contradictions with other regulatory frameworks, particularly between ventilative cooling practices and security concerns. As exemplified by several respondents, this practice often conflicts with police recommendations, insurance conditions, and alarm systems: *“If someone burglarizes us while the window is open, we will be held responsible. So, we don’t leave them open when we’re not there”* (Household 7).

Incentives

Despite the existence in Belgium of a dedicated public program supporting energy-efficient measures in buildings (Gouvernement wallon, 2022), no measure currently targets solar shading or ventilative cooling. Household 6 criticized this current subsidy schemes, suggesting, for example, that *“financial incentives for solar blinds would probably be more relevant than for triple glazing”*.

3.2. Know-how and Routines

Awareness, Skills and Capacities

Occupants' knowledge has a strong influence on comfort expectations and behaviour (Brown & Cole, 2009) but also in the adoption of innovations (Rogers, 2003). Authors have thus warned about the importance of properly disseminating information to the occupants (Mlakar & Štrancar, 2011; Tabatabaei Sameni et al., 2015). Yet, the study revealed large discrepancies between households. Well-informed households, such as in Cases 10 and 12, could influence or support the design process to integrate solar shading and ventilative cooling effectively. By contrast, limited awareness among others was evident: Household 2 admitted, *"I have no information and no knowledge of all this"*, while Household 12 noted a *"real lack of information"* available to the public. This lack of awareness reduces demand from owners, which enterprises identified as the second most significant barrier to solar shading implementation during design (Figure 9). Limited awareness not only restricts residents' ability to make informed choices but also reduces pressure on designers and builders.

Over time, practical experience partially compensates, as occupants attempt to mitigate overheating using available means (curtains, openable windows) or by adding devices post-occupation. Awareness also shapes how passive controls are used. Household 12 reported that *"[children] have difficulty understanding that, when it's hot outside, you have to close the windows"*, while Household 10 noted *"when we leave for the day, we try to close all the screens"*.

Among enterprises, most of them recognized summer thermal comfort as a growing priority, with solar shading widely acknowledged (see Figure 2 and Figure 8). Ventilative cooling, however, is often misunderstood, its requirements being confused with hygienic ventilation by both enterprises and occupants. As Manufacturer A explained, *"I always have to explain the difference"*. The frequent use of technical professional terminology, such as *"purge ventilation"*, may reinforce this confusion. Consequently, although boosting mechanical ventilation is frequently perceived as a cooling strategy, residential airflow rates are typically limited to hygienic needs (~1 air change per hour, (NBN, 1991)), which is not enough for effective cooling (International Energy Agency, 2018a).

Occupants also reported recurring problems with automated system settings. Household 13 noted, *"It is like the technology is in advance compared to the building trades that install it"*, while a manufacturer admitted, *"We have only one person capable of installing these kinds of technologies"*. The lack of technical expertise thus limits the availability and practical efficiency of passive controls.

Professionals Routines

In the absence of explicit regulatory requirements (see Section 3.1b), the effective implementation of passive measures relies not only on awareness but also on the involvement and capacities of designers and professionals (Behar, 2016). The findings from the data analysis suggest, however, that current work routines do not systematically integrate summer comfort considerations.

Household 2, for example, described the process of “*obtaining information as time-consuming and discouraging*”, and observed “*the limited knowledge and consideration among some enterprises*”. This likely results from the fragmentation of roles and competences among building trades (Bartiaux et al., 2014). Household 6 also remarked that enterprises “*don’t sell what doesn’t interest them*”.

However, over time, occupants often become frustrated with the lack of guidance received during design and construction. As Household 7 noted: “*The carpenter who installed the frames could have said: don’t forget to make this window openable, or don’t you need mosquito nets that I could add for you?*” Household 3 highlighted the role of designers in such situations stating: “*Designers should have proposed options such as improved shading for south-facing windows*”.

Despite clearly recognising the relevance of passive controls (see Figure 8), the sampled enterprises acknowledged that insufficient time, resources, and knowledge dedicated to assessing, coordinating, and informing clients (Figure 9 and Figure 10) contributes to the lack of implementation of passive strategies.

Occupant Routines and Habits

Occupants play a considerable role in controlling summer thermal conditions (Mavrogianni et al., 2014; Ozarisoy & Elsharkawy, 2019). Consistent use has here been regularly found to be hindered by competing priorities, daily schedules, and lifestyle constraints. For example, Household 2 noted having “*little time in the mornings before work to adjust their solar shading devices*” and explained that absence during the day limits active management, making overheating more severe than when present at home. Pets might further influence routines: Household 2 declared to keep the door between the hallway and living area “*always closed... so that the dog does not go upstairs*”, whereas Household 6 preferred to keep “*the door open all day to accommodate their dogs*”.

These findings suggest that effective summer comfort measures require not only technical provisions but also alignment with everyday habits and household realities (Stazi et al., 2017). In many cases, such usage issues could have been discussed during the design process and addressed through appropriate design choices and device selection.

3.3. Teleoaffective Structures

Perceived necessity

Perceived necessity plays of course a critical role in driving actions and determining priorities within the built environment (Hong et al., 2015; Murtagh et al., 2019).

Among the sampled enterprises, solar shading was here generally recognised as necessary and reliable, whereas ventilative cooling, though positively perceived, was considered less indispensable (see Figure 8). This difference may reflect enterprises’ awareness of how occupants’ routines and habits condition the actual usefulness of ventilative cooling.

Among end-users, perceived necessity of passive controls was closely linked to accumulated practical knowledge. While some households questioned their relevance (Households 1 and 7),

others described them as essential based on lived experience. Household 12, for instance, characterised exterior shading as “potentially indispensable”, while noting that “significant awareness is needed to justify investments”. These perceptions suggest that necessity is not intrinsic to the technology itself, but emerges through experience, understanding, and contextual awareness.

Perceived efficiency

Perception of innovation is a key determinant of technology adoption (Rogers, 2003). Solar shading was also widely perceived as effective, particularly when its performance could be directly experienced. Household 6 reported that external screens “*made a huge difference, effectively lowering indoor temperatures after experiencing peaks of 33°C*”, reinforcing confidence in their efficiency.

Positive experiences with automation further highlighted its perceived efficiency, notably its ability to compensate for human error—such as “*not forgetting to close solar protections before leaving*” (Household 13)—and to integrate contextual parameters, for example by “*accounting for variations in weather conditions (rain, wind, etc.)*” (Household 11).

However, efficiency perceptions were tempered by reported limitations. A recurrent source of dissatisfaction concerned system rigidity, with frequent cloud cover triggering repeated screen movements and requiring manual intervention (Household 12). In Case 11, the automated roof window opening system was ultimately dismantled due to concerns about algorithm reliability and lack of adaptability. Even among non-equipped households, indirect experiences shaped perceptions: Household 9 cited a friend’s experience where “the closure of screens blocked them outside”. Drawing on its own technological experience, Household 12 also raised concerns about long-term efficiency, including maintenance costs, system durability, and potential obsolescence. These findings confirm that perceived efficiency is strongly shaped by prior experience (Boso et al., 2020).

Perceived economic value

The importance of socio-economic status and attitudes towards energy conservation behaviour in residential buildings is established in the literature (Brown & Cole, 2009; Guerra-Santin et al., 2016). Cost was here identified by enterprises as the main barrier to the implementation of solar shading (Figure 9). This finding is consistent with occupants’ interviews. Several respondents (Households 6, 7, 12), despite their elevated socio-economic status, emphasised the unreasonable price of external shading devices and related options such as automation. As one participant stated: “*Why pay so much for that?*” (Household 12). Others questioned the cost–benefit ratio of such interventions, for example: “*Why invest hundreds or thousands of euros for discomfort lasting only a few weeks?*” (Household 7).

For ventilative cooling, cost did not emerge as a barrier, likely because current integration typically relies on already existing building elements rather than dedicated devices.

Aesthetics

Aesthetics plays a significant and multifaceted role in influencing the priorities set during building construction processes (Bugenings et al., 2025; Day et al., 2020). Aesthetic integration was identified by enterprises as the third most important barrier to the adoption of solar shading (Figure 9). This concern also emerged during household interviews. For instance, Household 6 noted: *“Architects sometimes prioritise aesthetics over performance, recommending interior blinds”*. Several other households also emphasised aesthetic considerations, with one respondent clearly stating: *“I don’t want this kind of ugly thing”* (Household 6).

Perception of alternative solution

Technological adoption depends on how potential adopters perceive the innovation compared to available alternatives (Rogers, 2003). Although the sampled enterprises were not generally inclined to advise on active cooling systems (see Figure 3), many occupants tended to compare passive strategies with active alternatives. As Household 6 remarked: *“An air conditioner costs less – it’s sad, but it’s the reality.”* For some, active solutions are considered indispensable, particularly for ensuring comfort during sleep (Household 11). Household 9 viewed active cooling as *“a possible future investment”*, a decision heavily influenced by their *“photovoltaic (PV) production”*. Others, however, identified the limited efficiency of portable air-conditioning units, which *“consume a lot to gain very little”* (Household 11), while some expressed reluctance to invest in equipment that *“will cool but also cost energy”*, acknowledging the more sustainable character of passive cooling techniques.

Client/Occupant Profiles, Values and Preferences

As often highlighted in the literature (Brager et al., 2015; Brown et al., 2015; Schweiker et al., 2016), interviews revealed that occupants’ values and preferences strongly influenced how strategies are implemented. These included consideration of tolerance for discomfort, need for quantification, desire for autonomy and control, openness to (smart) technologies, willingness to dedicate time and sustainability consciousness. Table 3 summarizes the encountered factors related to occupant’s values and preferences. These findings underscore the importance of accounting for a diversity of user preferences when defining control strategies (Nagy et al., 2023).

Nevertheless, the interviews revealed that, during periods of pronounced discomfort (e.g., heatwaves), occupants’ priorities tend to shift. In such situations, the need to mitigate overheating could temporarily override other comfort-related considerations, including access to natural light (e.g., Households 1, 3, 4), outdoor views (e.g., Households 3, 6, and 14), or protection against insect intrusion (e.g., Households 1 and 13). This might lead some households (e.g., Household 8) to adopt temporary measures, such as installing white sheets as provisional solar shading solutions.

Table 3. Identified factors related to the occupants' values and preferences.

Element	Description	Representative Quotes
Desire for control vs. autonomous systems	Tension between convenience of automation and desire for personal oversight.	<i>"An automatic system could be more performant than doing it manually" (HH1).</i> <i>"I deactivated it because I did not master when it opens nor when it closes" (HH11).</i> <i>"I feel like I'm not driving my car anymore" (HH4).</i>
Openness to (smart) technologies	Willingness and attitude toward adopting, using, and experimenting with new (IoT) technological solutions.	<i>"I would like to have a programmable unit that could be linked to indoor temperature or set to a vacation schedule" (HH13).</i> <i>"An app for that could be very nice" (HH2).</i> <i>"I am not very good with everything electronic". (HH5)</i>
Willingness to dedicate time	Time required from occupants to operate (and maintain) passive strategies.	<i>"In the morning, I have no time for that" (HH2).</i> <i>"We are all so busy" (HH6).</i>
Sustainability-consciousness	Preference for low-impact solutions.	<i>"... for a pure question of environmental preservation and a reduction in energy consumption" (HH13).</i> <i>"Completely aberrant from an ecological point of view" (HH6).</i>
Tolerance for discomfort	Acceptance of occasional summer discomfort.	<i>"As long as it remains short, I think we can adapt" (HH1)</i>
Tolerance of implications of use	Acceptance of implications of passive control uses (see Table 4).	<i>"Not easy to open... it annoys me". (HH2)</i> <i>"When protecting from heat, we are in the dark". (HH4)</i>
Desire for autonomy	Strong preference for self-reliance and avoiding dependency on single energy sources or fully automated systems.	<i>"I don't like my whole house to depend on a single energy source... if things open automatically, we depend on electricity... I'd prefer to manage it myself" (HH2).</i>
Need for quantification	Desire for measurable comfort gains before adopting new practices or technologies.	<i>"What will I gain? Half a degree?" (HH7)</i>

3.4. Material Arrangements

Availability and Visibility

The degree to which (the results of) an innovation is visible to others plays a key role in technological diffusion (Rogers, 2003).

As summarised in Figure 3, the sampled enterprises (n = 167) listed the cooling strategies to mitigate overheating they usually recommend for new and renovated dwellings. Results indicate that most enterprises (60%) *often or always* consider solar shading, whereas only 8.4% *never* do. External solar shading, typically manually operated, was the most frequent option (see Figure 4 and Figure 6). Regarding ventilative cooling, 51.5% of respondents often or always consider this strategy, usually via manually openable windows or mechanical ventilation boosts (Figure 5 and Figure 6), while 25.2% rarely or never do (Figure 3). In contrast, reversible heat pumps and air conditioning are *often or always* considered by 28.7% and 7.8% of respondents, respectively.

Importantly, the recommended strategies are not always implemented (Figure 7). Only 57% of enterprises reported that the proposed solar shading devices were typically integrated during construction, and 69% for ventilative cooling. Figure 9 and Figure 10 present the identified reasons for these discrepancies, which are discussed further below.

On-site household interviews confirmed these trends. Among the 14 dwellings examined (Table 1), only two included effective solar controls at the end of construction. Many large, glazed surfaces remained unprotected, likely due to their perceived value for winter solar gains. In dwellings 1–9, construction practices rarely adapted to the individual characteristics of the dwelling, despite evident summer overheating risks. Solar shading was often installed post-occupation, typically after occupants experienced prolonged periods of thermal discomfort. Manufacturers E and F noted that “*most solar shading sales occur reactively during hot days*”, with immediate availability becoming critical. External devices parallel to glazing were reported as the most common devices; manual operation predominated, with some seasonal movable and/or automated screens (Table 1). Internal curtains, despite their lower effectiveness in reducing solar heat gains (Firląg et al., 2015), were also frequently used as solar control.

The implementation of ventilative cooling was similarly reactive, mainly via manual window opening, constrained by security and insect intrusion, hence limiting cooling potential (International Energy Agency, 2018b). One dwelling (Case 11) employed a dedicated louver, providing a secure alternative (Bugenings et al., 2025). Manufacturers indicated that such devices are increasingly available in the Belgian residential market, whereas they were previously “*reserved for commercial buildings or for neighbouring countries*” (manufacturers C, E). Some households temporarily boosted mechanical ventilation (cases 5, 8 and 14), while others used automated roof windows (case 11), active cooling (case 11), Personal Comfort Systems (fans (case 3 and 8)), or portable air conditioners (cases 4 and 7)).

Despite the recognized importance of visibility for the diffusion and effective use of technological innovations (Behar, 2016), the integration of passive strategies remained limited in practice, particularly during construction. Nevertheless, occupants’ discomfort often prompted the adoption of additional devices, with some planning further interventions, such as external shading screens (cases 4 and 14) or active cooling (case 9).

Technical Feasibility

One of the most influential factors shaping the implementation of passive controls concerns their *ease of technical integration* (Karvonen, 2013). Several respondents stressed that the absence of preparatory measures – such as space for devices, electrical wiring or dedicated anchor points – can significantly limit feasible solutions, especially regarding solar shading.

Similarly, for example, another respondent (Household 10) emphasized that solar screens “*must be integrated very early in the project*” because retrofitting otherwise requires “*adding boxes and stuff*” leading to both “*higher costs*” and “*aesthetic compromises*”. Things are a bit different for ventilative cooling, as it could rely partially on the latent technical potential of building elements (e.g., operable windows). Yet, as highlighted by Household 1: “*one operable window could be missing upstairs in the hall*”, considerably reducing the ventilative potential. Such design omissions create lasting barriers that are difficult to correct once the building is completed. This highlights a form of technological lock-in: once construction choices are made, subsequent integration could become more complex.

Finally, *extensibility and upgradability* of building elements or constructional details emerged as an opportunity. For instance, most of the encountered roof windows offered integrated opportunities for subsequent upgrades (e.g., solar shading, motorized opening, automation, etc.). This has allowed various dwellings to further equip their roof windows with the necessary solar shading devices (Table 1).

Implications of use

Implications of use emerged as critical factors limiting the routinisation of passive controls (Dengel & Swainson, 2012; McLeod & Swainson, 2017). Table 4 lists all user-related implications identified during occupants’ interviews. For example, Household 13 declared to rarely use its louver for ventilative cooling because it is “*not equipped with mosquito nets*”. Conversely, Household 1 reported being against solar shading due to their visual impact, while mentioning issues such as obstructed views or reduced daylight.

Table 4. List of use-related limitations identified during interviews.

Elements		Description	Representative Quotes
Risks with the Openness to the Outdoor Environment	Visual Impact / Daylight	Obstruction of view or of daylight reduces acceptance	<i>"When protecting from heat, we are in the dark". (HH4)</i>
	Security / Theft Risk	Fear of intrusion limits window opening	<i>"If we leave a tilt-and-turn window, you are not insured... we close because of the insurance" (HH3). "We deactivated the opening automation when absent because of the burglar risks" (HH11).</i>
	Insect Intrusion	Presence of mosquitoes and flies' limits window use	<i>"I hate bugs, mosquitoes, and flies... I have mosquito nets everywhere; it's essential". (HH2)</i>
	Weather Exposure	Rain and drafts force windows to remain closed	<i>"I use tilt position to prevent water entry while maintaining ventilation". (HH2) "I have a rain sensor for the automation of this roof window". (HH11)</i>
	External Noise	Noise from neighbours, traffic, etc. disrupts ventilation practices	<i>"Noise wakes the children, so we keep windows closed". (HH7)</i>
Ease of Use		Time or physical effort required for operation; actions perceived as burdensome	<i>"Not easy to open... it annoys me". (HH2) "I don't always have the strength... they are high up". (HH7) "If I had to lower all the blinds every day, no, I wouldn't do it". (HH10)</i>
Flexibility / Seasonal Adaptation		Solutions that can be easily installed, removed, or deployed seasonally are sometimes preferred	<i>"Placed at the beginning of summer... and then you don't worry about it again". (HH2) "You can place it only for the season when it's useful... no disadvantages in winter". (HH3)</i>
Functional Versatility		Devices serving multiple purposes facilitate use	<i>"Screen doubles as a mosquito net". (HH13)</i>
Noise		Noisy automation deters intensive use	<i>"It should be used intensively, but acoustically, it's horrible". (HH9)</i>
Maintenance / Lifespan		Maintenance, cleaning, or element replacement reduces adoption	<i>"In 5 or 10 years, we won't be able to find a replacement remote control" (HH12)</i>
Privacy and Data Security		Data security of smart systems	<i>"All data are secured locally... Unlike many other manufacturers, we do not collect user data". (Manufacturer A)</i>

4. LIMITATIONS

Practices are inherently context-dependent, varying according to climate, building type, and socio-cultural values (Strengers & Maller, 2011). In this study, the context corresponds to Belgium (Cfb climate according to the Köppen-Geiger climate classification (Peel et al., 2007)), with a focus on single-family, highly insulated dwellings, mostly located in suburban areas and occupied by their owners.

The voluntary nature of the online survey may have introduced a bias, as its dissemination mostly relied on recommendations and the steering committee's networks. Hence, the participating enterprises might have been those already interested and more engaged in the topic. As such, the reported practices of enterprises may not be fully representative.

This study also considered the implementation of passive controls as a practice shared among multiple stakeholders including end-users, enterprises and policymakers. In reality, different configurations and relationships between these stakeholders exist. As an example, designers and building trades may collaborate as a *design-and-build* team or operate separately. Within the trades, the division of roles and competences can differ, being either general – as in the case of contractors – or specialised. These different configurations can play an important role in the building process (Behar, 2016). Within our context, openable windows, for instance, are generally realised by specific enterprises according to the designer's plans, sometimes in a non-standardised manner (e.g., with free dimensions). The production and installation of solar shading, in contrast, are usually undertaken by other specialised trades or directly by manufacturers. These specificities contribute to a certain fragmentation of roles, which is recognised as an important barrier to the effective implementation of new practices (Bartiaux et al., 2014). An in-depth analysis of the roles, relationships, and mutual influences of all stakeholders would provide valuable insights, yet this analysis lies beyond the scope of this study.

5. CONCLUSIONS

Among environmental controls, solar shading and ventilative cooling are widely recognised as key passive strategies for enhancing summer thermal comfort in buildings. These strategies contribute to mitigating the risk of overheating, supporting free-running buildings and creating favourable conditions for more sustainable, high-temperature cooling systems. EPBD regulations have introduced overheating indicators to stimulate, among other, the use of passive controls for newly built dwellings. Nevertheless, their practical implementation in newly built dwellings remains limited, particularly in heating-dominated temperate climates where such practices are not culturally embedded, highlighting the need for in-depth investigation.

Engineering literature often frames barriers to their implementation as a set of individual factors, with practical efficiency largely shaped by occupant influence. Here, common practices of each stakeholder involved in decision-making (enterprises, policymakers, and end-users) were examined through an iterative qualitative approach – featuring interviews, online surveys, and focus groups. Adopting a Social Practice Theory lens on the results, this study enabled the identification of key elements – organised as material arrangements, institutional procedures, know-how and routines, and teleoaffective structures – which underpin current practices related to the implementation of passive controls in newly-built dwellings in the oceanic temperate climate context of Belgium.

The findings highlighted a chain of missed connections: low awareness among clients and lack of direct imposition by regulations reduce demand, while insufficient professional guidance, occupant

knowledge and involvement lower the effectiveness of available solutions. Also, cost appeared as a decisive barrier to the adoption of solutions, with the risk of favouring cheaper or more immediately accessible alternatives despite lower long-term sustainability.

Practical experience was, however, found to influence the perceived necessity of passive controls, thereby encouraging their integration and use. The results also revealed that, when the design and/or construction process does not incorporate passive control strategies, their subsequent integration can become technically complex, costly, and aesthetically unsatisfactory, reflecting a form of technological lock-in.

Occupant routines, habits and preferences were also found to strongly shape the practical use of summer comfort strategies as often highlighted in the literature. Yet, these factors mainly linked with user profiles and needs are often overlooked or insufficiently considered during the design stage. This results in the underuse of passive controls when conditions and implications of use interfere with occupants' needs and possibilities (presence, willingness and time to anticipate discomfort, etc.). Results also demonstrated that occupants' ability to adapt their routines during specific periods, temporarily accepting the implications of use when faced with significant discomfort.

Taken together, these results demonstrate that the implementation of passive strategies is more than a purely technical issue and should be understood as part of evolving social practices. Supporting the reconfiguration of the elements that shape these practices is likely to be necessary for the effective implementation of passive controls and the development of more climate-resilient residential buildings in heating-dominated temperate climates.

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B.2. Contributions to the research sub-questions

How are passive controls currently integrated into newly built dwellings (RQ3)?

Chapter VI and Chapter VII, presenting the results of survey and interviews campaigns, gave an overview of current practices regarding the integration of summer passive controls.

Regarding solar shading integration, the results highlighted a tendency towards omission during the construction stage, frequent use of internal solutions, and reliance on manual control. More specifically:

- Only 17% of the cases in Sample A.1 (n=149) and 33% in Sample A.2 (n=23) had solar-shading devices installed by the end of construction.
- In Sample B, only 11.7% of enterprises reported that the prescribed solar-shading devices were always installed during the construction phase.
- More than one-third of respondents in Sample A.1. reported using light-coloured internal curtains as shading.
- Very few systems were equipped with automated control. In lots of cases, motorised systems remained manual.

Regarding ventilative cooling, results revealed an almost exclusive reliance on manual window opening mainly during the daytime:

- In sample A.1, for instance, more than 70% of respondents reported using windows opening to cool rooms.
- Night windows opening was only practiced by 11% of households in the living rooms and by 40% in the bedrooms.
- A dedicated secured grille for ventilative cooling was found in only one dwelling from sample B (n=14).

Results also show that ventilative cooling is often misunderstood and confused with hygienic ventilation (see Chapter VII).

Chapter VII further examined the factors shaping the integration of passive controls through the lens of Social Practice Theory. The chapter framed this process as the result of interacting elements among institutionalised procedures, teleoaffective structures, know-how and routines, and material arrangements. The findings indicated that, despite the calculation of an overheating indicator under the EPBD framework [166] and growing awareness among professionals, limited knowledge and teleoaffective considerations, such as the perception that the small number of hot days in the current climate does not justify dedicated measures, appeared to contribute to the limited integration of passive controls.

Nevertheless, experiencing discomfort appear, in most cases, sufficient to motivate reactive behavioural response leading to the integration of dedicated devices:

- Two-thirds of the solar shading devices encountered in sample A.1 (n = 149) were installed after several years of occupation, often after experiences of discomfort (see Chapter VII).
- Most sales of solar shading occur during hot summer days according to the interviews of enterprises presented in Chapter VII.
- Approximately 40% of houses constituting sample A.1 were finally equipped, at least partially, with external devices (see Chapter III).
- Some occupants in Sample B also reported temporarily installing protective devices during heatwaves (see Chapter VII).

The integration of passive controls, mainly shading devices in this case, is therefore often driven by changes in teleoaffective structures arising from experiences of discomfort. This reactive form of integration could, however, also encounter substantial constraints as highlighted in Chapter VII. When passive controls are not incorporated during the design and construction process, their later integration could become technically complex, costly, and aesthetically unsatisfactory, reflecting a form of technological lock-in.

What factors shape the effectiveness of passive control use (RQ4)?

Practices regarding the use of passive controls in actual conditions, were mainly evaluated through occupants' interviews (Chapter VII) and measurements campaign (Chapter VI).

The monitoring campaign confirmed that proper control of ventilative cooling and solar shading have the capacity to considerably improve the indoor summer thermal conditions. Nevertheless, the results also confirmed that occupant behaviour plays a decisive role in the control of summer thermal conditions [186, 225]:

- Two buildings with similar characteristics were, for example, found to encounter the best and worst overheating situations of the sample A.2 (n=23) (see Chapter IV and Appendix C);
- Statistical analyses presented in Chapter VI did not show that the presence of solar screens, windows openings practices, or higher thermal inertia led to significant improvements in summer thermal conditions, suggesting that improvements in technical characteristics alone are not sufficient and that more effective operation is also necessary.
- Similarly, the combination of these three strategies did not result in any statistically significant improvement, although extreme conditions were encountered in the absence of solar shading.

In all encountered cases, the use of these techniques, when present, was however conditioned to the manual use by the occupants. This type of operation was found to be typically reactive (see Chapter VI), triggered by the onset of discomfort rather than by preventive anticipation. Here, results illustrated for example that facing higher temperatures prompts for windows opening. This finding is consistent with the literature on occupant behaviour. Window opening is generally driven primarily by thermal sensation, whereas the use of shading devices, when available, is more often prompted by visual discomfort, such as glare, direct solar penetration onto task areas, or excessive indoor illuminance [226].

Operation appeared also constrained by practical implications of use. Chapter VII provided a comprehensive overview of these implications. Identified factors include ease of use (time and physical effort required), flexibility, risks associated with openness to the outdoor environment (visual impact and daylight, security and theft risk, insect intrusion, weather exposure, and external noise), functional versatility, generated noise, maintenance requirements and lifespan, as well as privacy and data security concerns. In frequent cases, these factors strongly condition occupants' willingness and ability to engage with adaptive control opportunities. For example, some encountered solar shadings were not actually used because of their visual impacts (darkness, perturbed view to the exterior). Ventilative cooling was found to be mainly practiced during the day in living rooms mainly for security reasons. This leads to question the effectiveness of the measure for cooling purpose as it strongly depends on external temperature.

Moreover, daily routines and lifestyle constraints of the occupants were found as strongly interfering with the continuous need of passive control operation in low-energy buildings. As shown by the statistical analyses presented in Chapter VI, routinised daytime absence emerged as one of the most influential factors affecting both perceived and measured summer thermal conditions. In this case, reactive behavioural responses are indeed not possible, making anticipatory actions necessary. Yet anticipatory operation requires prior awareness, and willingness to devote time, and a sufficient level of engagement, which may limit its practical adoption. Additional constraints arise when occupants are not present in the specific room where an action would be beneficial, or when they are physically unable to operate controls, thereby increasing the vulnerability of certain population groups (e.g., the elderly) [227, 228].

However, a certain fluidity in teleoffective structures was observed when occupants faced significant discomfort, allowing passive controls to be used despite practical constraints that would usually be considered unacceptable.

Together, these findings confirm that occupants' operation of passive controls does not follow a static "dose-response" relationship [47]. Rather it reflects complex and dynamic interactions between perceptions of the indoor environment, technical characteristics, preferences, profiles and daily routines of occupants.

B.3. Conclusion

The results of Part B showed that the integration and use of passive controls are not yet routinely prioritised in newly built low-energy houses in Wallonia, despite the inclusion of an overheating indicator in the EPBD framework and growing awareness among professionals.

On the one hand, the findings indicated that owners' awareness of overheating risks is an important driver of the preventive integration of passive controls during the design and construction stages. However, this anticipatory approach tends to remain confined to a niche of well-informed stakeholders. Practically, it appears to face significant barriers including cost, limited awareness and teleoffective aspects (perceived necessity due to limited number of hot days in the current climate, etc.).

On the other hand, direct experience of overheating discomfort was found to be, in most cases, the primary trigger for the subsequent installation and use of passive controls. This reactive form of adaptation may nevertheless also face substantial constraints. When preparatory measures, such as openings enabling cross or stack ventilation, electrical wiring, anchor points, or reserved space for solar-shading devices, are not incorporated during design and construction, the later installation of passive controls can become technically complex, costly, or aesthetically unsatisfactory, reflecting a form of technological lock-in.

The findings also confirmed that occupant practices play a decisive role in the effective control of indoor thermal conditions during summer. The operation of passive controls often appeared to be constrained by daily routines and practical concerns, including effects on daylight and views, security, noise, insect intrusion, and the need for sustained or anticipatory action. These constraints may conflict with the continued operation required to maintain acceptable summer thermal conditions in low-energy dwellings.

More broadly, the findings of Part B reveal a gap between EPBD policy ambitions, which favour the anticipatory integration of passive controls, and real-world practices, which remain predominantly reactive.

VIII.1. The need for greater consideration of thermal adaptation processes

While climate change calls for dedicated summer thermal adaptation strategies in buildings, only a limited number of newly built low-energy houses were found in this study to preventively address this need. As highlighted in Part A of this research, frequent overheating situations are already encountered, confirming concerns arising from other contexts (see Section I.1.3).

Practically, the findings do not attribute responsibility to any single building characteristic – as it is sometimes suggested in the literature (cf. Table I.9 p.63) – given the complex and dynamic nature of overheating. Rather, they suggest that appropriate design, combined with the proper integration and operation of passive controls based on solar gains control and heat dissipation would likely have prevented these situations.

Work conducted in the frame of IEA Annex 62 [169] highlighted the role of certain EPBD calculation methods - especially those based on monthly energy balance calculation - which may contribute to underestimating the need to properly implement dedicated strategies. The analysis conducted in Chapter VII depicted a more complex situation: the limited perception of necessity and awareness among clients and the lack of direct regulatory requirements reduce demand, while insufficient professional guidance, occupant knowledge, and involvement, reduce the effectiveness of available solutions. Cost also emerged as a decisive barrier. As such, Part B of this study corroborate that the integration of passive controls is only an emerging practice that today tends to remain confined to a niche of informed stakeholders with sufficient economic resources [169, 170].

These findings question therefore how to move towards more socially shared routines embedded in the design, construction, and everyday use of buildings to adequately address the growing need for summer thermal adaptation strategies in context where it is not culturally embedded.

According to Social Practice Theory, practices do not simply appear. Rather, they evolve, spread, emerge, or disappear through the reconfiguration of their constituent elements, or through the transformation of the practice itself [229].

Rather than focusing primarily on the implementation of technical solutions and subsequently guiding occupants towards their proper use and operation, this theoretical lens shifts attention towards the reconfiguration of the elements that constitute existing practices and that practically may support summer thermal adaptation processes. Such an approach is consistent with IEA EBC Annex 69, which advocates integrating behavioural, psychological, and physiological adaptation mechanisms into the design and operation of low-energy buildings [230]. The present study extends this understanding by emphasising the social and cultural contexts within which these practices are embedded, as discussed, for example, in Chapter VII. Accordingly, attention must extend beyond the technical strategies themselves to the processes through which they are integrated and used, as well as to the purposes they ultimately serve.

Based on the evidence-based results generated throughout this study, the followings sections discuss the identified and complementary practical ways of achieving this perspective, highlighting:

- the need to move beyond traditional passive solar design;
- the need for more incremental adaptive strategies;
- the need for more occupant-centric control strategies;
- the need to shift from comfort to health considerations.

VIII.2. The need to move beyond traditional passive solar design

Passive solar design refers to building design principles that favour solar energy and local climatic conditions to improve indoor thermal performance without relying on mechanical systems. Traditionally, in heating-dominated climates, it focuses on building orientation, window placement, solar gain optimisation (with fixed shading device), thermal mass, and insulation to reduce heating demand [231].

These design strategies were developed in the past, with insulation and airtightness levels significantly lower than those commonly achieved today. This evolution considerably changes the thermal behaviour of buildings calling for dedicated strategies. As an example, Figure VIII.1 illustrates the balance between heat gains and heat losses in a theoretical room during a typical clear-sky summer day in Belgium. It highlights the predominance of solar heat gains over heat losses in the absence of dedicated strategies (left), thereby demonstrating the need for further heat gains control and heat dissipation strategies (right).

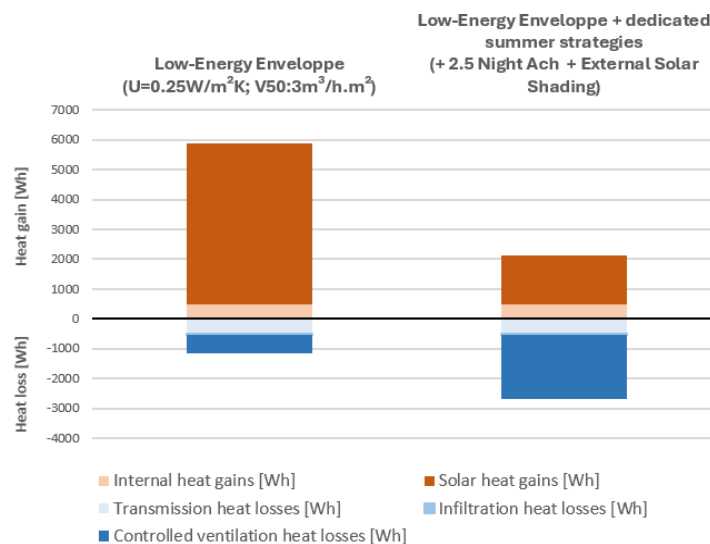


Figure VIII.1. Thermal balance in low energy buildings with (right) and without (left) dedicated summer thermal strategies during a typical summer day. Theoretical example for a south oriented room. Main hypothesis: floor area: 10 m²; ceiling height: 3 m; mean

daily thermal conditions: 25°C indoors and 20°C outdoors; glazed surface area: 2 m²; orientation: south; corresponding daily solar irradiation: 3.8 kWh/m² (clear sky).

However, while solar heat gains are recognised as a main source of heat in dwellings [131], and that its valorisation during the heating season is comparatively reduced [232] in highly insulated buildings, they are still in practice often viewed primarily through a beneficial winter lens rather than as a major source of summer discomfort. As such, the findings of this research corroborate those of previous studies (see Table I.9) , particularly by showing that:

- Excessive heat from solar radiation was reported in 65% of the dwellings included in the Post-Occupancy Evaluation (subsample A.1(n=149)) presented in Chapter III.
- Frequent situations presenting large, exposed, and unprotected glazed surfaces were observed during the on-site visits (subsamples A.2 (n=23) and B (n=14)).

Not protecting exposed windows in these highly insulated dwellings could lead in heat accumulation and high temperature peaks (see for example Appendix C). Statistical analyses further showed that solar shading was more commonly installed in houses presenting the largest glazing areas (see Chapter VI). While climate change may require the generalised and optimised control of solar gains during summer (see Appendix H), the appropriateness of such extensive glazed surfaces, which considerably increase the need for dedicated solar-control strategies should therefore be questioned.

In addition, ventilative cooling, which is often regarded as an effective way to dissipate accumulated heat and cool the indoor environments in temperate climates [233] was frequently found to be misunderstood or confused with hygienic ventilation. The frequent use of terminology, such as “*Intensive ventilation*”, may reinforce this confusion. In a study of energy-efficient homes in Belgium [142], residents with mechanical ventilation systems (System D) reported being told by installers that windows should not be opened to ensure the optimal performance and efficiency of the heat recovery system. While this advice is valuable for the heating season (winter), the study noted that it is often misapplied by occupants during the summer. If the role of the installers could not be verified in the present study, results from Chapter VII shown that

boosting mechanical ventilation is frequently perceived as a cooling strategy by occupants and enterprises (see also Appendix E). If these systems are generally equipped with summer bypass in the Belgian context, eliminating this contributor to overheating situation (cf. Table I.9), residential airflow rates are however typically limited to hygienic needs (~1 air change per hour, [234]), which is not sufficient for effective cooling [169].

In practice, ventilative cooling through window opening was often the only means of evacuating accumulated heat in the analysed low-energy houses. As illustrated in Appendix C, window opening during the night time is particularly efficient to evacuate accumulated heat and maintain indoor temperatures, especially when outdoor temperature present large daily variations. Although most occupants reported using it to cool rooms (see Chapter VI), it was however found to be mainly practised in living rooms during the daytime (see, for example Chapter VI). Its use appeared also often constrained by limited or absent openings or by the possible nuisance of the outdoor environment (risk of rain, insects, noise, pollution, etc.) raising questions about the practical effectiveness of the strategies implemented (see Chapter VI and Chapter VII).

On the one hand, ventilative cooling has the potential to play an increasing role under future climatic conditions, likely because heat dissipation will be required over longer periods as illustrated by the sensitivity analysis presented in Appendix G. On the other hand, its proper implementation requires dedicated attention, particularly regarding how it could be better integrated and operated in residential buildings. Possible solutions include secure openings, dedicated ventilation grilles, and appropriately sized mechanical ventilation systems. Such developments may be necessary to encourage broader uptake and achieve the higher air-change rates that may be required under future climate conditions to compensate higher external temperatures (see for example Appendix H).

Thermal mass, which is also recognised as having a considerable influence on the thermal behaviour of buildings, was not found to be highly influential in practice (see Chapter VI), probably because it is

insufficient on its own to compensate for inadequate solar-gain control and ventilative cooling. Also, although it may remain particularly effective during short, intense heatwaves, its relative contribution decreases under future climatic conditions (see Appendix G).

Taken together, these results highlight that the design and operation of nZEB houses remain today primarily focused on reducing heating energy demand by applying passive solar guidelines while paying less attention to, or underestimating, the need to mitigate overheating risks.

More specifically, these findings underscore the need to move beyond passive solar design and its traditionally winter-centred paradigm, and to properly address the crucial need to limit solar gains exposure and to offer more effective heat dissipation strategies.

VIII.3. The need for more incremental adaptive strategies

Summer thermal adaptation is often understood as the integration of dedicated strategies during the design and construction stages of buildings (see Section I.1.1.6).

On the one hand, passive control combining appropriate technical characteristics and optimised operation will become increasingly necessary to maintain free-running buildings in the future (see Appendix H), or at least to allow the use of high-temperature active cooling systems [105].

On the other hand, preventively addressing the need for dedicated summer thermal adaptation strategies does not yet appear to be routinised in current practices. By contrast, as demonstrated in Part B, practical experience of overheating was found to be the primary driver for the integration of summer thermal adaptation strategies.

Recognising and supporting occupants' behavioural responses when facing overheating appears therefore crucial and invites to consider incremental integration pathways as part of broader social adaptation processes.

Figure VIII.2 illustrates the principle of such incremental opportunities. In practice, examples were observed through specific building components (e.g. roof window systems) and construction details that offer extensibility and upgradability opportunities.

Extensibility, similarly, to its use in computer science, should be understood here as the ability of a system to be expanded or enhanced with new features, functions, or capabilities without requiring major changes to its existing structure or disrupting its core operation [235]. In such, extensibility refers to how easily a system can accommodate future growth, adaptation, or customization by adding new components rather than modifying/replacing existing ones. In our context of interest, it can be linked to technical solutions designed so additional features

(solar shading, mosquito protection, secure grids, motorisation, sensors, etc.) can be integrated over time.

Upgradability is linked to the ability of a system to be made more powerful or efficient [236]. In the present context, it should favour experience-based improvements of (automated) systems (i.e. control algorithms, solar gains control efficiency, etc.).

These findings invite therefore to recognise and value an adaptive capacity of buildings that could be defined as “*a design attributes allowing the incremental integration of passive controls through extensibility and upgradability features aiming at improving both their technical and operational characteristics*”.

More generally, this definition calls to requestion the way summer thermal adaptation is generally seen in building engineering literature (see Section I.1.1.6), inviting to think summer thermal adaptation of buildings not as the need to reinforce the preventive integration of the best technical solutions during the building design and construction stages, but rather on reconfiguring (elements of) existing practices to facilitate the natural behavioural reactive response of occupants in the integration and use of passive control.

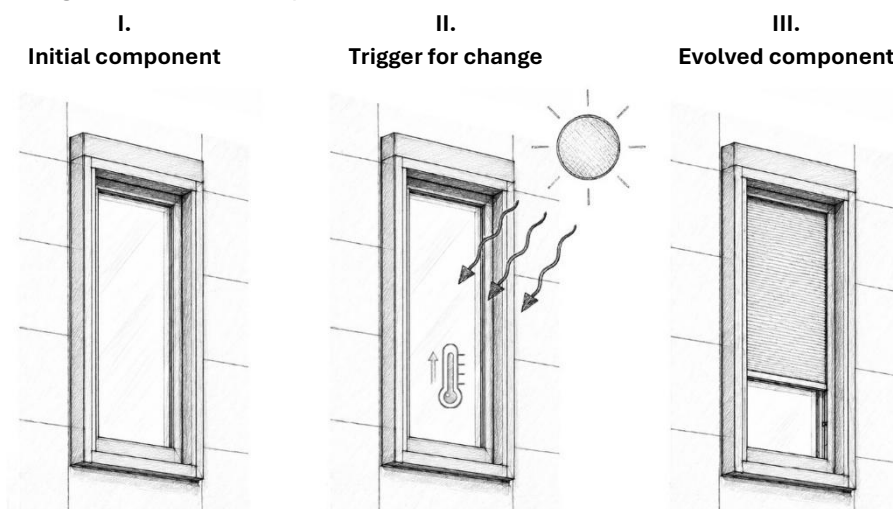


Figure VIII.2. Example of incremental adaptive strategies

VIII.4. The need for more occupant-centric control strategies

Building engineering traditionally focuses on technical performance when defining design and operational choices. This approach is largely reinforced by regulatory frameworks such as the EPBD [160], which primarily aim to promote the most energy-efficient components and control strategies, often considering occupant behaviour as a barrier to this efficiency [237].

The results of Part B corroborate that occupant behaviour plays a decisive role in the regulation of indoor summer thermal conditions [186, 225]. Beyond this well-established influence, the continuous operation of passive controls throughout the building was found to be more critical than their intrinsic technical performance (see for example Chapter IV and Appendix G). As such, Chapter VI further highlighted the need to consider occupants' presence and work routines and how it can conflict with the need for continuous operation in low-energy dwellings. The usual presence during the day combined with the availability of passive controls was indeed found to be the most determining (and statistically significant) combination of factors. As illustrated in Chapter VI, it allowed improvements for both measured and perceived summer thermal conditions suggesting forms of behavioural and psychological adaptation.

Implications related to use – such as daylight and visual impacts, security concerns, noise, insect intrusion, and the need for continuous or anticipatory operation – were also frequently found insufficiently addressed during the design stage, thereby limiting the effective and sustained use of passive control strategies (see Chapter VII).

Together these findings highlight that the effectiveness of passive controls often relies on a delicate balance between technical performance and personal convenience, calling for more occupant-centric approaches.

Occupants centric design and operation put user preferences in the centre of the design decision making process. Discussion on Occupant-Centric Controls that have emerged these last years [238] are however essentially based on technological approach aiming at sensing indoor environment quality, occupants' presence and interactions with buildings components, in order to improve energy efficiency, IEQ, and occupant comfort without impacting usability and perceive control for the occupants [239].

In the context of the growing development of smart buildings [159], the integration of Internet of Things (IoT) technologies [240] offers clear potential to support occupants in operating environmental controls or to optimise their functioning autonomously. Connected devices can sense relevant parameters at appropriate times and locations and trigger adequate responses. However, only a limited number of automated systems were identified in this study, and several occupants reported having discontinued their use due to dissatisfaction with system behaviour (see Chapter VII). These findings suggest that occupants' openness to smart technologies and their need for control are also critical determinants of practical effectiveness.

The choice of operational mode – manual, automated, or smart-assisted (see, for example, ISO 52016-3 [210]) – should therefore respond not only to technical efficiency requirements but also to occupant routines, preferences and needs. Figure VIII.3 presents a proposal for such a decision scheme, aimed at selecting operational strategies in residential buildings based on these considerations.

More generally, the findings of this study suggest that rather than prioritising purely technical implementation [133, 152] occupant-centric design should rather put occupants' preferences, values and routines as the core elements of the design. As such, it should firstly aim to align implications of use of passive controls with occupants' values and preferences [241] as well as with their routines, needs, and socio-economic realities.

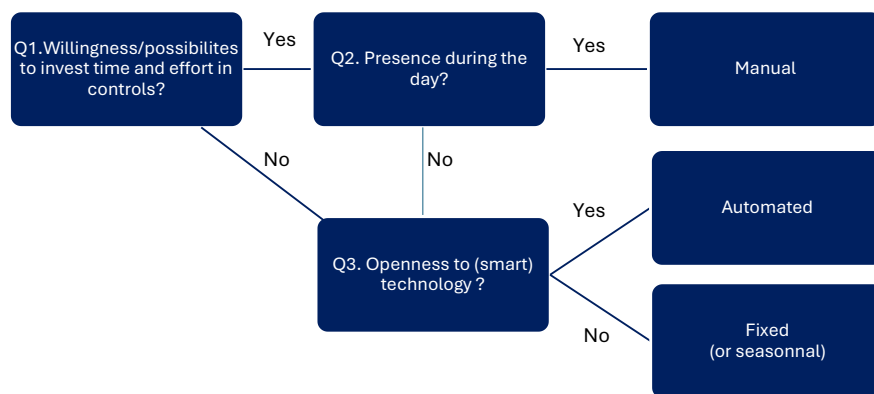


Figure VIII.3. Example of a scheme for selecting operation type based on occupants' profile in residential buildings.

VIII.5. The need to switch from comfort to physiological and health considerations

Like many other studies (cf. Table I.5 and Table I.10), this research relies mainly on comfort metrics to examine summer thermal conditions.

In the context of climate change, the pursuit of comfort at all times and in all situations, including extreme conditions, could lead to active cooling systems being considered the default scenario [242]. This could induce additional environmental impacts that may further reinforce global warming on a broader scale [243]. In this respect, although adaptive conditions may need to be differentiated between living and sleeping environments [244], the use of static comfort models in sleeping environments was found to be particularly restrictive in the context of climate change (see, for example, Chapter V), calling for dedicated attention.

Research on physiological heat adaptation has, for instance, highlighted the powerful role of acclimatization. It has been demonstrated through laboratory experiments that repeated heat exposure prior to heat stress can significantly improve physiological responses [245, 246]. These improvements include a reduction in core temperature, enhanced heat dissipation through the skin, more efficient evaporative cooling via sweating, reduced cardiovascular strain, and improved glucose and fat metabolism. These findings provide a physiological explanation for the natural acclimatization observed in field studies, which show that living in warmer climates is associated with higher preferred indoor temperatures [247]. They also support the fundamental principles of adaptive thermal comfort developed for non-mechanically cooled buildings [248].

Similar to other indoor environmental quality (IEQ) domains, the ambition to design healthier buildings [47, 249] therefore calls for a shift from the pursuit of uniform, constant, and thermally neutral indoor summer conditions, toward a more dynamic indoor climate that varies on diurnal and seasonal scales [250, 251].

However, as highlighted by Pallubinsky [252], heat exposure can be a double-edged sword. On the one hand, careful and controlled exposure to heat may simultaneously reduce energy consumption, enhance heat tolerance, and potentially generate health benefits [253]. On the other hand, excessive heat poses a significant health risk for vulnerable populations with limited adaptive capacity, such as elderly or very young children [254].

Taken together, these considerations call for the exploration of adaptive opportunities that prioritise physiological adaptation without compromising health, rather than seeking to eliminate thermal discomfort at all costs.

Although several approaches have already been proposed in this direction, such as the application of heat-stress metrics (Heat Index for example [40]), a more detailed understanding of physiological adaptation processes and their limits is still required to support their practical implementation.

More specifically, as illustrated in Figure VIII.5, which proposes an adaptation of current adaptive thermal comfort models, these considerations raise three main questions:

1. Under which conditions is physiological adaptation possible, depending on occupants' activities and individual vulnerabilities (α)?
2. What level and duration of thermal exposure are required to trigger physiological adaptation (x_1)?
3. Where are the limits of this adaptation, beyond which heat exposure may pose a risk to human health (x_2 and x_3)?

Further research on physiological adaptation is therefore clearly needed to better define these conditions, triggers, and limits.

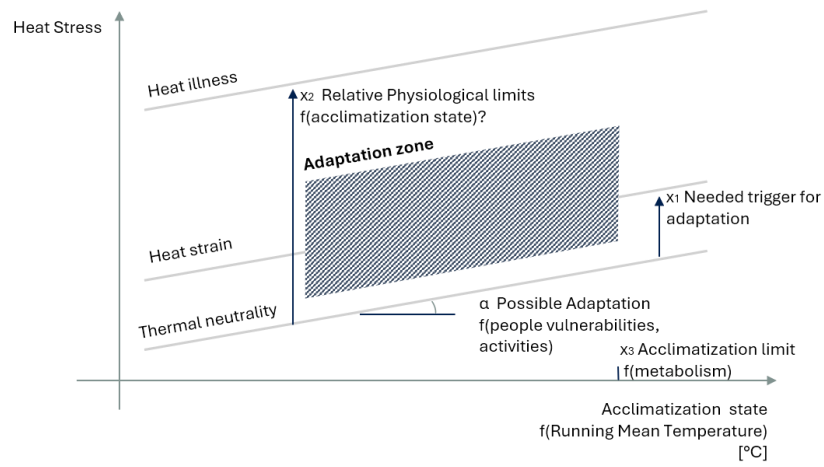


Figure VIII.4. Key limits to be defined for the practical integration of physiological adaptation into building design.

IX.1. Addressing the main research question

This section aims to address the main research question formulated as follows (see Section I.3 p.69):

*How can design practices evolve
to more effectively support summer thermal adaptation
through passive strategies in low-energy residential buildings?*

Summer thermal adaptation in buildings is often presented, in building engineering research and dedicated public policies, as the need to favour the preventive integration of dedicated strategies during the design, construction and/or renovation stages. The selection of these strategies is generally informed by quantitative technical assessments and aims to limit energy use and the risk of discomfort under current and future climatic conditions.

The present study has shown and discussed the limitations of such an approach in a context where summer thermal adaptation is not yet culturally embedded. In contrast, it has highlighted the importance of the adaptive processes developed by building occupants when experiencing overheating situations.

Applying a Social Practice Theory lens to these findings therefore invites not only to encourage the preventive consideration of summer thermal adaptation, but also to recognise and support identified processes of adaptation. This perspective highlighted:

- The need to move beyond traditional passive solar design (see Section VIII.2);
- The need for more incremental adaptive strategies (see Section VIII.3);
- The need for more occupant-centric control strategies (see Section VIII.4);
- The need to switch from comfort to physiological and health considerations (see Section VIII.5).

Taken together, these considerations invite to think buildings as adaptable frameworks offering gradual opportunities for adaptive action while protecting occupants by limiting exposure to health risks.

Applied to building design, this perspective suggests the distinction of three levels of adaptive strategies in buildings, according to the degree to which adaptation is embedded in the initial design, enabled for future modification, or activated during use. These levels are here after named as fixed built-in strategies, embedded adaptive capacity and operable controls (Figure IX.1).

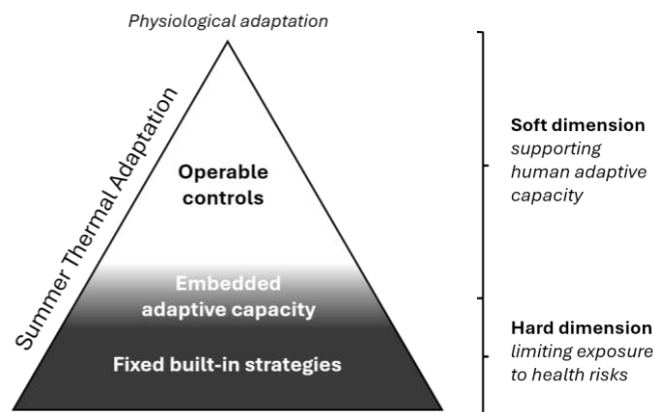


Figure IX.1. Types of adaptive strategies for summer thermal adaptation in buildings, their corresponding adaptation dimensions, and their role in supporting human physiological adaptation.

Fixed built-in strategies refer to relatively permanent design features that are integrated during the design and construction stages and that shape the building's baseline thermal behaviour. These strategies are generally difficult to modify once the building is completed and are not adjustable during everyday use. They include, for example, the building's orientation, form, envelope insulation and airtightness, window size, position and thermal characteristics, fixed shading elements, thermal mass, spatial layout, and the basic potential for natural ventilation.

These strategies define the initial passive performance of the building and determine the extent to which it is inherently exposed or protected from summer heat, including high outdoor air temperatures and solar

radiation. Their main role is therefore to limit the impact of climatic stressors on the indoor environment, thereby helping to prevent indoor conditions from reaching levels that may compromise occupants' health, especially that of vulnerable occupants. Their efficiency can be quantitatively assessed using conventional building-engineering tools and methods, such as whole-building energy simulations.

Embedded adaptive capacity refers to the capacity of the building or its components to accommodate future adaptive measures, upgrades, extensions or modifications. It corresponds to a form of preparedness or design openness that allows the building to evolve over time using offered extensibility and upgradability opportunities (see Section VIII.3). This may include technical compatibility, reserved space, accessible fixing points, suitable façade or window-frame design, electrical provisions, or other design choices that make it possible to add, improve or automate adaptive measures later.

This level is therefore positioned between fixed design and operational control. It does not correspond to adaptation in itself, but rather to the capacity embedded in earlier design decisions to enable future adaptation. It therefore seeks to offer a potential for future adaptive measures, comprising both technical and operational improvements that may become progressively necessary, even if they currently lack cultural embeddedness.

Operable controls refer to elements or systems with a strong influence on indoor thermal conditions, which can be adjusted, activated, or regulated during occupancy in response to changing climatic and indoor conditions. They include manually or automatically operated devices such as openable windows, shutters, blinds, solar screens, curtains, vents, night-ventilation devices, sensors, actuators and control systems. Their main role is to support human adaptation by allowing occupants, or automated systems acting on their behalf, to modify the indoor environment in real time. They represent the most dynamic level of adaptation, where the building's physical possibilities interact with everyday practices and control decisions. Unlike fixed built-in strategies, their performance depends not only on their technical characteristics but also on their operation, timing, accessibility, usability, automation

logic and acceptance by occupants. Their effectiveness therefore depends not only on whether they are available or technically efficient, but also on whether they can realistically be understood, accessed, operated, maintained and accepted in everyday life. In such, they should respect diverse preferences and everyday practices, while also ensuring affordability and inclusiveness. This complexity therefore calls for evaluation methods that consider technical performance alongside with practical implications of integration and use and its compatibility with everyday life.

The designer's role in articulating these different levels can be further specified through the distinction between the hard and soft dimensions of adaptation (see Section I.1.1.4). The hard dimension mainly concerns the material and technical embedding of passive strategies and adaptive capacity in the design of the building. The soft dimension concerns the social, practical and organisational conditions that support the integration, acceptance and use of passive controls during occupation. On the one hand, designers contribute to the hard dimension by technically embedding fixed passive strategies and adaptive capacity into the building design, thereby reducing exposure to summer heat and keeping open possibilities for future adaptation. On the other hand, they contribute to the soft dimension by supporting the integration and use of passive controls, favouring solutions that are understandable, accessible, acceptable and compatible with occupants' everyday practices. From this perspective, the role of designers is not limited to the specification of technical or material solutions. It also consists in articulating the hard and soft dimensions of adaptation.

More broadly, these considerations call for a shift in design practices that recognises the limitations of purely technological approaches and places greater emphasis on enabling and supporting human thermal adaptation processes and their reactive nature. This evolution requires enhanced multidisciplinary collaboration among health professionals, designers, end users, building contractors, manufacturers and policymakers. Such collaboration is needed to support the development of effective, acceptable and socially shared practices that prioritise both health protection and physiological adaptation.

Enabling the evolution of these practices through design is likely to be one of the most promising pathways towards supporting effective human adaptation to heat within the built environment.

IX.2. Practical recommendations

“Practices have a history and depend on the social context; however, they can also develop and change over time”

Warde, 2005 [255]

The results of this study confirm the urgent need to make the climate adaptation of buildings a priority. They also demonstrate that addressing summer thermal adaptation in dwellings is more than a technical issue. Chapter VII usefully analysed it as a matter of shared and/or conflicting social practices [229] of different stakeholders intervening in buildings processes [256].

As such, energy policies and related regulatory frameworks such as the Energy Performance of Buildings Directive (EU) 2024/1275 [153] have probably an important role to play in embedding properly summer thermal adaptation considerations. However, to foster broader societal engagement, they may also need to extend beyond their traditional preventive and technical performance-based approaches (cf. Section I.1.2.3 p.40).

If the results of this research certainly call for raising public awareness, educating stakeholders and embedding summer thermal adaptation within supportive educational programmes and policy frameworks, adopting a Social Practice Theory lens primarily invite policymakers, end-users, and enterprises to work together to (re)align the elements of their respective practices and to develop new, more socially shared ways of addressing adaptation. From this perspective, policies are not seen as external instruments seeking to impose technically appropriate practices. Rather, they are themselves understood as integral components of social practices [229].

The practical and policy recommendations that emerge from this analysis differ therefore from those of more classical engineering, which primarily focuses on technical considerations that can be enforced or imposed through dedicated standards [257, 258]. They also differ from those of more classical ABC (Attitudes, Beliefs, and Choices) theories

[229, 259] which frame behavioural change mainly in terms of individual cognitive determinants.

Table IX.1 outlines action-oriented proposals aimed at engaging each stakeholder in these evolving practices. These recommendations were developed through dedicated focus groups with different stakeholders involved in the building construction process, mainly with enterprises (n=49 comprising architects, building contractors, manufacturers and engineers), with additional input from one policymaker, within the framework of the SOFTSummer action-oriented research project (see Section II.1 p.77)[212].

Organised in four categories – Raise awareness and support implementation; Enable extensibility and upgradability to avoid lock-in effect; Promote occupant-centred control strategies; Develop targeted products for heatwaves – they aim to enhance the normative, cognitive, and symbolic embeddedness together with available technical features. They do so by leveraging elements of existing practices as opportunities, including the current EPBD legal framework and existing incentive programmes. As such, these recommendations remain highly context-dependent, as is often highlighted in social practice studies [229]. However, they could probably resonate in many countries with heating-dominated temperate climates. Nevertheless, further investigation is needed to assess their concrete and broader applicability, for example by examining the frequent fragmentation of stakeholder roles within building processes, which has been found to be highly influential in other studies [260].

Table IX.1. Recommendations for evolving practices (results from Chapter VII).

	Supporting stakeholders				
	End-Users	Enterprises			Policy makers /Public administration
		Designers	Contractors	Manufacturers	
A. Raise awareness and support implementation					
A.1 Carry out information campaigns aimed to raise awareness of ways of preserving summer thermal comfort in homes.		x	x	x	x
A.2. Provide incentives for the installation of passive controls.					x
A.3 Include direct and explicit minimum requirements indicators in Energy Performance Certificate.					x
A.4. Develop simple but explicit assessment tools able to quantify the actual impact on summer comfort.					x
A.5. Raise awareness among enterprises about ventilative cooling techniques.		x		x	x
A.6. Raise occupants' awareness about the importance of preventive and anticipative control.		x	x	x	x
B. Enable extensibility and upgradability to avoid lock-in effect					
B.7. Design the construction details (and electrical supply) to enable specific devices to be installed later.		x	x		
B.8. Develop integrated and extensible windows/frame elements.				x	
B.9. Recognise the extensibility and upgradability potential in regulations for new and existing buildings.					x
C. Promote occupant-centred control strategies					
C.10. Make the implications of use of the various systems more explicit to facilitate comparison.		x	x	x	
C.11. Consider the occupant's profile and preference in the proposed strategies and operation system (fixed, manual, automated).	x	x	x		
C.12. Integrate commissioning and certification procedures (for automated systems).				x	x
D. Develop targeted products for heatwaves					
D.13. Develop (highly) efficient products for temporary use.				x	
D.14. Develop tools to support better control (anticipative, predictive): information campaign, notifications, etc.				x	x

IX.3. Methodological and theoretical contribution

IX.3.1. On methods to collect evidence-based data

Recurrent performance gaps between design intent and real-world outcomes have been observed [261]. Evidence-based results are therefore crucial for informed decision-making and action at the design, construction, and policy levels.

On the one hand, collecting such evidence-based data requires careful, meticulous, and often time-consuming methods, particularly when comprehensive set of confounding and independent variables (e.g. detailed building characteristics, user habits and profiles, etc.) must be gathered alongside the variables of interest [262].

On the other hand, achieving sufficient sample sizes is necessary to ensure minimum representativeness and adequate statistical power [263].

To address this challenge, the present research proposed a multilevel approach tailored to the collection of robust evidence-based data. As presented in Section II.2, this approach consisted of successive stages focusing on progressively smaller, more detailed subsamples. The size of each subsample (i.e. number of buildings analysed) was defined to enable comprehensive and detailed application of the selected methods. The case studies within each subsample were selected not only based on occupant consent but also to ensure representativeness (in terms of characteristics and results) of the previous level. In this way, each subsample was informed by the results of the preceding level, guiding both cases selection and further analysis.

The present study demonstrates the capacity of this replicable multilevel approach to generate high-quality evidence-based data while maintaining sufficient sample size to ensure statistical power and representativeness.

IX.3.2. On methods to qualify summer thermal indoor conditions in residential conditions

Characterising overheating in buildings is typically done by quantifying exceedances relative to predefined thresholds (see Table I.8 p.61).

Recent developments carried out as part of IEA Annex 80 [111] have proposed new indicators for testing buildings' climate resilience based on the integration of exceedances over time (degree-hours) and across the whole building (multizonal integration). Although these approaches are very useful for comparing situations (construction choices, buildings, changes in climate, etc.) or to conduct sensitivity analyses, they do not offer a comprehensive understanding of summer thermal behaviour of a building.

First, because the relationship between temperatures exceedances and occupant thermal perception vary according to the space use (see Chapter IV and previous section).

Second, because the highest temperature exceedances ($>28^{\circ}\text{C}$) remain localised despite a certain homogenisation of temperatures within the thermally protected volume in highly insulated dwellings, as highlighted in Chapter IV.

Considering both local (=by room) small and large exceedances in a parallel and combined manner appears therefore necessary to obtain a comprehensive understanding of the building summer thermal behaviour. The approach developed in CIBSE TM52 [110] and TM59 [53] was found to be aligned with these needs, justifying its use throughout this study.

IX.3.3. On methods to assess climate change impacts on indoor environments

Studies focusing on climate change adaptation in the built environment have emerged over the past decade (see Section I.1.1.6 p.46). Mainly based on whole Building Energy Models, they have progressively addressed significant challenges linked with the transfer of knowledge from climate modelling to building engineering practices: uncertainties and stochastic behaviour associated with projections; substantial computational time and analytical methods needed to deal and transform large datasets; etc. [62] [264].

Chapter V presented one of the first attempts to introduce future climate data derived from dynamic downscaling experiments into building simulation in the Belgian context. Compared with other methods such as Morphing and Stochastic weather generators, these data offer the possibility for localised long-term assessments based on stronger physical basis (see Section I.1.1.6 p.40). In doing so, the present study offers matter for discussion on methodological approaches to be adopted when engaging such evaluations.

IX.3.3.1 The need for calibrated models

ASHRAE Guideline 14 [265] is among the most widely recognized references for the calibration and validation of building energy models, presenting useful metrics for assessing model accuracy. Chapter V highlighted the importance of such calibration processes in ensuring realistic simulations of indoor summer thermal conditions. Furthermore, it proposed an original calibration methodology based not only on the detailed integration of data collected during on-site visits and measurement campaigns, but also on the explicit consideration of uncertainties associated with these input parameters within the optimisation process (Figure IX.2).

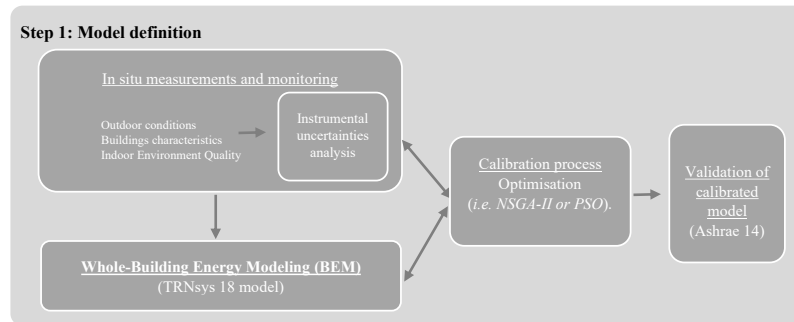


Figure IX.2. An uncertainties analysis-based method for building model calibration, as proposed in Chapter V.

This replicable method proved to offer realistic output while keeping a physical and design sense of the resulting model (Figure IX.3). Model calibration processes are however still not common practices (cf. Table I.5 p.42). These results therefore call for its consideration as a crucial step in methodological frameworks dedicated to heat adaptation studies using whole-building energy models [113] [112].

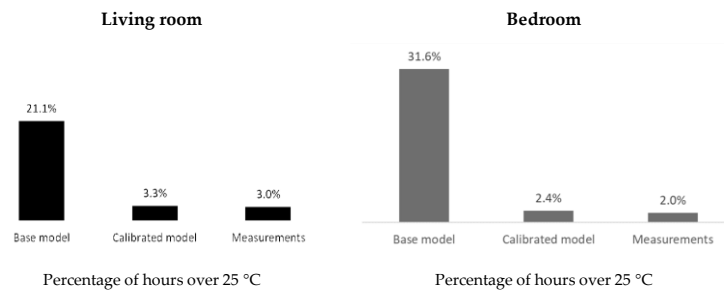


Figure IX.3. Capability of the model developed in the frame of Chapter V to estimate time exceeding 25 °C in the living room (left) and in the main bedroom (right) compared to the measured values.

IX.3.3.2 The need for long term and multi-year future weather datasets

Similarly to Yang [62], Chapter V tested the direct use of multi-year datasets as methodological approach for future thermal conditions projections. Compared with other studies based on the use of typical and extreme weather files such as TMY or EWY (see Section I.1.1.6 p.40), this method was found to be particularly adapted to summer thermal adaptation studies as it gives a more comprehensive description of the conditions variability (Figure IX.4). This does not question the relevance of TMY or EWY files for other purposes, such as annual energy performance assessment or system sizing. Rather, it highlights their limitations when the objective is to characterise the diversity, recurrence, and intensity of summer thermal conditions. In this respect, the method avoids, besides the inevitable simplifications associated with the production of typical meteorological year (TMY) files [266], the unsolvable question of which situation should be prioritised when studying adaptation in an uncertain and changing climate: *Mean or extreme? Based on Temperature or Irradiance? Longest or most intense event?*

The main barrier to this multiyear implementation is however the needed computational time [264]. If, in the frame of this work, it has been found acceptable (around 10 min for a 30 years multizone runs), this computational time will certainly continue to decrease in the future.

Bedroom

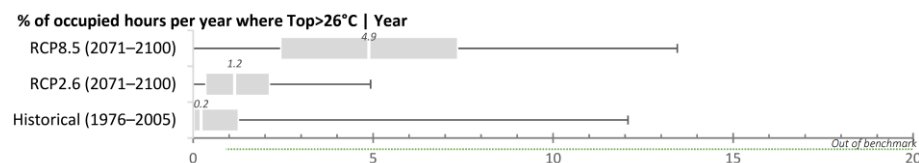


Figure IX.4. Example of results from multiyear simulation: thermal comfort evaluation under historical (1976–2005), RCP2.6 (2071–2100), and RCP8.5 (2071–2100) scenarios for the main bedroom of Sample A3.

IX.3.3.3 The need for a comprehensive comparison and analysis of available future climate data

Since the work presented in Chapter V was conducted, substantial progress has been made, and several sources of future weather datasets have become available to the building sector [19] [21, 22].

Table IX.2. presents an overview of today's available data. These data differ one from the others by several aspect: GCM and RCM used, periods and GHG emission pathways considered, format, type of validation/calibration process, etc.

Table IX.2. Overview of future climate data available for Whole Energy Building Simulations in the Belgian context.

S	ALARO-0	COSMO	MAR	REMO15
Authors	RMI-UGent	KUL	ULiège	IEA EBC Annex 80
Publication year	2016	2021	2021	2024
General Circulation Model (GCM)	CNRM-CM5	EC-Earth5	BCC-CSM2-MR, MPI-ESM.1.2, MIROC6	MPI-ESM-LR
Regional Circulation Model (RCM)	ALARO-0	COSMO-CLM6	MAR	REMO15
Scenario	RCP2.6 RCP4.5 RCP8.5	RCP8.5	SSP2-4.5 SSP3-7.0 SSP5-8.5	RCP8.5
Periods covered	historical and future	historical (1975–2004); long-term future (2069–2098)	historical (2001–2020); mid-term future (2041–2060); long-term future (2081–2100)	historical (2001–2020); mid-term future (2041–2060); long-term future (2081–2100)
Spatial resolution	4km	2.8 km	5 km	12.5 km (Europe) -
Location	Belgium	6 cities	12 cities	2 (15 worldwide)
UHI model	SURFEX, Urbcli	Terra_Urb 2.0	Included	No
Bias Correction	No (control run)	Univariate Quantile Mapping procedure	No (control run)	Multivariate Correction with N-dimensional probability density function transform (MBCn) Quantile Delta Mapping (QDM)
Type of data	Raw data	Typical years (TMY, TDY) Extreme years (DSY, ECY, EWY). Multi-year (on demand)	Typical Meteorological Year (TMY); eXtreme Meteorological Year (XMY); Heatwave event (HWE); (Multi-year on demand)	Typical Meteorological Year (TMY); Heatwave Year (HWY); Multiyear (MY);
Source	[20]	[19]	[22]	[25]

Current studies employing these data are often based on the use of one solely source [109] [108]. Uncertainties are however inherent to climate change and each of these sources represents one possible future climate realization. Considering multiple climate models is therefore essential for designing resilient buildings. To the author knowledge, no integrated initiative to conduct comparative analysis have yet been conducted in the Belgian context.

Figure IX.5. presents a first comparison of the available datasets (further developed in Appendix F) in their ability to reproduce the historical number of summer days ($T_{\max} > 25^{\circ}\text{C}$) in Belgium compared to the ERA5 reanalysis of historical data [267] for Uccle, the main meteorological station of Belgium. This graph not only shows important difference between these data (that should here constitute the reference run), but it also highlights some unrealistic values obtained for some GCM-RCM combinations. If (multivariate) Bias Correction [21] seemed therefore needed to offer more realistic climate conditions, at least for historical conditions, they also hypothesised constant correction (and restriction) of future extreme signal.

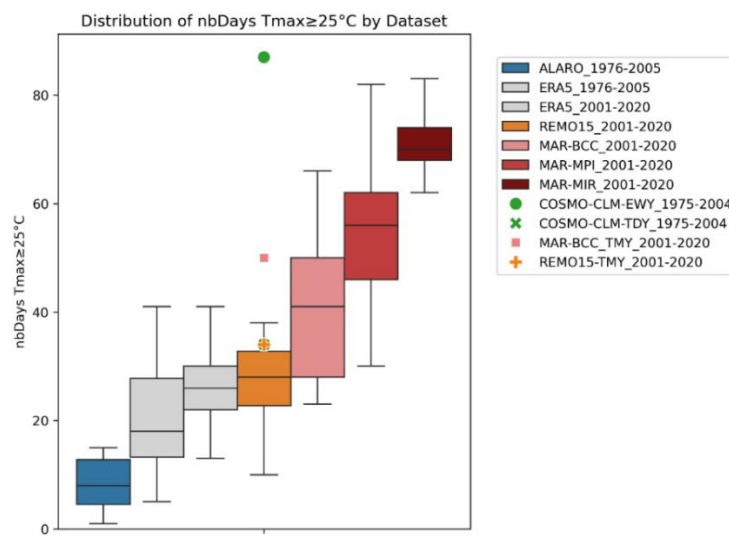


Figure IX.5. Ability of available datasets to reproduce the number of summer days ($T_{\max} > 25^{\circ}\text{C}$) in Uccle (Belgium) for historical periods in comparison with ERA5 Reanalysis. Analysis by the author.

While additional datasets, incorporating the Shared Socioeconomic Pathway (SSP) of the IPCC Sixth Assessment Report (AR6) [25], will soon be produced within the CORDEX² project [268], these findings call for comprehensive analysis and comparison of available future climate data. Such work should offer meticulous description of all hypotheses underlying the production of these data together with clear implications for building engineering.

IX.3.4. On adaptive thermal comfort in dwellings

The present research provides both supporting and contrasting insights regarding the applicability of the adaptive thermal comfort model in residential contexts [269].

First, the results of Chapter IV showed that, in sleeping environments, tolerance to temperature deviations are lower than in living rooms. This finding supports studies and benchmarks – such as TM59 [53] – recognising reduced adaptive opportunities in bedrooms [270]. Nevertheless, as illustrated in Chapter V, the use of a static temperature threshold (e.g. 26°C) to account for reduced adaptive opportunities during sleep—thereby assuming no physiological adaptation—appears highly restrictive in the context of climate change and calls for further investigation.

Second, daytime occupant presence (combined with the availability of passive controls) was found to be the only statistically significant parameter influencing both perceived and measured summer thermal conditions in Sample A.2 (n = 23) (see Chapter VI). Continuous presence not only affects the ability to operate environmental controls effectively but may also influence occupants' physiological responses, particularly in comparison with individuals exposed during the day to mechanically controlled environments (e.g. at work or in their car). This suggests that reactive responses form an integral part of occupants' adaptive capacity, even if they may be associated with temporary discomfort. In this respect, commonly used overheating indices (Table I.8 p.61), based on adaptive thresholds, were found to be unable to accurately predict the high occurrence of perceived discomfort or to represent the necessary

stimuli for physiological adaptation, thereby raising questions about the validity of the thresholds on which these criteria are based.

Taken together, these findings indicate that further research on adaptive thermal comfort in residential environments should be grounded in health-related considerations and should account for patterns of space use as well as the history of indoor and outdoor thermal exposure experienced by occupants.

IX.3.5. On adopting sociotechnical lenses

Social Practice Theory (SPT) progressively emerged during this research as an alternative methodological and theoretical approach. As detailed in Chapter VII, adopting this SPT lens allowed a more comprehensive qualitative assessment of current practices shifting the focus from technical or individual behaviours to social practices [271]. In addition to classical behavioural aspects, this lens highlighted the weight of routines in the practical implementation of passive controls. From a practical perspective, it helped to identify the main drivers shaping the integration and use of passive controls. This questioned the preventive and purely technical optimisation approach commonly adopted in building engineering (see Section I.1.1.6 p.40) and invited greater consideration of occupants' needs, preferences, behaviours, and routines as key design parameters for achieving more effective outcomes in real-world conditions.

In doing so, this work extended the application of SPT to underrepresented areas of inquiry and to new geographical contexts, confirming its ability to generate new insights, particularly fitting with adaptation studies [272].

IX.4. Limitations

Building practices are inherently context-dependent, varying according to climate, building type, and socio-cultural values [200]. The present study focused on low energy single-family houses in the Belgian context. Belgium is characterised by a Cfb oceanic temperate climate according to the Köppen–Geiger climate classification [24]. This climate type is particularly prevalent in Western Europe, covering parts of countries such as France, the UK, the Netherlands, and Germany, as well as regions in South America and Oceania. The results of this study could probably be generalised to these contexts, although with caution.

All the analysed houses were owner-occupied (by families without identified health vulnerabilities) and located in suburban areas not directly affected by Urban Heat Island (UHI) effects. These conditions influence their exposure to overheating risk (e.g. absence of UHI effects but greater direct exposure to passive solar gains), their ability to implement passive strategies effectively (e.g. socioeconomic levels, lower transaction costs due to home ownership [273]), and the effectiveness of the deployed strategies (e.g. lower outdoor temperatures, quieter environments, etc.).

Overall, the sample analysed in this research was found to benefit from relatively favourable conditions, with the potential, although not always fully exploited, to implement effective cooling strategies. Extending the findings of this study to other contexts should therefore be undertaken with caution, considering building characteristics (e.g. thermal performance, typology), occupant status (owners versus renters), occupant vulnerability (e.g. elderly populations), and exposure to heat stress resulting from the surrounding environment (e.g. Urban Heat Island effects). It therefore represents only one specific segment of the broader population and building stock. Nonetheless, these characteristics—combined with the voluntary commitment to participate in the study—strengthen the quality of the data collected and reinforce the significance of the results.

This study also considered the implementation of passive controls as a practice shared among multiple stakeholders including end-users, enterprises and policymakers (see Section II.2 p.80). Several configurations and relationships between these stakeholders exist. As an example, designers and building trades may collaborate as a *design-and-build* team or operate separately. Within the trades, the division of roles and competences can differ, being either general – as in the case of contractors – or specialised. These different configurations can play an important role in the building process [260]. These specificities contribute to a certain fragmentation of roles, which is recognised as an important barrier to the effective implementation of new practices [274]. An in-depth analysis of the roles, relationships, and mutual influences of all stakeholders would provide valuable insights especially when formulating practical implementation (see Section IX.2.2.4 p.46).

More generally, the results of this study indicate that summer thermal adaptation in residential buildings is an emerging practice. Awareness and dedicated knowledge have been identified as important factors contributing to the early stage of this development [259]. The Social Practice Theory framework adopted in the last part of this thesis focuses mainly on incorporated knowledge (through routines, habits, etc.) and does not provide clear insights into how awareness can be raised. Complementary studies grounded in alternative theoretical frameworks, such as the Multi-Level Perspective (MLP) [275], could provide valuable insights into the communication and diffusion mechanisms required to support the emergence and sustained adoption of adaptation practices.

IX.5. Perspectives for future research

The present research contributes to increasing awareness of the gaps between design intent and real-world outcomes. It was conducted within specific boundary conditions (temperate climate, low energy houses, semi-rural environments, etc.).

On the one hand, the resulting findings invite further in-depth analysis of:

- How to support and scale up practices related to the integration and effective use of passive controls. Following the SPT analysis conducted in this study, a Multi-Level Perspective studies [275] analysis can provide a better understanding of the conditions that may support or constrain their wider transformation and institutionalisation. by analysing interactions, levers and barriers across levels (e.g. niche, regime, and landscape levels).
- How policies can practically integrate the need to support evolving practices.
- How the (often fragmented) roles of stakeholders affect the implementation of passive controls and how these barriers could be overcome.
- How automated controls would gain public acceptability and effectively help in optimising passive control.

On the other hand, they call for research beyond these boundary conditions, specifically addressing more vulnerable contexts (e.g., elderly population, urban environments).

Methodologically, it addresses some previously identified methodological gaps that need further support:

- *Post Occupancy Evaluation* (through surveys and monitoring) is essential for informed and effective decision-making in building design, construction processes, and policymaking. It should therefore become common practice, especially when dealing with adaptation measures.
- *Cross-disciplinary lenses* (here mainly linked to social sciences and building engineering), going beyond classical theoretical silos, are essential to capture the complexity of real-world

outcomes, particularly when addressing human–built environment relationships.

In doing so, the study identifies additional gaps that still need to be addressed:

- *Lack of standardised POE methods* [276]: Addressing this gap could enable greater benchmarking and easier comparison between studies.
- *Lack of consideration of the dynamic and complex nature of human responses to IEQ stimuli* [262]: The present study highlighted conflicting IEQ-related factors interfering with the proper use of environmental controls (e.g., light versus heat). It also showed that the reactive nature of human responses evolves as a function of perceived discomfort levels. These findings therefore call for a better understanding of the psychological and physiological factors influencing inter- and intra-individual responses to IEQ stimuli, as well as of the synergistic or antagonistic interactions among these factors, which may shape both environmental perceptions and adaptive behaviours [47].
- *Lack of comparative studies on available future climate data*: Several sources of future climate projections are now available in the Belgian context for the building sector. Comprehensive comparative analyses are needed to validate the robustness of these datasets, particularly regarding their ability to represent extreme events [264].
- *Lack of adaptive and health-oriented metrics verified in residential contexts*: Dedicated evaluation metrics based on an improved understanding of adaptive opportunities and health effects in residential contexts – especially in sleeping environments [244] – are necessary to properly inform building and systems design practices.

Ultimately, this research shows that advancing adaptation in the built environment requires strengthened transdisciplinary research linking building engineering with health, climate, and social sciences. Such approaches are necessary to evolve towards socially embedded practices capable of delivering effective real-world outcomes.

Appendix A. Post-occupancy evaluation survey

Appendix A presents the post-occupancy evaluation survey developed as part of the MEASURE project (see Section II.1 p.80 and Section II.4.2.1100), in collaboration with Sophie Obyn (Research Assistant, UCLouvain). The results obtained using this data-collection method for Sample A.1 (n=149) (see Section II.3.1 p.83) are presented and discussed in the paper reproduced in Chapter III. Further methodological details about the survey development can be found in [217].

Enquête de satisfaction

Merci d'avoir accepté de participer à notre grande enquête de satisfaction !

L'objectif de cette enquête est d'évaluer dans quelles mesures les techniques constructives et les systèmes (chauffage, ventilation, etc.) à la base des bâtiments à hautes performances énergétiques permettent de donner satisfaction aux occupants.

Le temps nécessaire pour y répondre est d'environ 25 minutes.

Si vous le souhaitez, vous pourrez interrompre l'encodage et y revenir plus tard.

En cas d'erreur, il est possible de revenir en arrière. Dans ce cas, veuillez à ne pas utiliser les flèches de votre navigateur mais uniquement le bouton spécifique en bas de page.

En cas de problème, n'hésitez pas à nous contacter à l'adresse suivante:

satisfaction-cale@uclouvain.be.

La cellule de recherche Architecture et Climat – UCL



Le Centre Scientifique et Technique de la Construction



Le Service Public de Wallonie - DG04



Remarque sur la protection de la vie privée

Les traitements de données à caractère personnel relatifs à cette enquête sont soumis à la loi belge (Loi du 8 décembre 1992 relative à la protection de la vie privée à l'égard des traitements de données à caractère personnel, modifiée par la loi du 11 décembre 1998 transposant la directive 95/46/CE du 24 octobre 1995 du Parlement européen et du Conseil relative à la protection des personnes physiques à l'égard du traitement de données à caractère personnel et à la libre circulation de ces données).

Dans le cadre de cette enquête, les informations à caractère personnel collectées seront traitées en toute confidentialité et anonymisées en vue de réaliser une étude scientifique ayant pour but d'évaluer les facteurs d'influence sur la satisfaction des occupants dans les habitations à hautes performances énergétiques. Aucun transfert de ces données à des tiers ne sera opéré.

Vous pouvez nous contacter par e-mail pour nous adresser toutes vos questions relatives à ces traitements à l'adresse email suivante : satisfaction-cale@uclouvain.be

Conformément à la loi, vous disposez d'un droit d'accès aux informations qui vous concernent ainsi qu'un droit de correction. Sur requête, vous avez donc la possibilité de connaître les données à caractère personnel vous concernant et de corriger les inexactitudes éventuelles. Si vous souhaitez exercer ces droits, contactez-nous à l'adresse mentionnée ci-dessus.

I. Introduction

Cette première partie a pour but principal d'identifier ce qui vous a poussé à participer à l'action "*Construire Avec L'Energie*".

1 Depuis quand habitez-vous dans votre logement ?

Veillez inscrire l'année dans le cadre ci-dessous :

...

2 Combien de personnes des catégories ci-dessous occupent votre logement ?

Choisissez la réponse appropriée pour chaque élément :

	1	2	3	4	5	+ de 5
Enfant(s), Etudiant(s), personne(s) scolarisée(s)	☐	☐	☐	☐	☐	☐
Travailleur(s) à temps partiel	☐	☐	☐	☐	☐	☐
Travailleur(s) à temps plein	☐	☐	☐	☐	☐	☐
Sans emploi	☐	☐	☐	☐	☐	☐
Pensionné(s)	☐	☐	☐	☐	☐	☐

3 Selon vous, quelles notions représentent le mieux la qualité d'un logement ?

Veillez sélectionner 4 réponses maximum

- ☐ Cadre de vie (ville, campagne, etc.)
- ☐ Proximité de facilités (école, commerces, transport, etc.)
- ☐ Esthétique (façades, finitions intérieures, etc.)
- ☐ Caractère patrimonial ou historique
- ☐ Histoire familiale du bâtiment/du terrain
- ☐ Coût d'achat / coût de construction
- ☐ Superficie de la maison / nombre et taille des pièces
- ☐ Organisation des pièces
- ☐ Orientation / ouverture vers l'extérieur et lumière naturelle
- ☐ Consommations / performances énergétiques
- ☐ Confort intérieur (température et qualité d'air agréables)
- ☐ Autre, précisez :

4 Dans quelle mesure les membres de votre foyer (y compris vous) s'intéressent-ils aux techniques suivantes ?

Choisissez la réponse appropriée pour chaque élément :

	Aucun intérêt	Manque de compréhension mais intérêt	Compréhension des principes techniques	Maîtrise des principes techniques
Système de chauffage	O	O	O	O
Système de ventilation	O	O	O	O
Construction et isolation	O	O	O	O

5 Quel a été l'argument principal qui vous a mené à faire le choix d'une habitation énergétiquement performante ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Economique : les primes
- ☐ Economique : le peu de frais énergétiques à l'usage
- ☐ Economique : la rentabilité à long terme
- ☐ Environnemental : la limitation de l'impact sur l'environnement (CO₂, ...)
- ☐ Anticipatif : sécurisation de l'avenir (indépendance énergétique, pour les générations futures, etc.)
- ☐ Confort et Santé
- ☐ Une autre raison, précisez : ...

6 Qui vous a orienté vers une habitation énergétiquement performante ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Votre architecte
- ☐ Un autre professionnel de la construction
- ☐ Une connaissance
- ☐ Vous-même
- ☐ Autre, précisez : ...

Des commentaires en rapport avec les questions précédentes? Merci de les indiquer ci-dessous :

...

II. Votre usage et vos habitudes

Cette partie nous permettra d'identifier si certains usages et habitudes ont une influence sur le niveau de satisfaction des occupants. Pour rappel, toutes les données seront traitées de manière strictement confidentielle et dans le respect de la loi sur la protection de la vie privée.

7 Quand votre logement est-il occupé de manière générale ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ En fin de journée et le weekend
- ☐ De manière continue (en journée aussi)
- ☐ Autre, précisez : ...

8 Vous ou un membre de votre ménage exerce-t-il une activité professionnelle à domicile (ou télétravail) au moins une fois par semaine ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Non

9 Si oui, de quel type d'activité s'agit-il ?

Veillez choisir toutes les réponses qui conviennent :

- ☐ Travail de bureau individuel
- ☐ Travail de bureau collectif
- ☐ Accueil de clientèle (médecin, dentiste, kiné, etc.)
- ☐ Garde d'enfants
- ☐ Service traiteur
- ☐ Service de repassage
- ☐ Autre, précisez : ...

10 De manière générale, lorsque vous êtes présent(s), à quelle température chauffez-vous le séjour en hiver ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Moins de 14 °C
- ☐ 14 °C
- ☐ 15 °C
- ☐ 16 °C
- ☐ 17 °C
- ☐ 18 °C
- ☐ 19 °C
- ☐ 20 °C
- ☐ 21 °C
- ☐ 22 °C
- ☐ 23 °C
- ☐ 24 °C
- ☐ Plus de 24 °C
- ☐ Je ne sais pas

11 Comment qualifieriez-vous la température entre les différentes pièces de votre logement en hiver ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Très uniforme (la même dans toutes les pièces)
- ☐ Plutôt uniforme
- ☐ Plutôt variable
- ☐ Très variable (différente entre les pièces)
- ☐ Je ne sais pas

12 Cet état de températures est :

Veillez sélectionner une seule des propositions suivantes :

- ☐ Volontaire : je/nous choisissons que ce soit ainsi
- ☐ Involontaire : je/nous n'en avons pas vraiment le contrôle
- ☐ Je ne sais pas

13 Comment trouvez-vous cet état de températures ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Confortable
- ☐ Supportable
- ☐ Inconfortable

14 De manière générale, arrêtez-vous le chauffage ou diminuez-vous la température dans les circonstances suivantes ?

Choisissez la réponse appropriée pour chaque élément :

	Oui	Non	Je ne sais pas
La nuit	O	O	O
En cas d'absence en journée	O	O	O

15 Un membre de votre ménage (ou vous-même) a-t-il pour habitude d'adapter le niveau de ventilation (coupure, diminution ou augmentation du débit de ventilation mécanique) ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Non
- ☐ Je ne sais pas

16 Si oui, dans quelles circonstances ?

Veillez choisir toutes les réponses qui conviennent :

- ☐ Lors de l'utilisation de la salle de bain et/ou de la cuisine
- ☐ La nuit
- ☐ En cas d'absence en journée
- ☐ En cas d'absence prolongée (vacances, ...)
- ☐ En fonction du nombre de personnes présentes dans la maison
- ☐ En fonction des conditions climatiques (grand froid, canicule, ensoleillement, etc.)
- ☐ Pour une autre raison, précisez : ...

17 Quand ouvrez-vous généralement les fenêtres ?

Choisissez la réponse appropriée pour chaque élément :

	En journée	La nuit	En journée et la nuit	Jamais
Dans le séjour en hiver	O	O	O	O
Dans le séjour, le reste de l'année	O	O	O	O
Dans la/les chambre(s) en hiver	O	O	O	O
Dans la/les chambre(s), le reste de l'année	O	O	O	O

18 Quelles sont les principales raisons pour lesquelles vous ouvrez vos fenêtres ?

Veillez sélectionner 3 réponses maximum :

- ☐ Par habitude
- ☐ Par besoin d'air
- ☐ Pour garantir une bonne qualité d'air
- ☐ Pour évacuer les odeurs
- ☐ Pour évacuer l'humidité
- ☐ Pour refroidir la pièce
- ☐ Pour s'ouvrir vers l'extérieur
- ☐ Autre, précisez : ...

19 Avez-vous bouché ou obturé une ou plusieurs bouches/grilles de ventilation?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Non
- ☐ Je ne sais pas

20 A quelle fréquence entretenez-vous ou faites-vous entretenir vos systèmes ?

Choisissez la réponse appropriée pour chaque élément :

	Jamais	Je ne l'ai pas encore fait	Lorsque je rencontre un problème	Moins d'une fois par an	Tous les ans	Plusieurs fois par an	Pas d'application / Je ne sais pas
Chauffage (chaudière par exemple)	☐	☐	☐	☐	☐	☐	☐
Ventilation (échangeur, gaines, filtres ...)	☐	☐	☐	☐	☐	☐	☐
Bouches/grilles de ventilation	☐	☐	☐	☐	☐	☐	☐

21 Comment vos habitudes ont-elles évolué par rapport à vos pratiques dans votre logement précédent ?

Choisissez la réponse appropriée pour chaque élément :

	Beaucoup plus	Plus	Idem	Moins	Beaucoup Moins	Je ne sais pas / Pas d'avis
Vous vous habillez chaudement en hiver	☐	☐	☐	☐	☐	☐
Vous vous habillez légèrement le reste de l'année	☐	☐	☐	☐	☐	☐
Vous faites attention à vos consommations d'énergie	☐	☐	☐	☐	☐	☐
Vous diminuez/arrêtez le chauffage en cas d'absence	☐	☐	☐	☐	☐	☐
Vous diminuez/arrêtez le chauffage la nuit	☐	☐	☐	☐	☐	☐
Vous diminuez/arrêtez le chauffage dans les pièces non utilisées/dans lesquelles il n'y a personne	☐	☐	☐	☐	☐	☐
Vous chauffez à une température élevée	☐	☐	☐	☐	☐	☐

Des commentaires en rapport avec les questions précédentes? Merci de les indiquer ci-dessous :

...

III. Equipements et consommations

L'objectif des questions qui suivent est double : identifier les équipements installés dans votre logement et avoir un premier aperçu des performances réelles de celui-ci.

22 Votre habitation est-elle équipée de :

Choisissez la réponse appropriée pour chaque élément :

	Oui	Non	Je ne sais pas
Panneaux solaires photovoltaïques (production d'électricité)	☐	☐	☐
Panneaux solaires thermiques	☐	☐	☐

23 Avez-vous installé les équipements suivants ?

Choisissez la réponse appropriée pour chaque élément :

	Non	Oui, pour pallier un inconfort	Oui, pour améliorer le confort	Oui, c'était prévu d'origine	Je ne sais pas
Protections solaires extérieures (élément fixe, toiles solaires, screens, stores vénitiens, etc.)	☐	☐	☐	☐	☐
Protections solaires intérieures (stores par exemple)	☐	☐	☐	☐	☐
Chauffage(s) d'appoint dans certaines pièces (chaufferettes)	☐	☐	☐	☐	☐
Appareil(s) de climatisation (pour refroidir certaines pièces/AIRCO)	☐	☐	☐	☐	☐
Humidificateur(s) (récipient d'eau sur radiateur par exemple)	☐	☐	☐	☐	☐
Déshumidificateur(s)	☐	☐	☐	☐	☐

24 Ces protections solaires (ou une partie) sont-elles automatisées (ouverture/fermeture automatiques) ?

Veillez répondre à cette question seulement si vous avez indiqué avoir installé des protections solaires (intérieures et/ou extérieures) à la question 23.

Veillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Non
- ☐ Je ne sais pas

25 Pour vous protéger de quoi avez-vous placé des protections solaires ?

Si votre logement dispose de protections solaires, veuillez choisir toutes les réponses qui conviennent :

- ☐ De la chaleur du soleil
- ☐ De l'éblouissement du soleil
- ☐ Des vues depuis l'extérieur de la maison (intimité)

26 Connaissez-vous le montant approximatif de votre facture d'électricité de l'année dernière ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Oui, en €/mois
- ☐ Oui, en €/an
- ☐ Oui, dans une autre unité
- ☐ Non

27 Si oui, pouvez-vous indiquer le montant approximatif de votre facture d'électricité ?

Montant à indiquer en chiffres uniquement (arrondir à l'unité) si vous avez coché une des deux premières propositions à la question précédente. Exemple : **120**

Si vous avez répondu « Oui, dans une autre unité », veuillez indiquer le montant en chiffres en précisant l'unité et la période couverte. Exemple : **3500 kWh par an**

...

28 Connaissez-vous le montant approximatif de votre facture de combustible (gaz, mazout, pellets, bois, ...) de l'année dernière ?

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Non

29 Si oui, pouvez-vous indiquer votre consommation en combustible (gaz, mazout, pellets, bois, ...) de l'année dernière, en précisant l'unité et la période couverte ?

Montant à indiquer en chiffres avec unité et période de couverture.

Exemple : **2000 litres de mazout par an**

...

Des commentaires en rapport avec les questions précédentes? Merci de les indiquer ci-dessous :

...

IV. Satisfaction générale

Les questions de cette section portent sur votre satisfaction par rapport à votre logement et ses techniques. **Nous souhaitons avoir votre avis général et non votre ressenti au moment même où vous complétez ce questionnaire.**

30 Recommanderiez-vous ce type de maison ?

Choisissez la réponse appropriée :

Totalement en désaccord	En désaccord	D'accord	Totalement d'accord	Sans avis
☐	☐	☐	☐	☐

31 Dans quelle mesure êtes-vous satisfait(e) ?

Choisissez la réponse appropriée pour chaque élément :

	Très insatisfait	Insatisfait	Plutôt insatisfait	Plutôt satisfait	Satisfait	Très satisfait	Je ne sais pas	Pas d'application
De votre habitation	☐	☐	☐	☐	☐	☐	☐	☐
Du bâtiment (enveloppe extérieure, qualité des matériaux)	☐	☐	☐	☐	☐	☐	☐	☐
Du coût de construction / prix de location	☐	☐	☐	☐	☐	☐	☐	☐
De vos consommations énergétiques	☐	☐	☐	☐	☐	☐	☐	☐

32 Par rapport aux ambiances intérieures, dans quelle mesure êtes-vous satisfait(e) ?

Choisissez la réponse appropriée pour chaque élément :

	Très insatisfait	Insatisfait	Plutôt insatisfait	Plutôt satisfait	Satisfait	Très satisfait	Je ne sais pas	Pas d'applica- tion
De la qualité de l'air intérieur	☐	☐	☐	☐	☐	☐	☐	☐
Du confort thermique (températures des différentes pièces, parois froides, surchauffe, etc.)	☐	☐	☐	☐	☐	☐	☐	☐
De l'apport de lumière naturelle dans les différentes pièces	☐	☐	☐	☐	☐	☐	☐	☐
De l'isolation acoustique par rapport au bruit venant de l'extérieur	☐	☐	☐	☐	☐	☐	☐	☐
De l'isolation acoustique intérieure (bruit entre les pièces)	☐	☐	☐	☐	☐	☐	☐	☐
De votre niveau de contrôle sur les températures intérieures	☐	☐	☐	☐	☐	☐	☐	☐
De votre niveau de contrôle sur la qualité de l'air	☐	☐	☐	☐	☐	☐	☐	☐

33 Par rapport aux installations techniques, dans quelle mesure êtes-vous satisfait(e) ?

Choisissez la réponse appropriée pour chaque élément :

	Très insatisfait	Insatisfait	Plutôt insatisfait	Plutôt satisfait	Satisfait	Très satisfait	Je ne sais pas	Pas d'applica- tion
De votre installation de chauffage	☐	☐	☐	☐	☐	☐	☐	☐
De votre système de ventilation	☐	☐	☐	☐	☐	☐	☐	☐
De vos protections solaires	☐	☐	☐	☐	☐	☐	☐	☐

Des commentaires en rapport avec les questions précédentes? Merci de les indiquer ci-dessous :

...

V. Satisfaction détaillée

Cette section porte plus spécifiquement sur votre ressenti et votre satisfaction par rapport au confort dans les différentes pièces.

34 En hiver, comment ressentez-vous la température intérieure dans les pièces suivantes ?

Choisissez la réponse appropriée pour chaque élément :

	Trop chaude	Légèrement trop chaude	Agréable	Légèrement trop froide	Trop froide
Cuisine	☐	☐	☐	☐	☐
Séjour	☐	☐	☐	☐	☐
Chambre	☐	☐	☐	☐	☐
Salle de bain	☐	☐	☐	☐	☐
Autres pièces	☐	☐	☐	☐	☐

35 En été, comment ressentez-vous la température intérieure dans les pièces suivantes ?

Choisissez la réponse appropriée pour chaque élément :

	Trop chaude	Légèrement trop chaude	Agréable	Légèrement trop froide	Trop froide
Cuisine	☐	☐	☐	☐	☐
Séjour	☐	☐	☐	☐	☐
Chambre	☐	☐	☐	☐	☐
Salle de bain	☐	☐	☐	☐	☐
Autres pièces	☐	☐	☐	☐	☐

36 Constatez-vous parfois ?

Choisissez la réponse appropriée pour chaque élément :

	Oui	Non	Je ne sais pas
Une augmentation trop lente de la température intérieure	☐	☐	☐
Une diminution trop lente de la température intérieure	☐	☐	☐
Une augmentation rapide et incontrôlée de la température intérieure	☐	☐	☐
Une augmentation rapide et non souhaitée de la température intérieure	☐	☐	☐

37 Rencontrez-vous, même rarement, les inconforts suivants dans certaines pièces de votre habitation ?

Choisissez la réponse appropriée pour chaque élément :

	Oui	Non	Je ne sais pas
Surchauffe (température trop élevée)	☐	☐	☐
Air lourd ou malsain	☐	☐	☐
Air humide	☐	☐	☐
Air sec	☐	☐	☐
Murs/plafonds froids	☐	☐	☐
Fenêtres froides	☐	☐	☐
Sols froids	☐	☐	☐
Sols chauds	☐	☐	☐
Chaleur trop importante des rayons du soleil	☐	☐	☐

38 De même, rencontrez-vous parfois les inconforts suivants ?

Choisissez la réponse appropriée pour chaque élément :

	Oui	Non	Je ne sais pas
Odeurs persistantes	☐	☐	☐
Grande quantité de poussières	☐	☐	☐
Courants d'air aux portes/fenêtres	☐	☐	☐
Courants d'air aux grilles/bouches de ventilation	☐	☐	☐
Air de ventilation trop froid (à la sortie de la bouche)	☐	☐	☐
Air de ventilation trop chaud (à la sortie de la bouche)	☐	☐	☐
Condensation ou moisissures à l'intérieur (murs, fenêtres, etc.)	☐	☐	☐
Condensation/buée sur la surface extérieure des vitrages	☐	☐	☐

39 Quand rencontrez-vous des problèmes de surchauffe (températures trop chaudes) dans les différentes pièces de votre habitation ?

Veillez répondre à cette question seulement si vous avez indiqué rencontrer des problèmes de surchauffe à la question 37.

Veillez choisir toutes les réponses qui conviennent :

	Jamais	Printemps	Eté	Automne	Hiver
Cuisine	☐	☐	☐	☐	☐
Séjour	☐	☐	☐	☐	☐
Chambre	☐	☐	☐	☐	☐
Salle de bain	☐	☐	☐	☐	☐
Autres pièces	☐	☐	☐	☐	☐

40 Quand rencontrez-vous des problèmes d'air trop humide dans les différentes pièces de votre habitation ?

Veillez répondre à cette question seulement si vous avez indiqué rencontrer des problèmes d'air humide à la question 37.

Veillez choisir toutes les réponses qui conviennent :

	Jamais	Printemps	Eté	Automne	Hiver
Cuisine	☐	☐	☐	☐	☐
Séjour	☐	☐	☐	☐	☐
Chambre	☐	☐	☐	☐	☐
Salle de bain	☐	☐	☐	☐	☐
Autres pièces	☐	☐	☐	☐	☐

41 Quand rencontrez-vous des problèmes d'air trop sec dans les différentes pièces de votre habitation ?

Veillez répondre à cette question seulement si vous avez indiqué rencontrer des problèmes d'air sec à la question 37.

Veillez choisir toutes les réponses qui conviennent :

	Jamais	Printemps	Eté	Automne	Hiver
Cuisine	☐	☐	☐	☐	☐
Séjour	☐	☐	☐	☐	☐
Chambre	☐	☐	☐	☐	☐
Salle de bain	☐	☐	☐	☐	☐
Autres pièces	☐	☐	☐	☐	☐

42 Quand rencontrez-vous des problèmes de qualité d'air insuffisante (air malsain, lourd, ...) dans les différentes pièces de votre habitation ?

Veillez répondre à cette question seulement si vous avez indiqué rencontrer des problèmes d'air lourd/malsain à la question 37.

Veillez choisir toutes les réponses qui conviennent :

	Jamais	Printemps	Eté	Automne	Hiver
Cuisine	☐	☐	☐	☐	☐
Séjour	☐	☐	☐	☐	☐
Chambre	☐	☐	☐	☐	☐
Salle de bain	☐	☐	☐	☐	☐
Autres pièces	☐	☐	☐	☐	☐

43 Etes-vous satisfait(e) des aspects suivants de votre système de chauffage ?

Choisissez la réponse appropriée pour chaque élément :

	Très satisfait	Satisfait	Plutôt satisfait	Plutôt insatisfait	Insatisfait	Très insatisfait	Je ne sais pas
Facilité de compréhension du fonctionnement	☐	☐	☐	☐	☐	☐	☐
Documentation disponible	☐	☐	☐	☐	☐	☐	☐
Capacité de réglage	☐	☐	☐	☐	☐	☐	☐
Bruit généré	☐	☐	☐	☐	☐	☐	☐
Fiabilité des installations (absence de pannes/bugs)	☐	☐	☐	☐	☐	☐	☐
Fréquence et durée des entretiens nécessaires	☐	☐	☐	☐	☐	☐	☐
Coûts des entretiens	☐	☐	☐	☐	☐	☐	☐

44 Etes-vous satisfait(e) des aspects suivants de votre système de ventilation ?

Choisissez la réponse appropriée pour chaque élément :

	Très satisfait	Satisfait	Plutôt satisfait	Plutôt insatisfait	Insatisfait	Très insatisfait	Je ne sais pas
Facilité de compréhension du fonctionnement	☐	☐	☐	☐	☐	☐	☐
Documentation disponible	☐	☐	☐	☐	☐	☐	☐
Capacité de réglage	☐	☐	☐	☐	☐	☐	☐
Bruit généré	☐	☐	☐	☐	☐	☐	☐
Fiabilité des installations (absence de pannes/bugs)	☐	☐	☐	☐	☐	☐	☐
Fréquence et durée des entretiens nécessaires	☐	☐	☐	☐	☐	☐	☐
Coûts des entretiens	☐	☐	☐	☐	☐	☐	☐

45 Etes-vous satisfait(e) des aspects suivants de vos protections solaires mobiles ?

Veillez répondre à cette question seulement si vous avez des protections solaires mobiles et automatisées.

Choisissez la réponse appropriée pour chaque élément :

	Très satisfait	Satisfait	Plutôt satisfait	Plutôt insatisfait	Insatisfait	Très insatisfait	Je ne sais pas
Facilité de compréhension du fonctionnement	☐	☐	☐	☐	☐	☐	☐
Documentation disponible	☐	☐	☐	☐	☐	☐	☐
Capacité de réglage	☐	☐	☐	☐	☐	☐	☐
Bruit généré	☐	☐	☐	☐	☐	☐	☐
Fiabilité des installations (absence de pannes/bugs)	☐	☐	☐	☐	☐	☐	☐

46 Vos systèmes fonctionnent-ils correctement ?

Choisissez la réponse appropriée pour chaque élément :

	Aucun problème depuis la mise en fonctionnement	Bien après ajustement/réglage de l'installation	Ok après habituatation	Pas de bons résultats	Pas d'application
Système de chauffage : bonne température au bon endroit et au bon moment	O	O	O	O	O
Système de ventilation : bonne quantité au bon endroit et au bon moment	O	O	O	O	O
Protections solaires	O	O	O	O	O

Des commentaires en rapport avec les questions précédentes? Merci de les indiquer ci-dessous :

...

VI. Questions finales

Ces dernières questions ont pour but d'identifier le public touché par l'action "*Construire Avec L'Energie*".

47 Combien de personnes des tranches d'âge ci-dessous occupent votre logement ?

Choisissez la réponse appropriée pour chaque élément :

	1	2	3	4	5	Plus de 5
0-2 ans	☐	☐	☐	☐	☐	☐
3-12 ans	☐	☐	☐	☐	☐	☐
13-24 ans	☐	☐	☐	☐	☐	☐
25-64 ans	☐	☐	☐	☐	☐	☐
65 ans et plus	☐	☐	☐	☐	☐	☐

48 Qui s'occupe des aspects techniques de votre logement (gestion des systèmes de chauffage et de ventilation) ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Moi uniquement
- ☐ Moi et quelqu'un d'autre
- ☐ Quelqu'un d'autre
- ☐ Je ne sais pas

49 Certains membres de votre foyer (ou vous-même) sont-ils :

Choisissez la réponse appropriée pour chaque élément :

	Oui (dont moi)	Oui (d'autre(s) membre(s) de la famille)	Non, pas particulièrement
Frileux	O	O	O
Sensibles à la chaleur	O	O	O
Sensibles au niveau respiratoire (asthmes, allergies, etc.)	O	O	O

50 Y a-t-il un (ou des) fumeur(s) dans votre maison ?

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Oui, il(s) fume(nt) à l'intérieur
- ☐ Oui, il(s) fume(nt) à l'extérieur
- ☐ Non

51 Quel est le plus haut type de diplôme obtenu par le(s) responsable(s) du ménage ?

Au besoin, veuillez préciser le champ 'Autre, précisez :'.

Veuillez sélectionner une seule des propositions suivantes :

- ☐ Primaire (pas de diplôme)
- ☐ Secondaire inférieur
- ☐ Secondaire supérieur
- ☐ Supérieur non-universitaire
- ☐ Universitaire
- ☐ Autre, précisez : ...

52 Vous êtes :

Veillez sélectionner une seule des propositions suivantes :

- ☐ Propriétaire
- ☐ Locataire

53 Si vous êtes propriétaire, comment avez-vous acquis votre habitation ?

- ☐ Nous l'avons fait construire
- ☐ Nous l'avons achetée
- ☐ Autre, précisez : ...

54 Vous êtes :

Veillez sélectionner une seule des propositions suivantes :

- ☐ Un homme
- ☐ Une femme

55 Vous êtes âgé(e) de :

Veillez sélectionner une seule des propositions suivantes :

- ☐ Moins de 20 ans
- ☐ 20-24 ans
- ☐ 25-29 ans
- ☐ 30-34 ans
- ☐ 35-39 ans
- ☐ 40-44 ans
- ☐ 45-49 ans
- ☐ 50-54 ans
- ☐ 55-59 ans
- ☐ 60-64 ans
- ☐ Plus de 65 ans

56 Accepteriez-vous que l'on effectue une campagne de mesures dans votre habitation (température, humidité et CO₂ par exemple) ?

Si vous souhaitez plus d'informations sur ce qu'implique et en quoi consiste la campagne de mesures, rendez-vous sur la page : <http://www.satisfaction-cale.be/monitoring/>

Veillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Non

57 Souhaitez-vous recevoir un ticket de loterie de type Win For Life ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Non

58 Souhaitez-vous être informé(e) des résultats de l'enquête ?

Veillez sélectionner une seule des propositions suivantes :

- ☐ Oui
- ☐ Non

59 Si vous avez répondu « oui » à au moins une des questions 56 à 58, merci d'indiquer vos coordonnées complètes ci-dessous afin que nous puissions vous recontacter (adresse complète et courriel) :

Nom et prénom	
Courriel	
Rue et numéro	
Code postal	
Ville	
Numéro de téléphone	

Des commentaires en rapport avec les questions précédentes ou avec le questionnaire dans son ensemble? Merci de les indiquer ci-dessous :

...

Merci pour votre contribution !

Si vous souhaitez connaître les résultats de cette enquête,
rendez-vous d'ici quelques mois sur le site:

www.satisfaction-cale.be/resultats.

En attendant, si vous souhaitez plus d'informations sur le projet de recherche et ses objectifs,
rendez-vous sur:

www.satisfaction-cale.be/infos.

Bonne continuation !

La cellule de recherche Architecture et Climat – UCL 

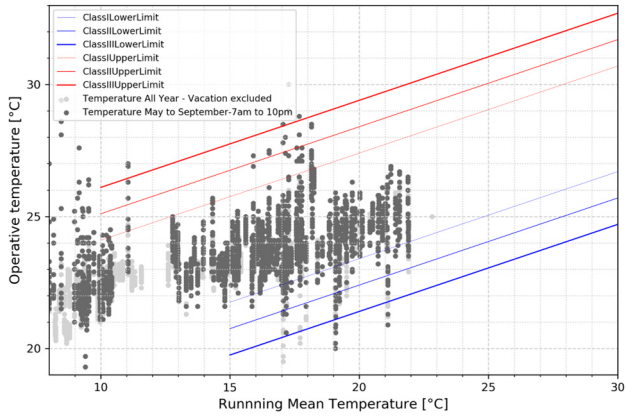
Le Centre Scientifique et Technique de la Construction 

Le Service Public de Wallonie - DG04 

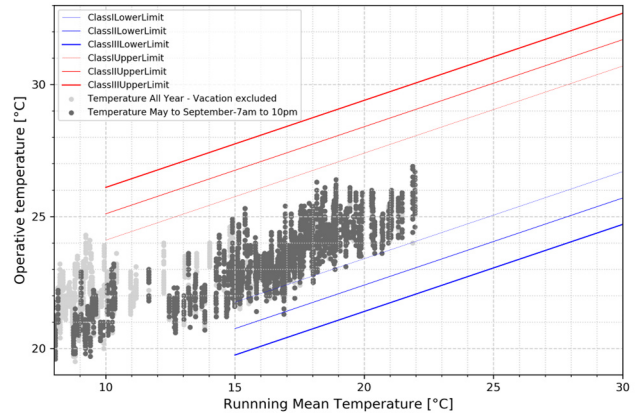
Appendix B. Analysis of measured indoor summer thermal conditions

Appendix B presents an initial analysis of indoor air-temperature data collected in 23 low-energy dwellings (sample A.2, see Section II.3.1 p.83) as part of the MEASURE project (see Section II.1 p.80). Conducted by the author of this thesis, the analysis compares the measured indoor conditions with the adaptive comfort limits defined in EN 15251 [219]. These data are further examined in Chapter IV.

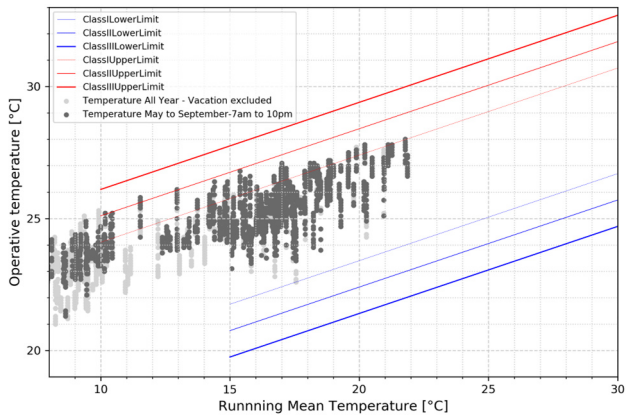
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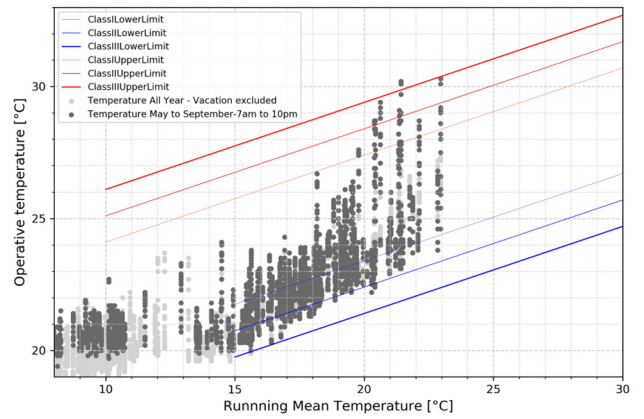
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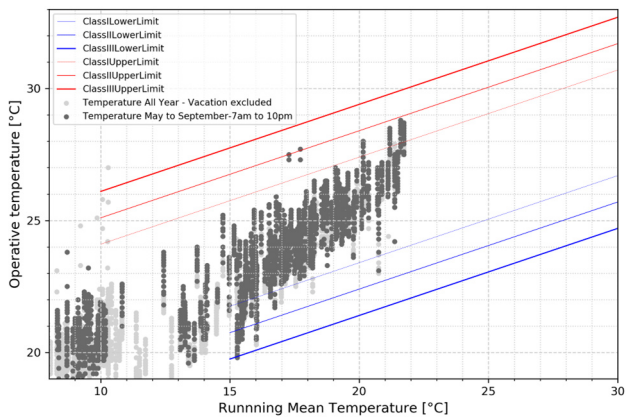
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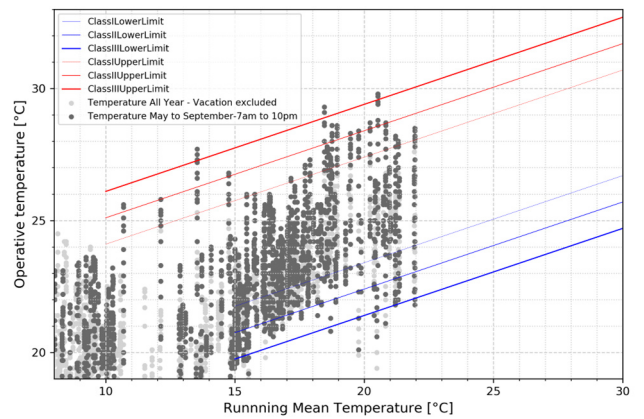
4 Living room



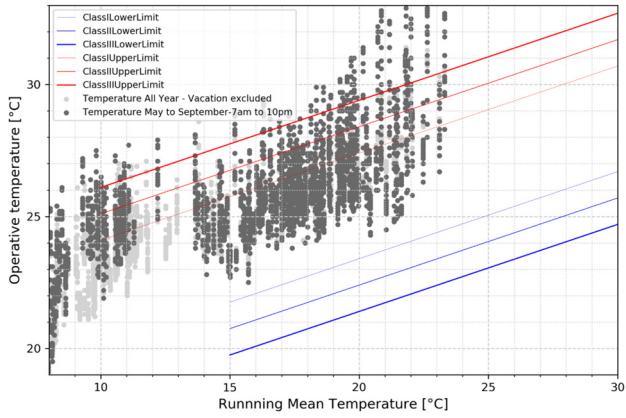
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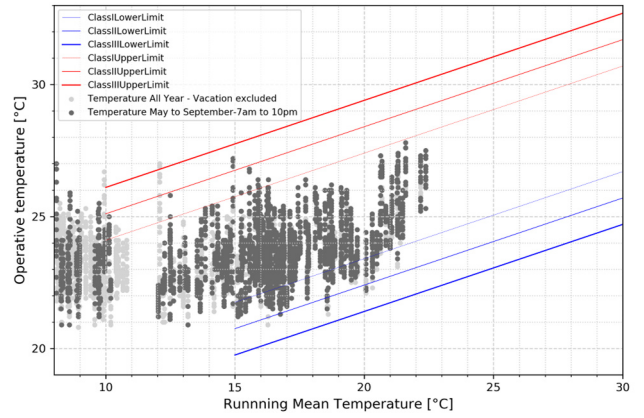
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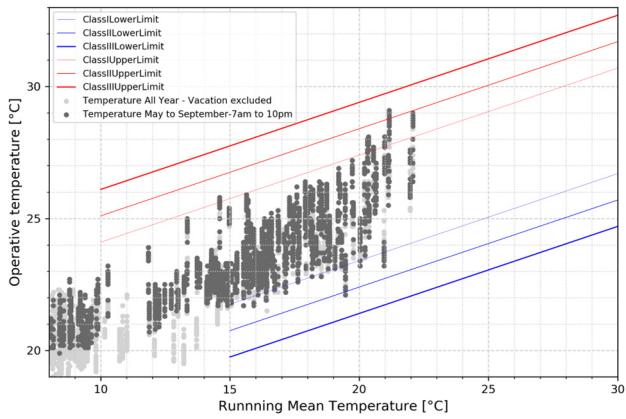
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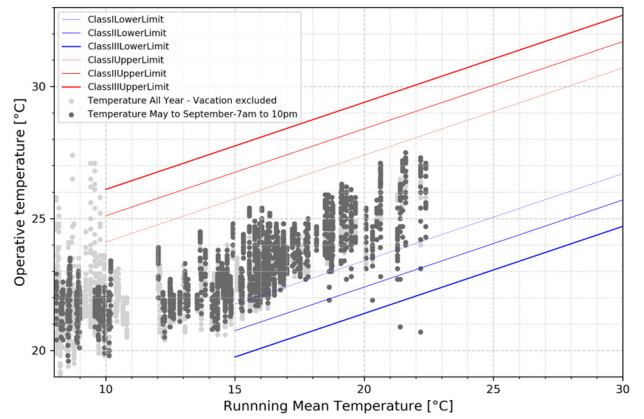
8 Living room



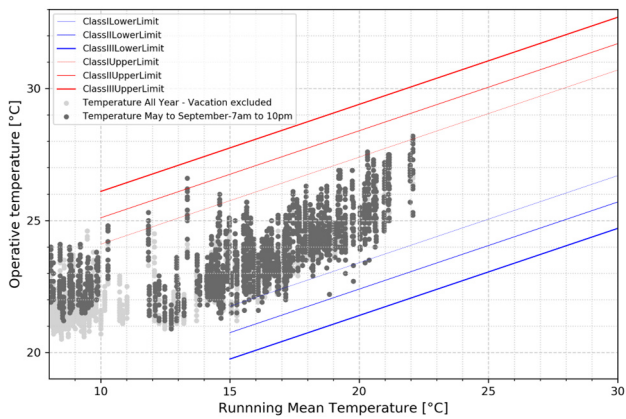
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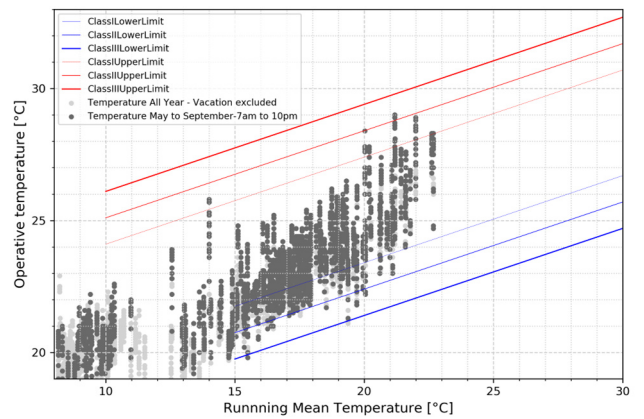
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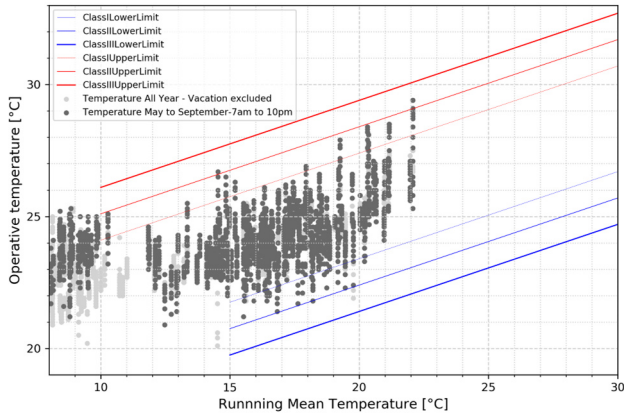
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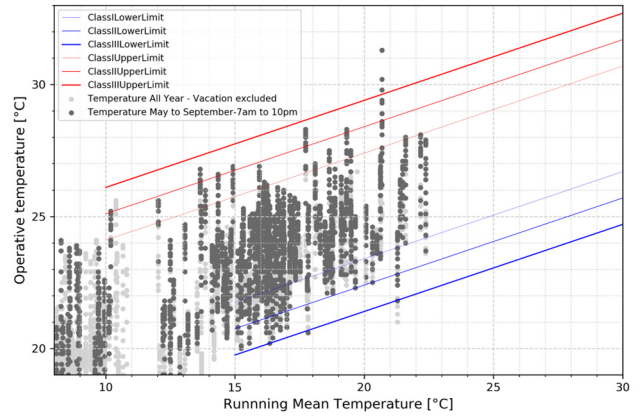
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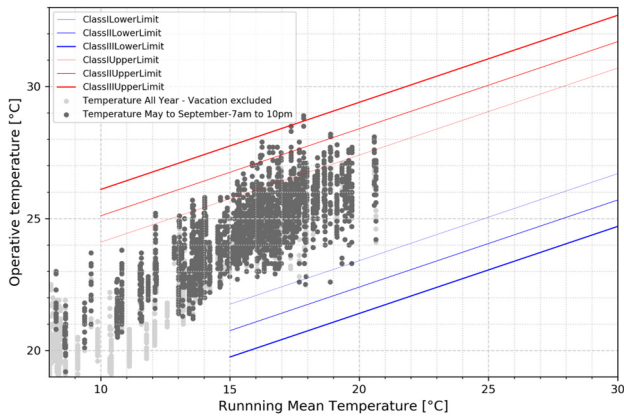
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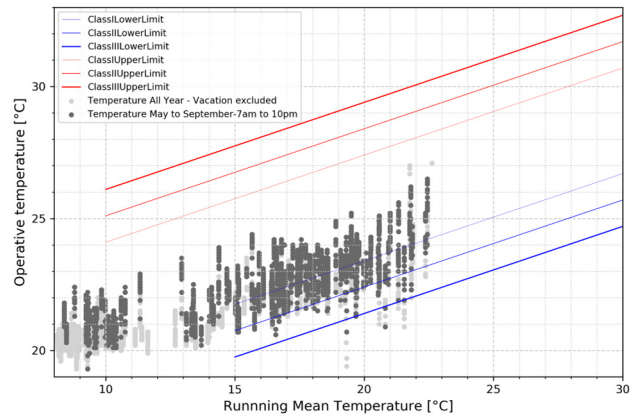
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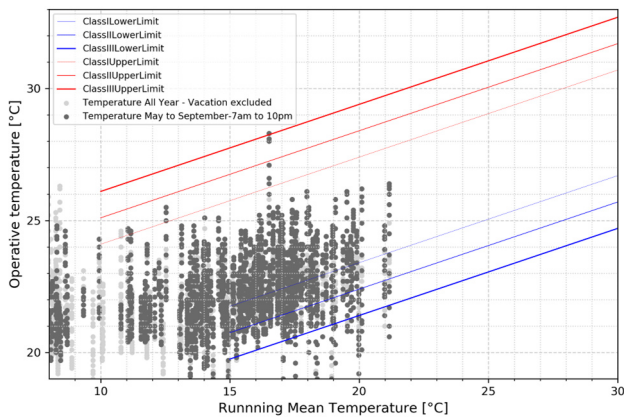
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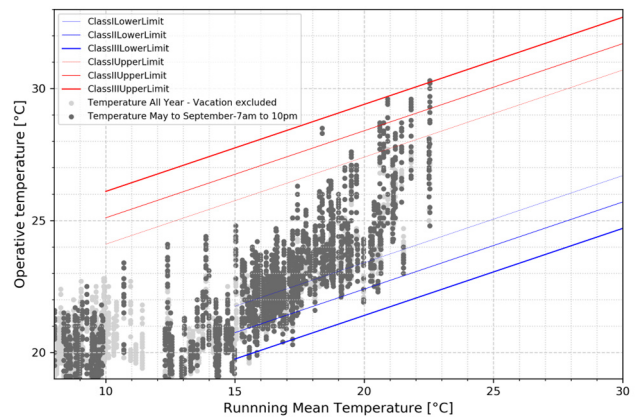
16 Living room



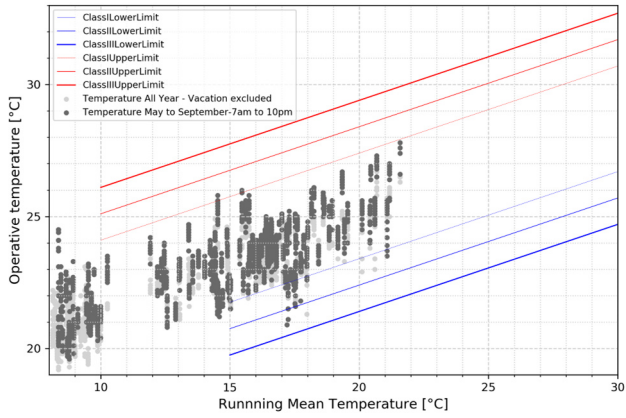
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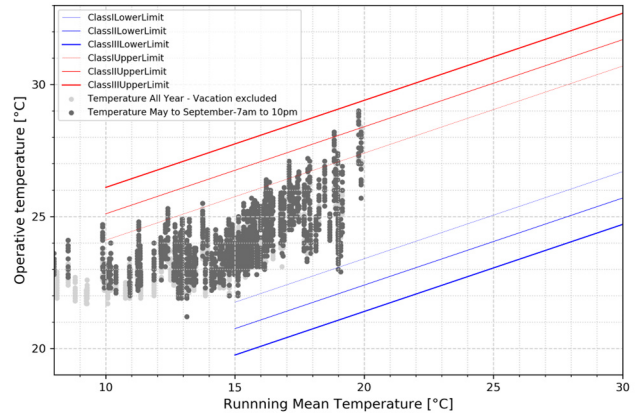
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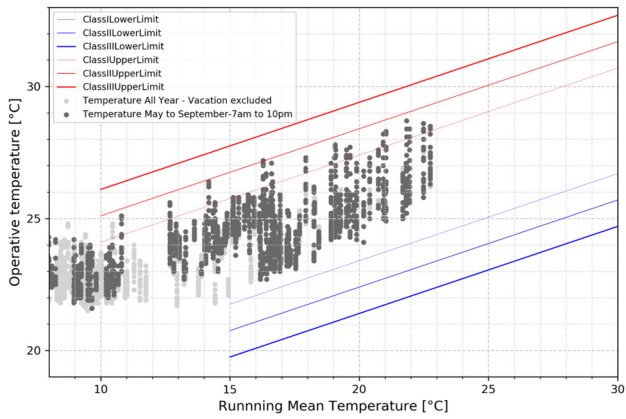
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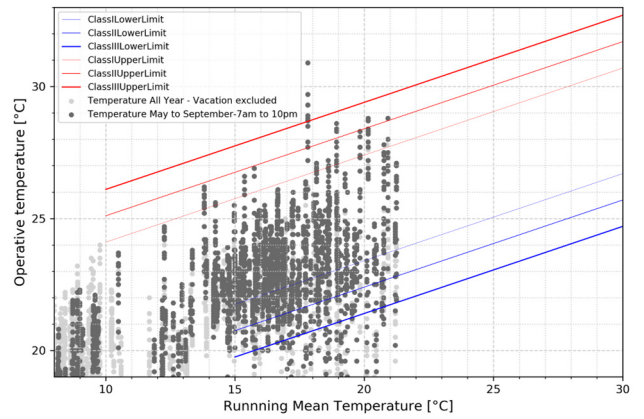
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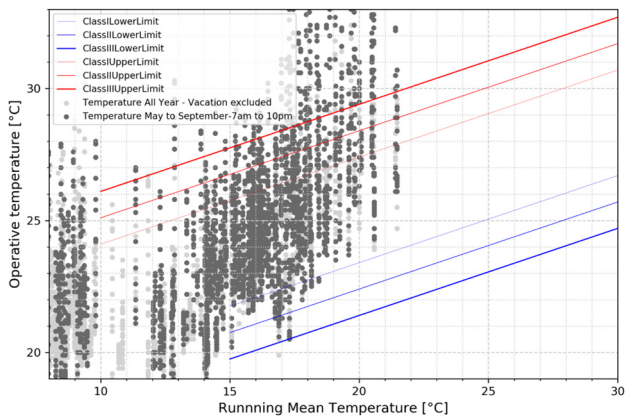
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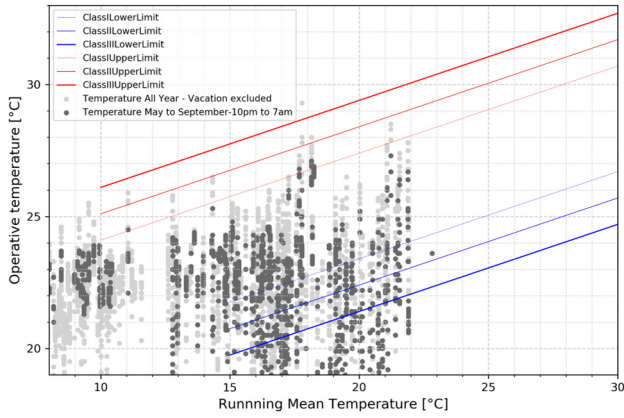
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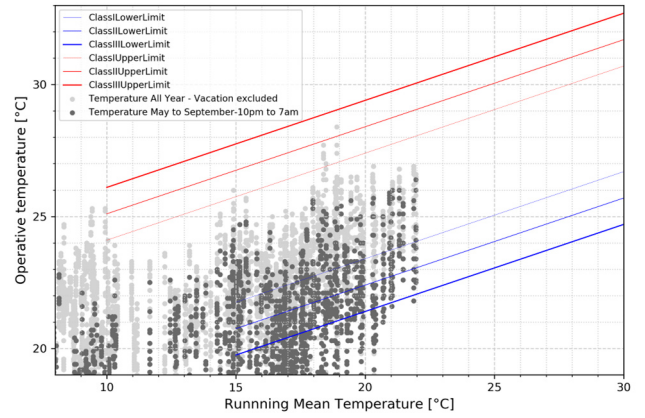
23 Living room



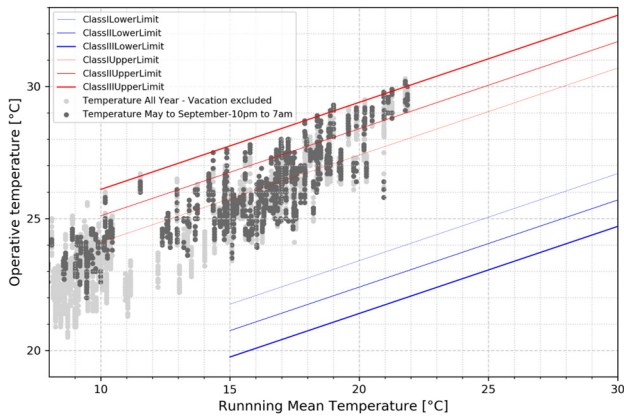
1 Bed room



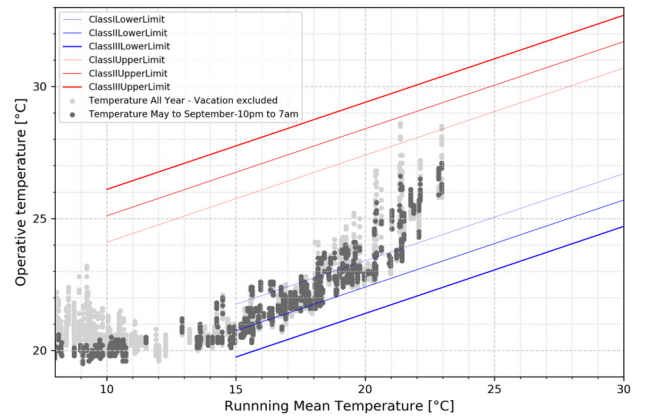
2 Bed room



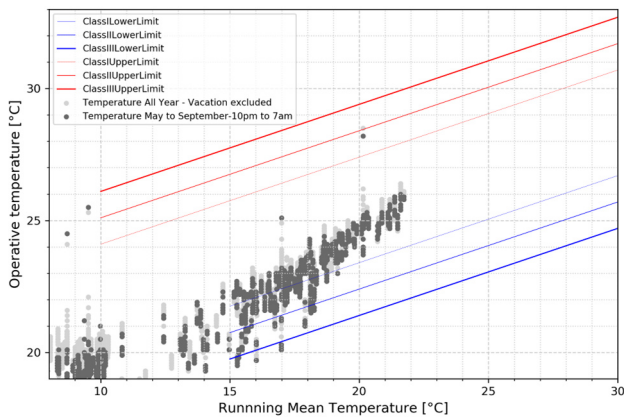
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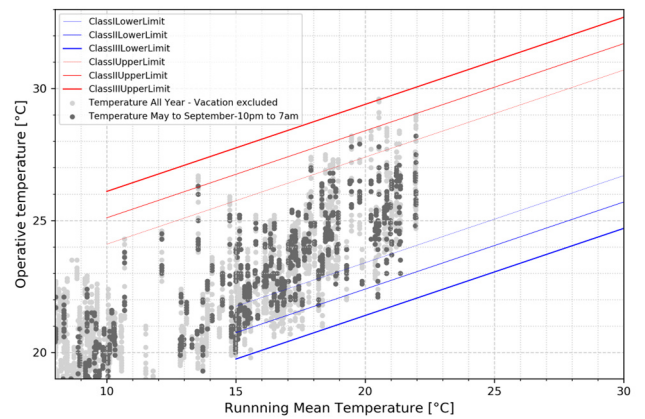
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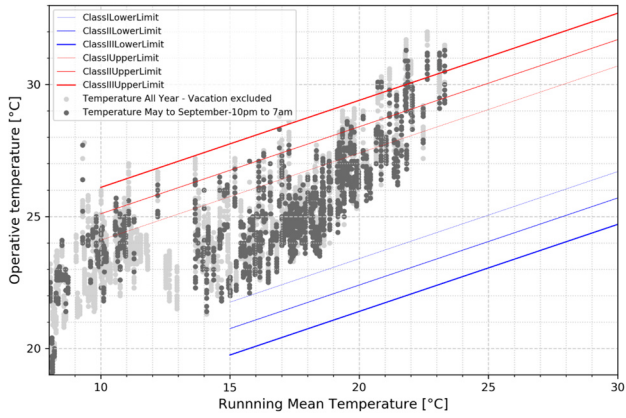
5 Bed room



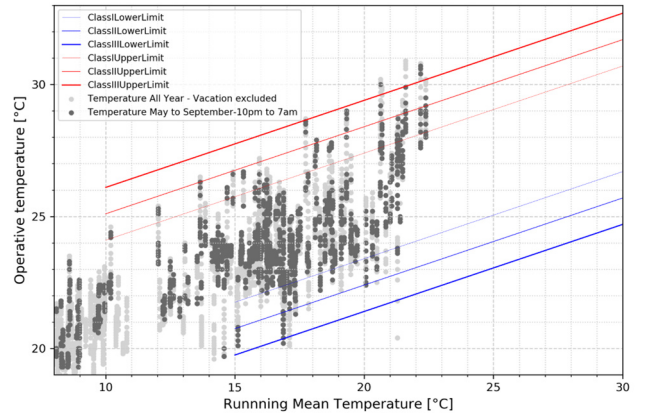
6 Bed room



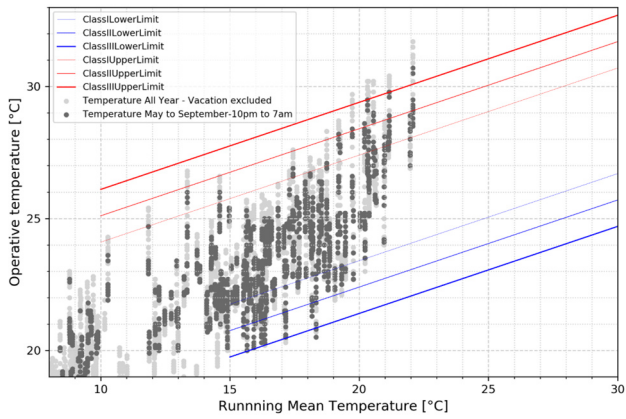
7 Bed room



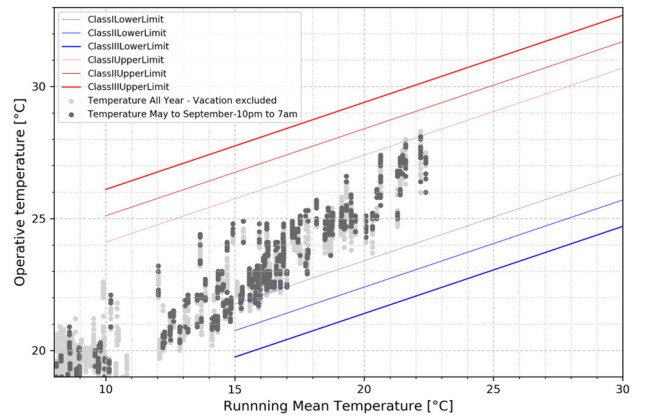
8 Bed room



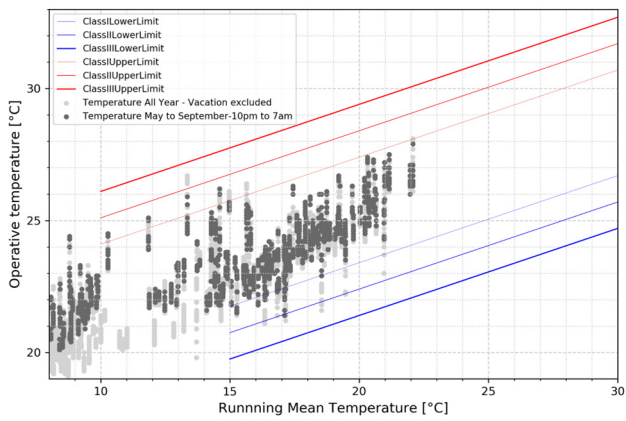
9 Bed room



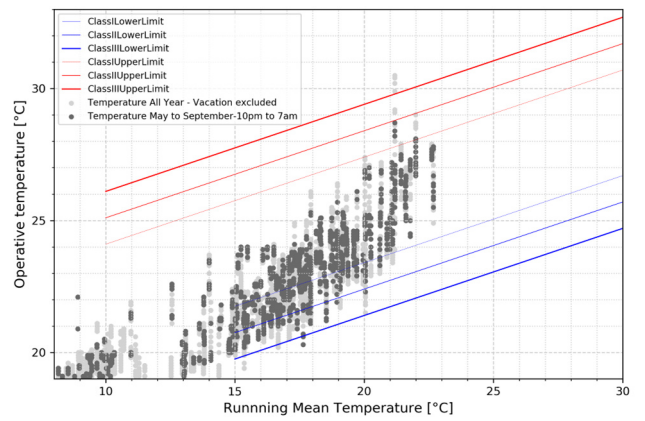
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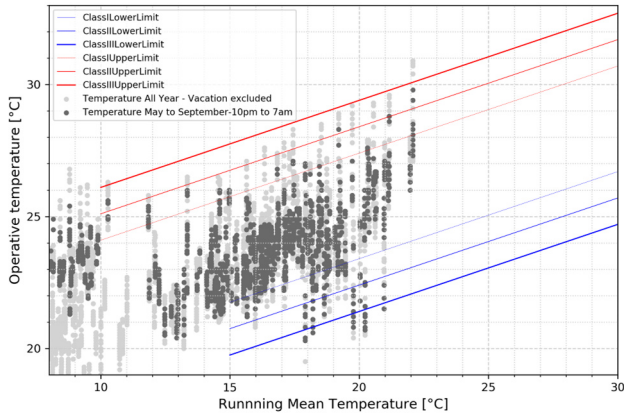
11 Bed room



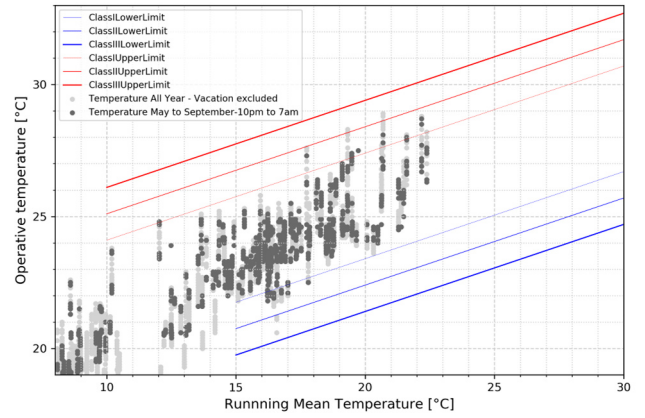
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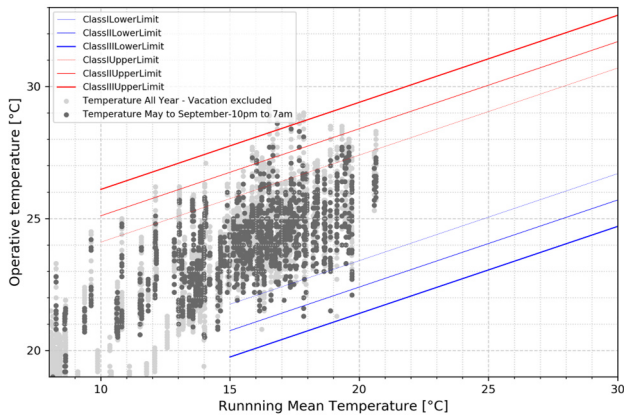
13 Bed room



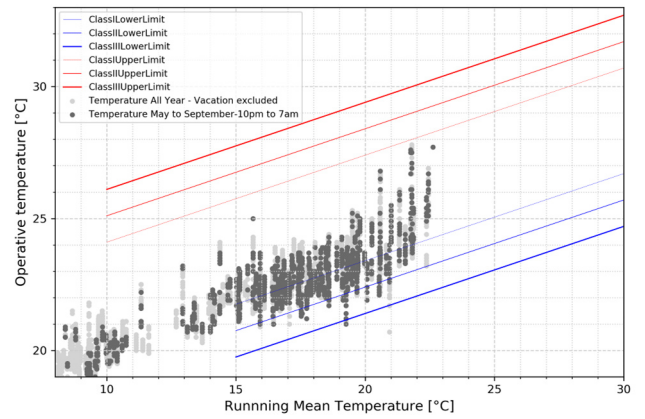
14 Bed room



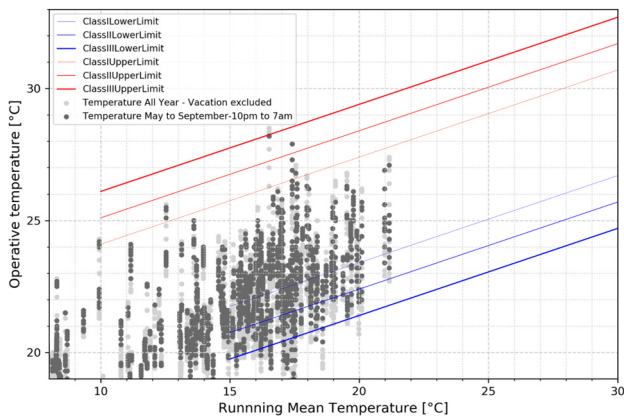
15 Bed room



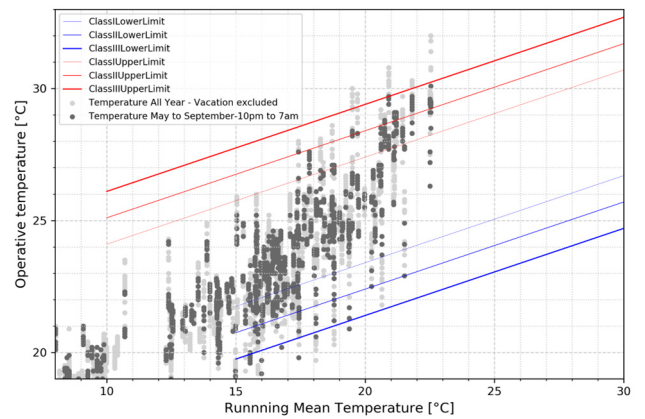
16 Bed room



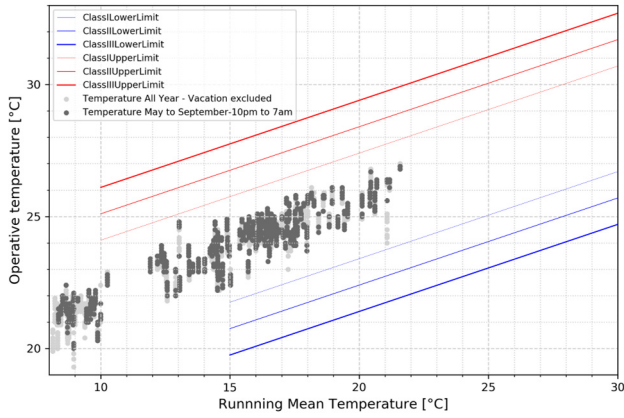
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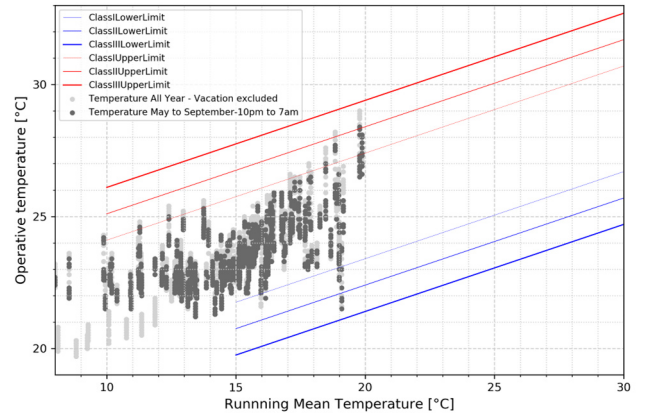
18 Bed room



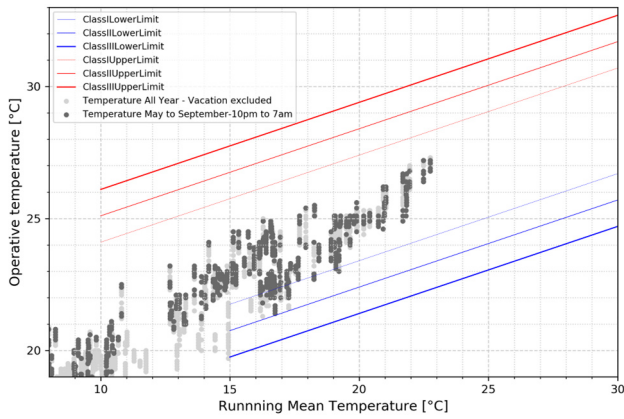
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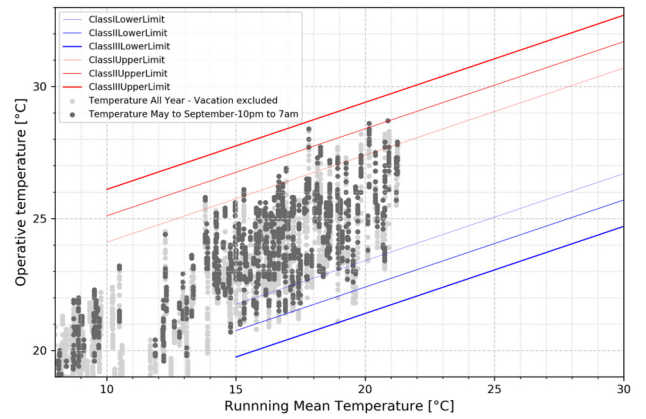
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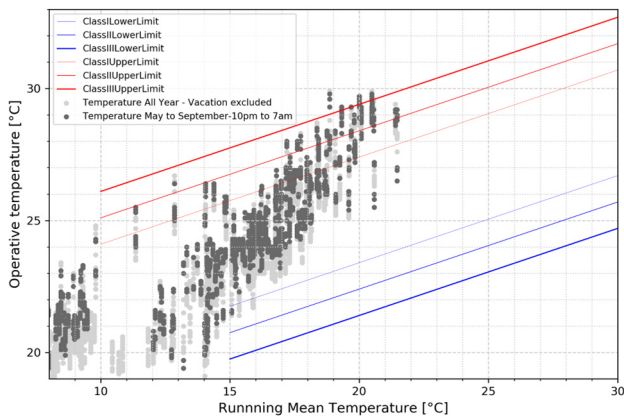
21 Bed room



22 Bed room



23 Bed room



Appendix C. Comparison of indoor thermal conditions in two neighbouring low-energy houses during the 2016 heatwave

Appendix C presents the measurement results for two monitored neighbouring houses, Stations 3 and 5, which were part of Subsample A.2 (see Section II.3.1 p.83). The two houses share similar constructive characteristics and were built as part of the same housing development. The analysis of the measurement data was conducted within the framework of the MEASURE project (see Section II.1 p.80), in collaboration with Véronique Vanwelde, Research Engineer at Buildwise. These data were more specifically analysed and published in [211] and [277].

Architectural plan

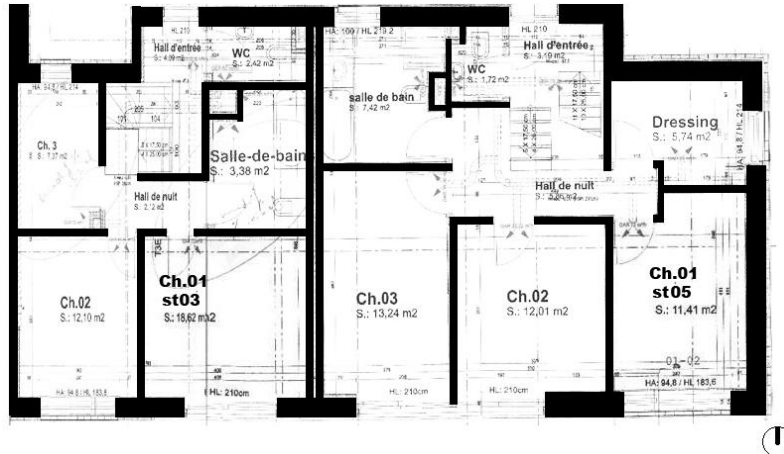


Figure i. Architectural plan of level 1 for stations 3 and 5.

Main volumetric and thermal characteristics

Table i. Main volumetric and thermal characteristics of stations 3 and 5.

		St03	St05
Heated floor area	[m ²]	119.7	151.7
Heated volume	[m ³]	449.4	567.4
Area of exposed surface	[m ²]	279.6	369.8
Compactness Ratio	[m]	1.6	1.5
Window to floor ratio	[%]	15	19.0
Airtightness n50	[1/h]	0.4	0.4
Mean U value	[W/m ² K]	0.19	0.18
Windows SHGC	[-]	0.54	0.54
Heating needs	[kWh/m ² .year]	9	5
Air Change per Hour (hygienic ventilation)	[h ⁻¹]	0.4	0.3
Main orientation	[-]	South	
Livingroom solar shading	[-]	Yes (internal light coloured)	No
Bedroom solar shading	[-]	Yes (internal light coloured)	No
Ventilative cooling by windows opening living room	[-]	Yes	No
Ventilative cooling by windows opening living room	[-]	Yes	No
Construction type	[-]	Woodenframe	
Daytime presence	[-]	Usual	No

Results:

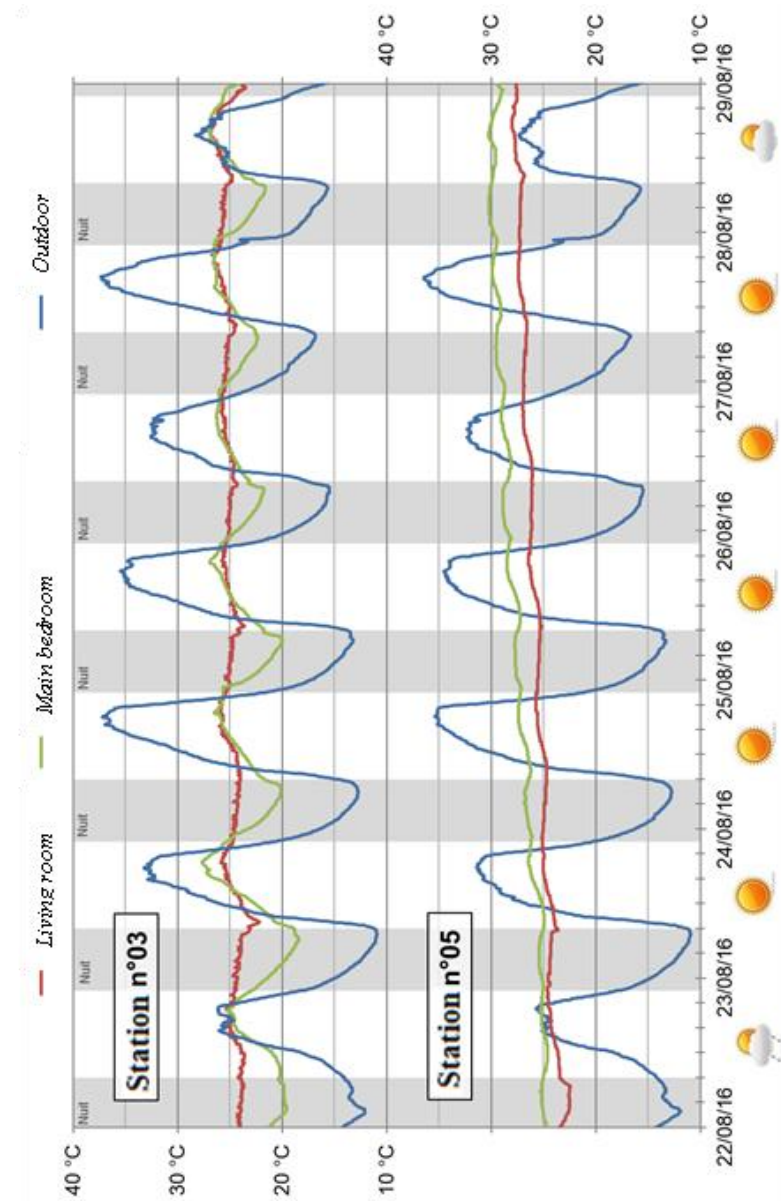


Figure ii. Evolution of the measured air temperatures in the main bedrooms and living rooms of two neighbouring houses (Stations 3 and 5), built as part of the same housing development, during the 2016 heatwave.

Key findings:

- Stations 3 and 5 are neighbouring semi-detached houses belonging to the same housing development and sharing similar construction characteristics and climatic exposure.
- Despite these similarities, the two dwellings exhibited markedly different indoor thermal conditions during the heatwave of 22–29 August 2016.
- In Station 5, temperatures in the living room and the south-facing main bedroom increased progressively, reaching approximately 30°C by the end of the heatwave.
- In Station 3, indoor temperatures remained relatively stable at around 25°C.
- The continuous closure of the internal white curtains in Station 3 combined with the slightly lower window-to-floor ratio (15% versus 19%) helped to limit solar heat gains.
- Night-time window opening enabled the evacuation of accumulated heat, as outdoor temperatures decreased substantially during the night.
- The combined use of solar protection and night ventilation prevented progressive heat accumulation in Station 3.
- The comparison shows that differences in occupants' operation of passive controls can contribute to indoor temperature differences of approximately 5°C, even between dwellings with broadly similar construction characteristics.

Appendix D. Semi-structured interview guide: example
for investigating end-user practices

Appendix D presents the semi-structured interview guide developed to investigate end-user practices in the operation of passive controls. It was developed as part of the SOFTSummer project (see Section II.1 p.80 and Section II.4.2 p.100), in collaboration with Julie Castreman, sociologist and research assistant at UCLouvain. The data collected from Sample B (see Section II.3.1 p.83) are further analysed and discussed in Chapter VII (Part B of this manuscript).

Guide d'entretien

Tout d'abord, je tiens à vous remercier d'avoir accepté de participer à cet entretien et de répondre à nos questions. Cette interview s'inscrit dans le cadre d'un projet de recherche qui s'intéresse au confort thermique estival dans les bâtiments résidentiels. Le projet implique trois institutions : l'UCLouvain, le CSTC (Centre Scientifique et Technique de la Construction) et le Cetic (Centre d'Excellence en Technologies de l'Information et de la Communication – recherche appliquée en informatique).

Pour les besoins de l'enquête, nous allons enregistrer notre entretien, êtes-vous bien d'accord ? Les résultats seront analysés dans le respect de la réglementation générale sur la protection des données (RGPD). (anonymisation, protection des données, droit de consultation et de modification des données, etc.)

Lors de cet entretien nous cherchons à comprendre vos habitudes en rapport avec le confort intérieur de votre bâtiment en été, nous ne voulons pas émettre de jugement. Il n'y a donc pas de bonnes réponses, nous expliquer vos habitudes nous aidera beaucoup plus que de nous donner une pratique « idéale ».

A. Expériences du confort d'été et stratégies mises en place

<i>Confirmer/commenter le problème de surchauffe et ses causes</i>
<i>Questions d'ouverture de l'entretien</i>
- Avez-vous parfois trop chaud dans votre maison en été ? - o Quand ? (saisons, durant une période spécifique (canicule ?), à certains moments de la journée ?) - o Où ? (dans quelles pièces ?) - À cause de quoi avez-vous trop chaud ? OU grâce à quoi n'avez-vous pas trop chaud ? - Que faites-vous ou quelqu'un d'autre quand vous avez trop chaud ? (rediriger au besoin au niveau du bâtiment) - Selon vous, votre maison se réchauffe-t-elle vite en été ? se refroidit-elle vite en été ?

Commenter la gestion de la surchauffe	
Questions axées sur la gestion en général (hors vague de chaleur)	
Protections solaires	Ventilation intensive
- Avez-vous des éléments/équipements qui protègent votre bâtiment du soleil ? - Fermez-vous vos tentures/stores/volets/... quand il y a du soleil ? - o Est-ce vous qui ouvrez/fermez habituellement les tentures/stores/volets/... ? (s'intéresser à la gestion au sein du ménage) - o Quelles sont les raisons pour lesquelles vous fermez vos tentures/stores/volets/... quand il y a du soleil ? Chaleur, lumière, ... - Quels tentures/stores/volets/... (intérieurs ou extérieurs) tirez-vous quand il y a du soleil ? - o Où ? - o Quand ? (le matin, en journée, le soir) - o Comment ? (ouverture complète, fermeture complète, ...) - o Pourquoi fermez-vous ces tentures/stores/volets/... en particulier ? (surchauffe dans la pièce, mode de vie, travail, au regard de la température extérieure/intérieure, ...) - Protégez-vous la maison du soleil lorsque vous partez la journée ? - Protégez-vous la maison du soleil lorsque vous partez durant une longue période (weekend, congés, ...) ? (l'été en particulier)	- Ouvrez-vous vos fenêtres en été ? - o Est-ce vous qui ouvrez/fermez les fenêtres habituellement ? (s'intéresser à la gestion au sein du ménage) - o Quelles sont les raisons pour lesquelles vous ouvrez vos fenêtres durant l'été ? Diminuer la température dans la maison, courants d'air, besoin d'air, odeurs, ... - Quelles fenêtres ouvrez-vous durant l'été ? - o Où ? (quelles fenêtres ?) - o Quand ? Quand ouvrez-vous ces fenêtres ? (jour, nuit, jamais ?, t° ext et int) - o Pourquoi ouvrez-vous/n'ouvrez-vous pas ces fenêtres en journée ? - o Pourquoi ouvrez-vous/n'ouvrez-vous pas ces fenêtres la nuit ? - o Est-ce que vous ouvrez/fermez certaines portes intérieures (entre pièces où ils ont ouvert) ? Pourquoi ? - o Comment ? (taille de l'ouverture, oscillo-battant, ...) - o Pourquoi ouvrez-vous ces fenêtres en particulier ? surchauffe dans la pièce ? mode de vie ? au regard de la température extérieure/intérieure ? - Est-ce que le fait de vous trouver dans une maison ossature bois/construction traditionnelle en béton/briques a un impact sur votre manière d'ouvrir/fermer vos fenêtres ? - Ouvrez/fermez-vous vos fenêtres lorsque vous partez la journée ? - Que faites-vous au niveau de l'ouverture/de la fermeture des fenêtres lorsque vous partez durant une longue période (weekend, congés,...)

- Est-ce que la connaissance de la météo du jour influence la manière dont vous vous protégez du soleil ? (faire attention à la t°)	- Est-ce que la connaissance de la météo du jour influence la manière dont vous ouvrez/fermez les fenêtres ? (faire attention à la t°)
<i>Questions axées sur la perception générale des moyens de lutte contre la surchauffe</i>	
Protections solaires	Ventilation intensive
- De manière générale, êtes-vous satisfaits des dispositifs dont vous disposez actuellement pour protéger votre maison du soleil ?	- De manière générale, êtes-vous satisfaits des dispositifs dont vous disposez actuellement pour dissiper la chaleur accumulée dans votre maison ?
- Est-ce que vous pensez que l'ensemble de ces dispositifs sont suffisants pour garantir le confort thermique dans votre maison en été ? /\ on se pose la question sur l'été. - Auriez-vous besoin d'autres choses pour garantir le confort (thermique) du bâtiment en été ? /\ Ne pas penser que infrastructures, techniques, habitudes, mais aussi, présence d'enfants, entourage, télétravail, ...	
<i>Questions axées sur la gestion en période de fortes chaleurs, caniculaire</i>	
Protections solaires	Ventilation intensive
- Est-ce que vos habitudes pour vous protéger du soleil changent durant les périodes de fortes chaleurs ? - Fermez-vous vos tentures/stores/volets/... la journée durant ces périodes de fortes chaleurs ? - o Pourquoi oui ? pourquoi non ? - o Où ? comment ? lesquels ? quand ?	- Est-ce que vos habitudes d'ouverture et de fermeture des fenêtres changent durant les périodes de fortes chaleurs ? - Fermez-vous vos fenêtres durant ces périodes de fortes chaleurs ? - o Pourquoi oui ? pourquoi non ? - o Où ? comment ? lesquelles ? quand ?

<i>Questions axées sur la perception en période fortes chaleurs, caniculaire</i>	
Protections solaires	Ventilation intensive
- En période de fortes chaleurs, êtes-vous globalement satisfaits des dispositifs dont vous disposez actuellement pour protéger votre maison du soleil ? (notamment les protections solaires et la ventilation)	- En période de fortes chaleurs, êtes-vous satisfaits des dispositifs dont vous disposez actuellement pour dissiper la chaleur accumulée dans votre maison ? (notamment les protections solaires et la ventilation)
- Est-ce que vous modifier certaines habitudes en période caniculaire ? (par exemple, les repas cuisson, les lieux de vie, couper le chauffage, etc.). - Est-ce que vous pensez que l'ensemble de ces dispositifs sont suffisants pour garantir le confort thermique dans votre maison en période caniculaire ? (notamment les protections solaires et la ventilation) - Auriez-vous besoin d'autres choses pour éviter la surchauffe du bâtiment en période de fortes chaleurs ? /!\ ne pas penser uniquement infrastructures, techniques, mais aussi habitudes, présence enfants, entourage, télétravail, ... - o Lesquelles ? Pourquoi ? - Selon vous, est-ce normal d'avoir chaud durant les périodes caniculaires ? Supportez-vous la chaleur durant quelques jours lorsqu'une canicule se produit ?	

B. Identification des freins et leviers à l'implémentation de stratégies passives

<i>Discuter des freins et leviers à l'implémentation de solutions de lutte contre la surchauffe</i>	
Protections solaires	Ventilation intensive
- Avez-vous déjà entendu parler de ces systèmes ? ○ Si oui, par qui ? - Est-ce que vous seriez prêt à installer des protections solaires proposées ? ○ Pourquoi oui ? pourquoi non ? - Pensez-vous que les solutions proposées seront suffisantes pour garantir le confort thermique en été ?	- Avez-vous déjà entendu parler de ces systèmes ? ○ Si oui, par qui ? - Est-ce que vous seriez prêt.e à ouvrir mieux vos fenêtres pour dissiper la chaleur et refroidir naturellement le bâtiment ? ○ Pourquoi oui ? pourquoi non ? - Pensez-vous que les solutions proposées seront suffisantes pour garantir le confort thermique en été ?
- Est-ce que recevoir une information en temps réel sur la gestion manuelle idéale d'ouverture et fermeture des fenêtres et des protections solaires vous aiderait ? (donner un exemple si incompréhension) ○ Via une application ? ○ Via des signaux lumineux ? ○ Via un sms ? ○ Via un réveil le matin ? ○ Autre chose ?	
- Est-ce que vous seriez prêt à investir dans un système de gestion automatisée (càd choses qui s'ouvrent et qui se ferment seules) pour l'ouverture et la fermeture de vos fenêtres ? (faire la différence entre gestion motorisée et gestion automatisée en donnant les définitions) ○ Pourquoi oui ? pourquoi non ? ○ Dans quels endroits de la maison ? (partout ? pièces communes ? chambres ?)	
<i>Question complémentaire sur la facilitation de l'implémentation des solutions</i>	
- Si demain les canicules devaient être beaucoup plus fréquentes, que feriez-vous ? - Est-ce que certaines choses vous inciteraient à franchir le pas (plus vite) ? ○ Subsidés, indications dans la PEB, le coût de l'énergie, etc.	
<i>Questions concernant la transition énergétique</i>	
- Pensez-vous que toutes ces mesures puissent avoir un impact positif sur l'environnement ?	

C. Questions de clôture, sociodémographiques et composition de ménage.

Question(s) de clôture

- Nous arrivons à la fin de l'entretien, souhaiteriez-vous ajouter quelque chose ?
- Si vous avez des questions ou que vous constatez des éléments non cités durant cet entretien cet été, n'hésitez à envoyer un mail à Véronique.

Questions générales sur la composition de ménage

- Combien de personnes vivent dans cette maison ?
- Qui vit avec vous (conjoint, enfants, parents, amis, ...) ?
- Quel est votre âge ? Quel est leur âge ?
- Quel est le niveau de diplôme le plus haut que vous ayez obtenu ? Qu'ils ont obtenus ?
- Quelle est votre profession ? Quelle est leur profession ?

Un grand merci pour votre participation à cette enquête et pour le temps que vous nous avez consacré !

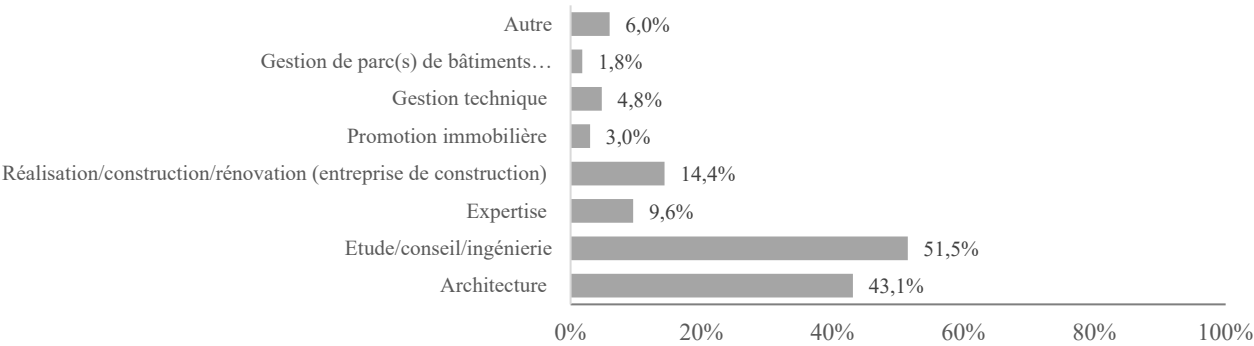
Appendix E. Survey of professional practices in the
integration of passive controls

Appendix E presents the survey developed to capture professional practices in the integration of passive controls and the corresponding data collected. It was developed as part of the SOFTSummer project (see Section II.1 p.80), in collaboration with Julie Castreman, sociologist and research assistant at UCLouvain. The data collected from the 167 professionals in Sample B are further analysed and discussed in Chapter VII (Part B of this manuscript).

Votre activité

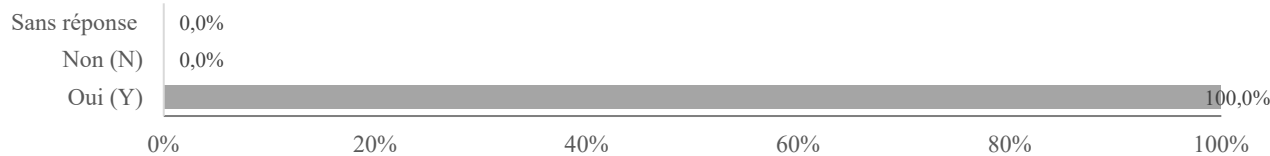
Quelle(s) sont les activité(s) de votre entreprise ? [Choix multiples]

Réponse	n	%
Architecture	72	43,1%
Etude/conseil/ingénierie	86	51,5%
Expertise	16	9,6%
Réalisation/construction/rénovation (entreprise de construction)	24	14,4%
Promotion immobilière	5	3,0%
Gestion technique	8	4,8%
Gestion de parc(s) de bâtiments (société de logements, etc.)	3	1,8%
Autre	10	6,0%



Travaillez-vous sur des projets de logements ? [Choix unique]

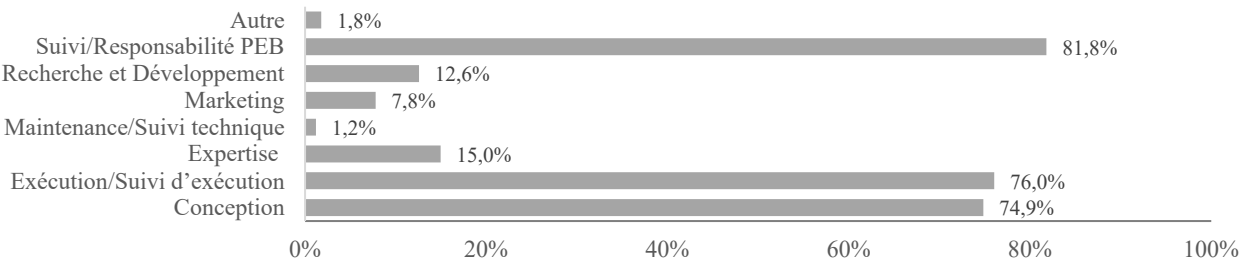
Réponse	n	%
Oui (Y)	167	100,0%
Non (N)	0	0,0%
Sans réponse	0	0,0%
Total	167	100,0%



Conditions : si « oui » à la question « travaillez-vous sur des projets de logements ? », alors, le répondant à accès au reste du questionnaire, si « non », alors le répondant arrive directement sur la question de fin.

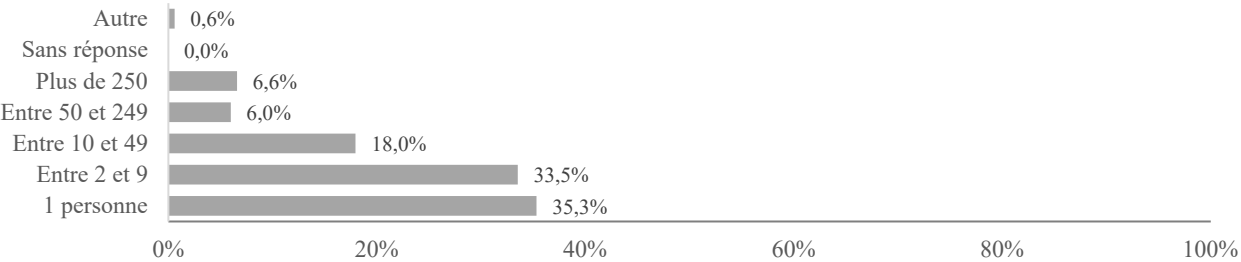
A quel(s) stade(s) du processus de construction intervenez-vous personnellement ? [Choix multiples]

Réponse	n	%
Conception	125	74,9%
Exécution/Suivi d'exécution	127	76,0%
Expertise	25	15,0%
Maintenance/Suivi technique	2	1,2%
Marketing	13	7,8%
Recherche et Développement	21	12,6%
Suivi/Responsabilité PEB	90	81,8%
Autre	3	1,8%



Combien de personne(s) travaille(nt) au sein de votre entreprise (en Belgique et ailleurs) ? [Choix unique]

Réponse	n	%
1 personne	59	35,3%
Entre 2 et 9	56	33,5%
Entre 10 et 49	30	18,0%
Entre 50 et 249	10	6,0%
Plus de 250	11	6,6%
Sans réponse	0	0,0%
Autre	1	0,6%
Total	167	100,0%



Quel est le nom de l'entreprise dans laquelle vous travaillez ? [Texte court]

Remove for privacy.

Quel est le nom de l'entreprise dans laquelle vous travaillez ? [Texte court] - suite

Remove for privacy

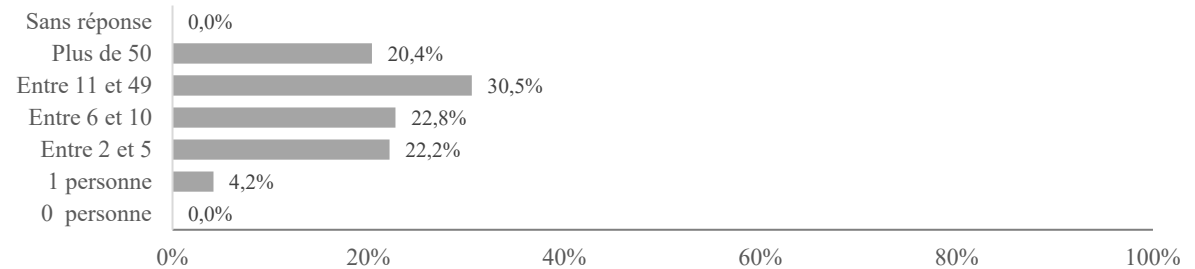
Votre pratique

Sur combien de projet(s)* de logement(s) neufs ou en rénovation importante** avez-vous travaillé au cours des deux dernières années ? [Choix unique]

*un projet peut contenir un ou plusieurs logements

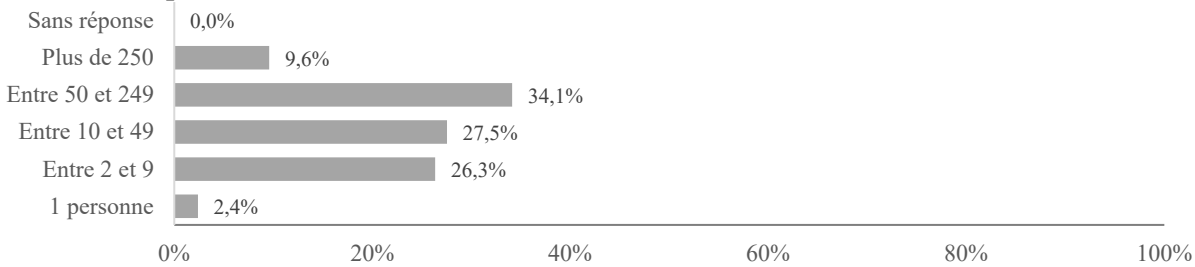
** travaux de rénovation d'extension ou de

Réponse	n	%
0 personne	0	0,0%
1 personne	7	4,2%
Entre 2 et 5	37	22,2%
Entre 6 et 10	38	22,8%
Entre 11 et 49	51	30,5%
Plus de 50	34	20,4%
Sans réponse	0	0,0%
Total	167	100,0%



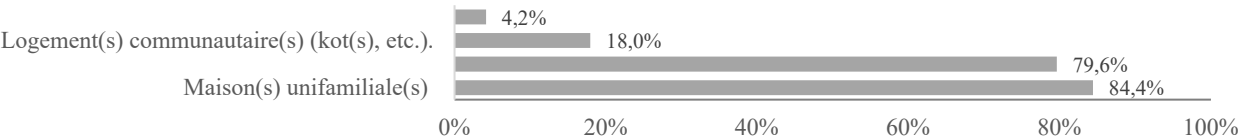
Combien de logement(s) cela concerne-t-il approximativement ? [Choix unique]

Réponse	n	%
1 personne	4	2,4%
Entre 2 et 9	44	26,3%
Entre 10 et 49	46	27,5%
Entre 50 et 249	57	34,1%
Plus de 250	16	9,6%
Sans réponse	0	0,0%
Total	167	100,0%



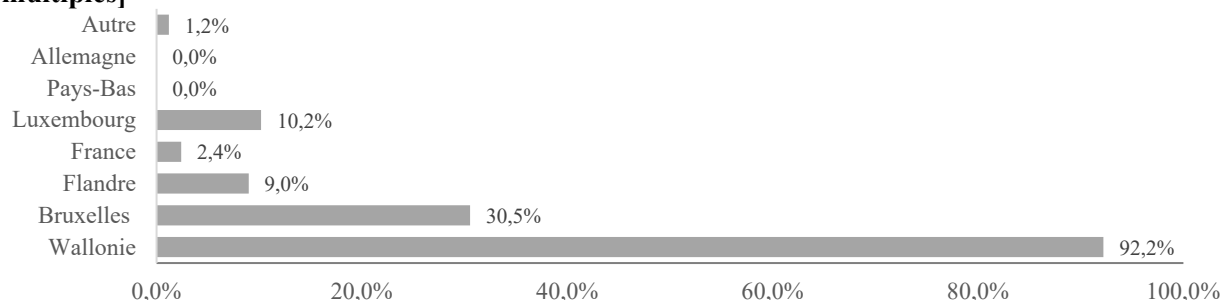
De quel(s) type(s) de logement(s) s'agissait-il ? [Choix multiples]

Réponse	n	%
Maison(s) unifamiliale(s)	141	84,4%
Appartement(s)	133	79,6%
Logement(s) communautaire(s) (kot(s), etc.).	30	18,0%
Autre	7	4,2%



Dans quelle(s) région(s) ces logements se trouvent-ils ? [Choix multiples]

Réponse	n	%
Wallonie	154	92,2%
Bruxelles	51	30,5%
Flandre	15	9,0%
France	4	2,4%
Luxembourg	17	10,2%
Pays-Bas	0	0,0%
Allemagne	0	0,0%
Autre	2	1,2%

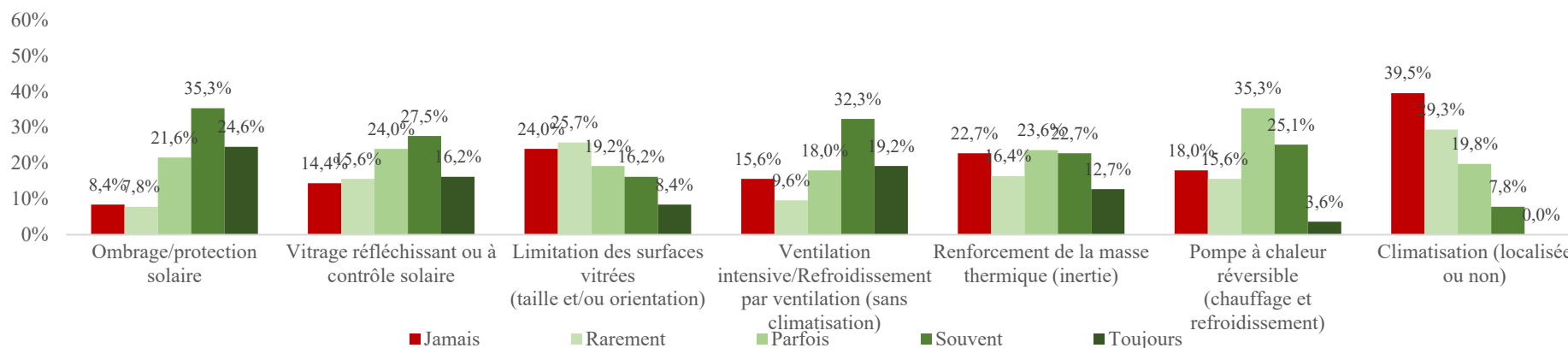


Sur ces projets*, avez-vous envisagé** les techniques suivantes ? [Choix unique par ligne]

* un projet peut contenir un ou plusieurs logements. Il s'agit de projet de logements neufs ou en rénovation lourde, autrement dit, ne conservant essentiellement que la structure portante du bâtiment.

**même si non réalisé

Dispositifs	Jamais		Rarement		Parfois		Souvent		Toujours		Je ne sais pas		Total	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Ombrage/protection solaire	14	8,4%	13	7,8%	36	21,6%	59	35,3%	41	24,6%	4	2,4%	167	100,0%
Vitrage réfléchissant ou à contrôle solaire	24	14,4%	26	15,6%	40	24,0%	46	27,5%	27	16,2%	4	2,4%	167	100,0%
Limitation des surfaces vitrées (taille et/ou orientation)	40	24,0%	43	25,7%	32	19,2%	27	16,2%	14	8,4%	11	6,6%	167	100,0%
Ventilation intensive/Refroidissement par ventilation (sans climatisation)	26	15,6%	16	9,6%	30	18,0%	54	32,3%	32	19,2%	9	5,4%	167	100,0%
Renforcement de la masse thermique (inertie)	25	22,7%	18	16,4%	26	23,6%	25	22,7%	14	12,7%	2	1,8%	110	100,0%
Pompe à chaleur réversible (chauffage et refroidissement)	30	18,0%	26	15,6%	59	35,3%	42	25,1%	6	3,6%	4	2,4%	167	100,0%
Climatisation (localisée ou non)	66	39,5%	49	29,3%	33	19,8%	13	7,8%	0	0,0%	6	3,6%	167	100,0%



Votre usage des protections solaires

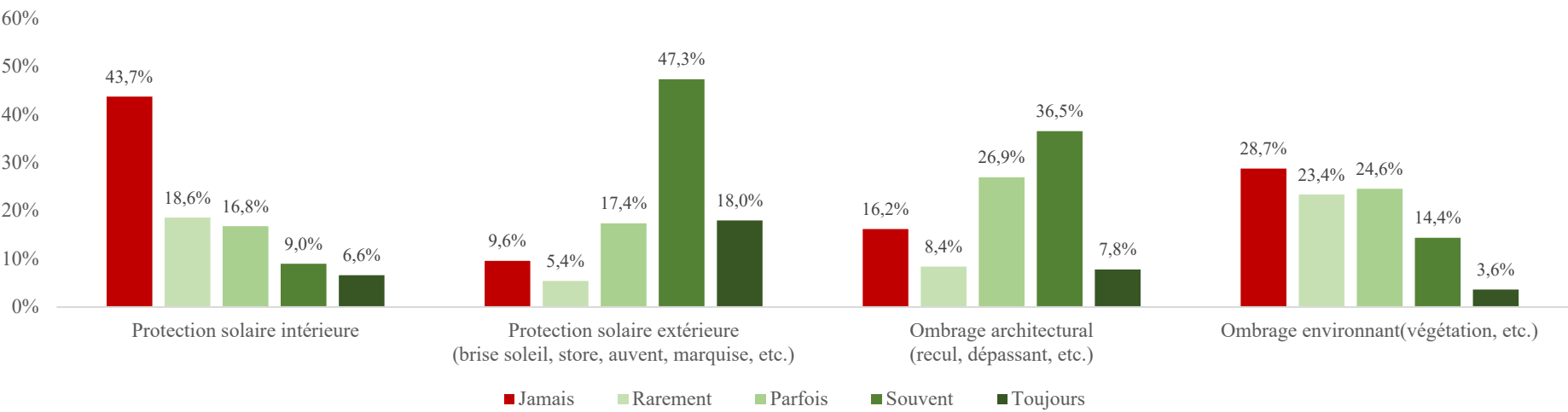
Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Sur ces projets*, avez-vous envisagé (même si non réalisé) les techniques suivantes ? » sous-question « ombrage/protection solaire ».

Pour ces projets de logements*, quel(s) dispositif(s) d'ombrage/de protection solaire avez-vous envisagé(s)** ? [Choix unique par ligne]

*réalisés au cours des deux dernières années, un projet pouvant contenir un ou plusieurs logements

**même si non réalisé

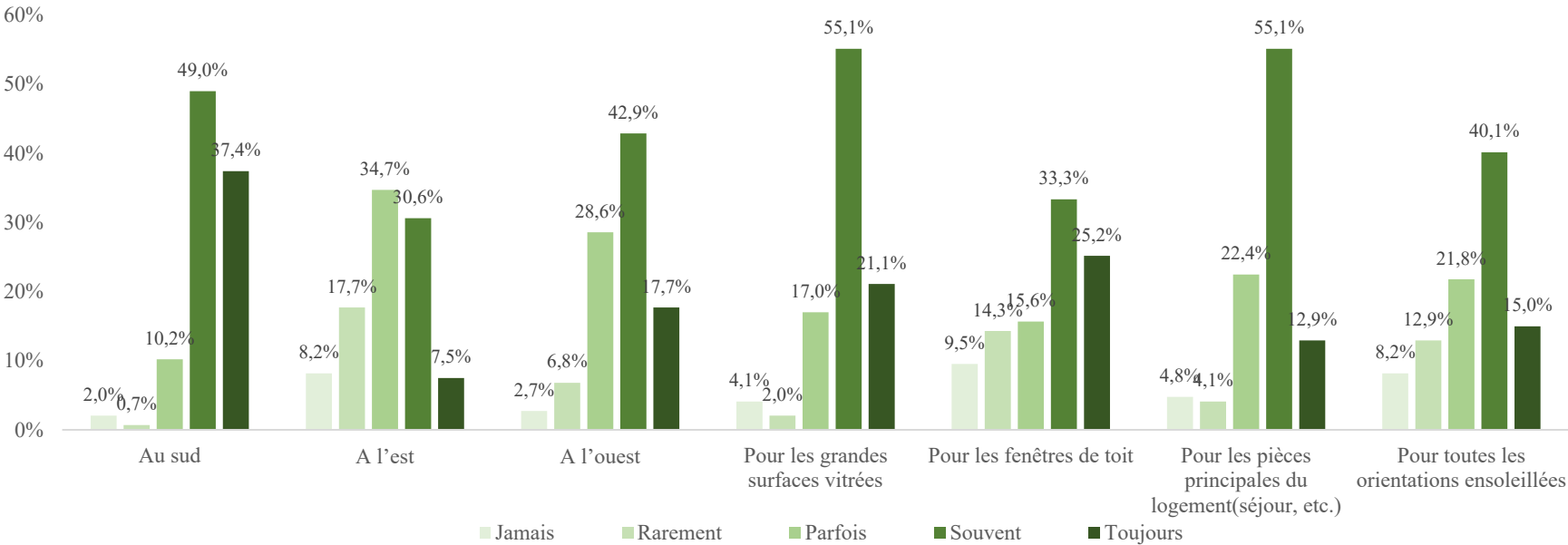
Dispositifs	Jamais		Rarement		Parfois		Souvent		Toujours		Je ne sais pas		Total	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Protection solaire intérieure	73	43,7%	31	18,6%	28	16,8%	15	9,0%	11	6,6%	9	5,4%	167	100,0%
Protection solaire extérieure (brise soleil, store, auvent, marquise, etc.)	16	9,6%	9	5,4%	29	17,4%	79	47,3%	30	18,0%	4	2,4%	167	100,0%
Ombrage architectural (recul, dépassant, etc.)	27	16,2%	14	8,4%	45	26,9%	61	36,5%	13	7,8%	7	4,2%	167	100,0%
Ombrage environnant(végétation, etc.)	48	28,7%	39	23,4%	41	24,6%	24	14,4%	6	3,6%	9	5,4%	167	100,0%



Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Pour ces projets de logements, quel(s) dispositif(s) d'ombrage/de protection solaire avez-vous envisagé(s) » sous-question « protection solaire extérieure (brise soleil, store, auvent, marquise, etc.) ».

Pour ces projets, dans quelle(s) configuration(s) avez-vous recommandé le placement de dispositif(s) d'ombrage/de protection solaire ?
[Choix unique par ligne]

Techniques	Jamais		Rarement		Parfois		Souvent		Toujours		Je ne sais pas		Total	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Au sud	3	2,0%	1	0,7%	15	10,2%	72	49,0%	55	37,4%	1	0,7%	147	100,0%
A l'est	12	8,2%	26	17,7%	51	34,7%	45	30,6%	11	7,5%	2	1,4%	147	100,0%
A l'ouest	4	2,7%	10	6,8%	42	28,6%	63	42,9%	26	17,7%	2	1,4%	147	100,0%
Pour les grandes surfaces vitrées	6	4,1%	3	2,0%	25	17,0%	81	55,1%	31	21,1%	1	0,7%	147	100,0%
Pour les fenêtres de toit	14	9,5%	21	14,3%	23	15,6%	49	33,3%	37	25,2%	3	2,0%	147	100,0%
Pour les pièces principales du logement(séjour, etc.)	7	4,8%	6	4,1%	33	22,4%	81	55,1%	19	12,9%	1	0,7%	147	100,0%
Pour toutes les orientations ensoleillées	12	8,2%	19	12,9%	32	21,8%	59	40,1%	22	15,0%	3	2,0%	147	100,0%

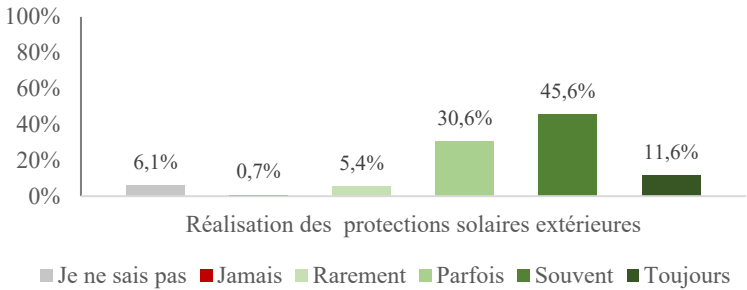


Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Pour ces projets de logements, quel(s) dispositif(s) d'ombrage/de protection solaire avez-vous envisagé(s) » sous-question « protection solaire extérieure (brise soleil, store, auvent, marquise, etc.) ».

Les dispositifs de protections solaires extérieures envisagés ont-ils finalement été réalisés* ? [Choix unique]

*présents à la fin du chantier

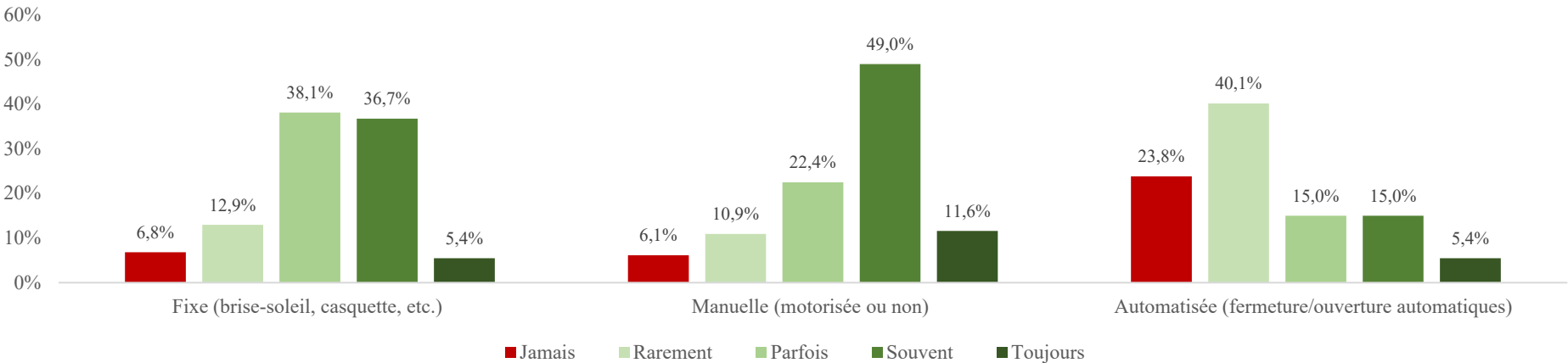
Réponse	n	%
Jamais	1	0,7%
Rarement	8	5,4%
Parfois	45	30,6%
Souvent	67	45,6%
Toujours	17	11,6%
Je ne sais pas	9	6,1%
Total	147	100,0%



Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Pour ces projets de logements, quel(s) dispositif(s) d'ombrage/de protection solaire avez-vous envisagé(s) » sous-question « protection solaire extérieure (brise soleil, store, auvent, marquise, etc.) ».

Quelle(s) gestion(s) avez-vous envisagée(s) pour les dispositifs de protections solaires extérieures ?

Dispositifs	Jamais		Rarement		Parfois		Souvent		Toujours		Je ne sais pas		Total	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Fixe (brise-soleil, casquette, etc.)	10	6,8%	19	12,9%	56	38,1%	54	36,7%	8	5,4%	0	0,0%	147	100,0%
Manuelle (motorisée ou non)	9	6,1%	16	10,9%	33	22,4%	72	49,0%	17	11,6%	0	0,0%	147	100,0%
Automatisée (fermeture/ouverture automatiques)	35	23,8%	59	40,1%	22	15,0%	22	15,0%	8	5,4%	1	0,7%	147	100,0%

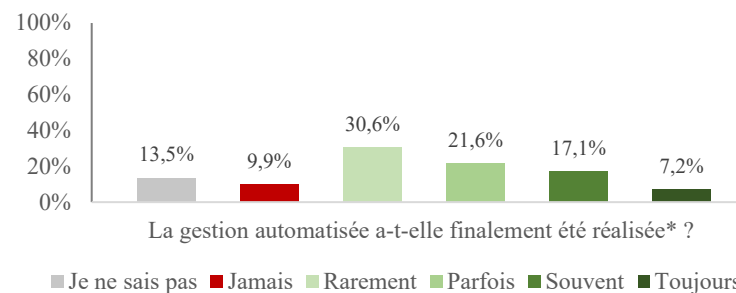


Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Quelle(s) gestion(s) avez-vous envisagée(s) ».

La gestion automatisée a-t-elle finalement été réalisée* ?

*présente à la fin du chantier

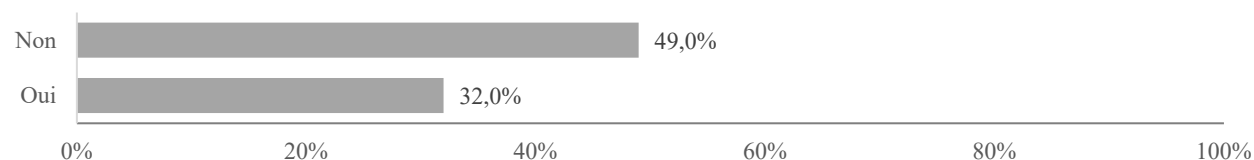
Réponse	n	%
Jamais	11	9,9%
Rarement	34	30,6%
Parfois	24	21,6%
Souvent	19	17,1%
Toujours	8	7,2%
Je ne sais pas	15	13,5%
Total	111	100,0%



Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Pour ces projets de logements, quel(s) dispositif(s) d'ombrage/de protection solaire avez-vous envisagé(s) » sous-question « protection solaire extérieure (brise soleil, store, auvent, marquise, etc.) ».

Avez-vous envisagé des dispositifs de protections solaires extérieures différents en fonction du type de logements ? (appartements, maisons, etc.) ? [Choix unique].

Réponse	n	%
Oui	47	32,0%
Non	72	49,0%
Je ne sais pas	28	19,0%
Total	147	100,0%



Conditions : si « Oui » à la question « avez-vous envisagé des dispositifs de protections solaires extérieures différents en fonction du type de logements ? (Appartements, maisons, etc.) ? »

Commentez la/les raison(s) pour la/lesquelles(s) vous envisagez des dispositifs de protections solaires différents en fonction du type de logements.

[Texte long]

En fonction de la destination du bâtiment (logements sociaux ou pas)

En fonction de la typologie des logements.

Variété des logements

Propriétaires occupants ou locataires —> choix différents

Appartements have less degrees of freedom, which often results in exterior screens. When it comes to elderly housing, solutions as markisolette are more appropriate, because Surchauffe calculée en fonction de la PEB notamment.

En fonction des utilisateurs, certains sont souvent présents d'autres non dans leur logement. et aussi en fonction du côté proactif ou non de ceux-ci.

De manière un peu caricaturale, les projets de logement collectif sur lesquels je suis amenée à travailler sont souvent du logement social, principalement des appartements

Chaque projet est différent, les pièces de vie et baies extérieures ne sont pas orientées de la même manière, les dimensions des ouvertures varient, le site à son influence robustesse et facilité d'utilisation lors de son utilisation qui risque d'être différente suivant que l'utilisateur sera locataire ou propriétaire

Dépend de la typologie, niveau d'habitabilité, budget, etc

Cela dépend de la conception du logement (architecture classique ou contemporaine)

Chaque projet est différent

Nous privilégions des aménagements architecturaux (typiquement des casquettes) pour créer un ombrage fixe. Ces dispositifs sont plus simple à intégrer en habitation

Les appartements sont plus souvent louer et on envisage des dispositifs moins compliqué

Budget

Les appartements de plus petites dimensions sont plus sensibles à la surchauffe que les maisons (plus faciles à ventiler naturellement par exemple).

Espace disponible

Budget et choix de l'architecte

Traitement différent, dépendant du projet et de son contexte

Dépend du schéma temporel d'occupation des logements.

Volets pour appartements à louer moins chers que BSO pour maison unifamiliale.

Typologie différente, ventilation traversante possible ou non, types de toiture et espaces sous toiture

Les taux de surchauffe sont souvent plus difficiles à gérer dans des appartements avec 1 seule ou 2 orientations, par rapport à des maison 3 ou 4 façades qui présentent

Je n'ai pas de recette universelle qui convient à tous les projets. J'essaye de trouver à chaque fois la solution la plus adaptée possible en fonction de la situation, des clients

L'ombrage architecturale lors de projet d'immeuble à appartement peut être envisagé étant donné qu'une collaboration avec l'architecte au stade conception est plus aisée

Question de coût si le logement est destiné à la location

Chaque projet est différent et chaque MO également.

Raisons techniques et adaptation à la configuration du logement.

En fonction des demandes de l'architecte et/ou du maître d'ouvrage sur le plan esthétique, financier et réglementaire (vis à vis du permis).

les immeubles à appartements peuvent parfois profiter des terrasses/balcons.

En raison de l'inertie existante du bâtiment

Commentez la/les raison(s) pour la/lesquelles(s) vous envisagez des dispositifs de protections solaires différents en fonction du type de logements.

[Texte long]-Suite

Cela dépend du projet, de localisation, du budget, mais pas forcément du type
cout, esthétique, encombrement

Pour les appartements il est d'abord envisagé un ombrage architectural type balcon si possible.

Plus grande liberté d'influencer un projet de maison unifamiliale, contact direct avec le client.

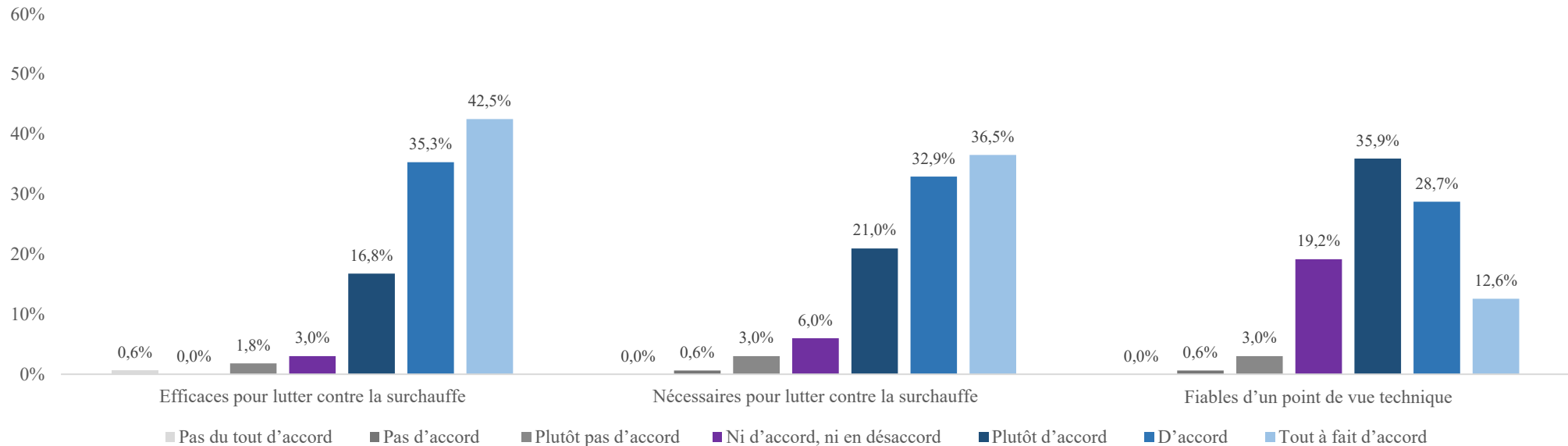
Suivant le type de logement et le budget disponible par nos clients, nous envisageons différents type.

Une protection solaire extérieure est définie dans ce qui suit comme un dispositif extérieur permettant de bloquer/limiter le rayonnement solaire avant qu'il
n'atteigne le vitrage. Plusieurs types de protections solaires extérieures existent. Elles peuvent être fixes, mobiles, saisonnières, provisoires, verticales, horizontales,
... Les questions qui suivent portent sur les protections solaires extérieures en général.

Que pensez-vous personnellement des affirmations suivantes ?

En Belgique, les protections solaires extérieures dans les logements sont...

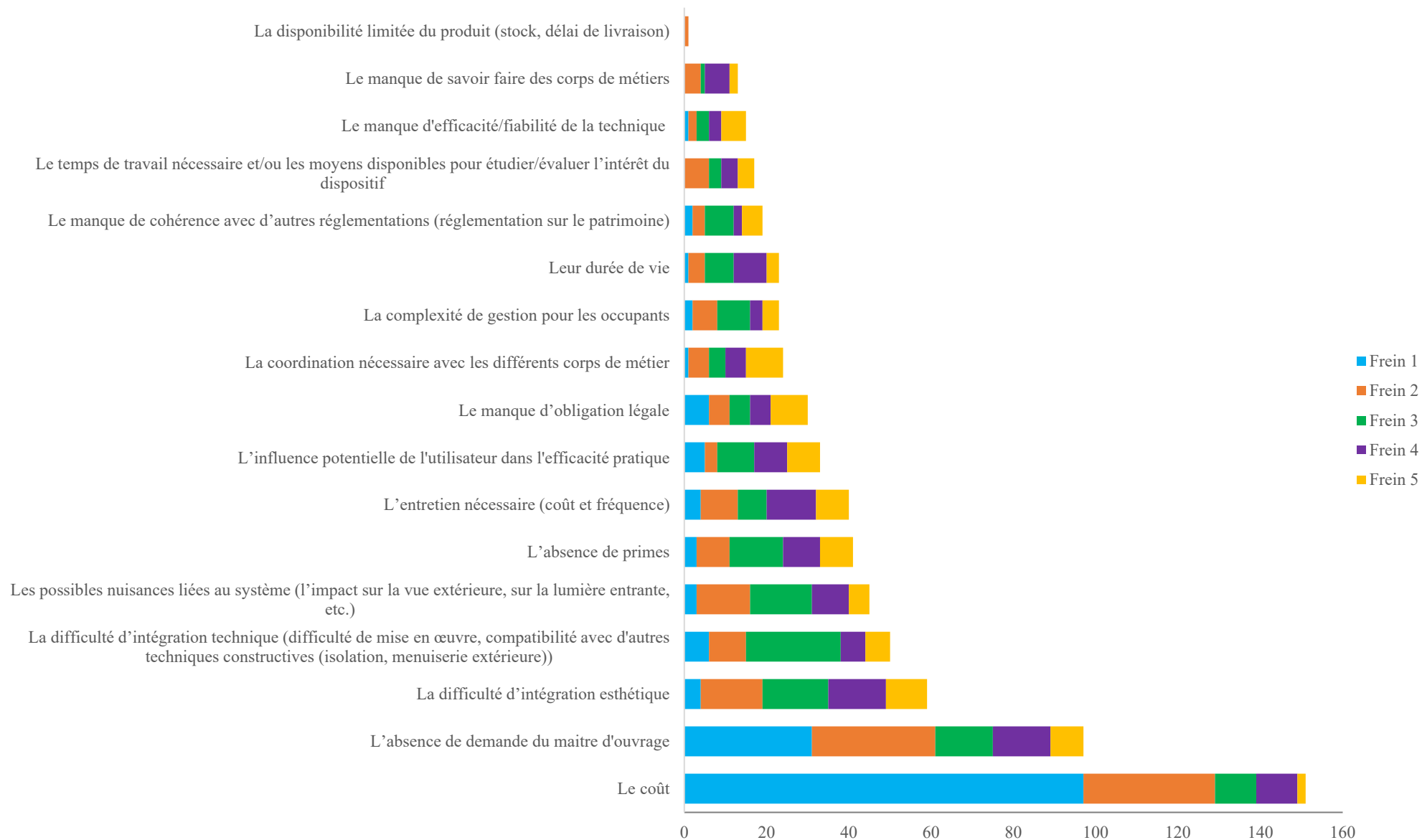
Dispositifs	Pas du tout d'accord		Pas d'accord		Plutôt pas d'accord		Ni d'accord, ni en désaccord		Plutôt d'accord		D'accord		Tout à fait d'accord	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Efficaces pour lutter contre la surchauffe	1	0,6%	0	0,0%	3	1,8%	5	3,0%	28	16,8%	59	35,3%	71	42,5%
Nécessaires pour lutter contre la surchauffe	0	0,0%	1	0,6%	5	3,0%	10	6,0%	35	21,0%	55	32,9%	61	36,5%
Fiables d'un point de vue technique	0	0,0%	1	0,6%	5	3,0%	32	19,2%	60	35,9%	48	28,7%	21	12,6%



D'après votre expérience professionnelle, qu'est-ce qui empêche le plus le placement de protections solaires extérieures dans vos projets de logement(s) [Classement]

Techniques	Frein 1		Frein 2		Frein 3		Frein 4		Frein 5		Total
	n	%	n	%	n	%	n	%	n	%	n
Le coût	97	58,1%	32	19,8%	10	6,5%	10	7,8%	2	1,8%	151
L'absence de demande du maitre d'ouvrage	31	18,6%	30	18,5%	14	9,1%	14	10,9%	8	7,2%	97
La difficulté d'intégration esthétique	4	2,4%	15	9,3%	16	10,4%	14	10,9%	10	9,0%	59
La difficulté d'intégration technique (difficulté de mise en œuvre, compatibilité avec d'autres techniques constructives (isolation, menuiserie extérieure))	6	3,6%	9	5,6%	23	14,9%	6	4,7%	6	5,4%	50
Les possibles nuisances liées au système (l'impact sur la vue extérieure, sur la lumière entrante, etc.)	3	1,8%	13	8,0%	15	9,7%	9	7,0%	5	4,5%	45
Le manque de valorisation dans les certificats PEB	1	0,6%	7	4,3%	9	5,8%	11	8,5%	14	12,6%	42
L'absence de primes	3	1,8%	8	4,9%	13	8,4%	9	7,0%	8	7,2%	41
L'entretien nécessaire (coût et fréquence)	4	2,4%	9	5,6%	7	4,5%	12	9,3%	8	7,2%	40
L'influence potentielle de l'utilisateur dans l'efficacité pratique	5	3,0%	3	1,9%	9	5,8%	8	6,2%	8	7,2%	33
Le manque d'obligation légale	6	3,6%	5	3,1%	5	3,2%	5	3,9%	9	8,1%	30
La coordination nécessaire avec les différents corps de métier	1	0,6%	5	3,1%	4	2,6%	5	3,9%	9	8,1%	24
La complexité de gestion pour les occupants	2	1,2%	6	3,7%	8	5,2%	3	2,3%	4	3,6%	23
Leur durée de vie	1	0,6%	4	2,5%	7	4,5%	8	6,2%	3	2,7%	23
Le manque de cohérence avec d'autres réglementations (réglementation sur le patrimoine)	2	1,2%	3	1,9%	7	4,5%	2	1,6%	5	4,5%	19
Le temps de travail nécessaire et/ou les moyens disponibles pour étudier/évaluer l'intérêt du dispositif	0	0,0%	6	3,7%	3	1,9%	4	3,1%	4	3,6%	17
Le manque d'efficacité/fiabilité de la technique	1	0,6%	2	1,2%	3	1,9%	3	2,3%	6	5,4%	15
Le manque de savoir faire des corps de métiers	0	0,0%	4	2,5%	1	0,6%	6	4,7%	2	1,8%	13
La disponibilité limitée du produit (stock, délai de livraison)	0	0,0%	1	0,6%	0	0,0%	0	0,0%	0	0,0%	1
Total	167	100,0%	162	100,0%	154	100,0%	129	100,0%	111	100,0%	

D'après votre expérience professionnelle, qu'est-ce qui empêche le plus le placement de protections solaires extérieures dans vos projets de logement(s) [Classement-2]



Selon vous, qu'est-ce qui permettrait de mieux intégrer les protections solaires extérieures dans vos projets de logement(s)[Texte long]

L'obligation légale	L'évaluation du risque de surchauffe dès le début de Meilleure résistance dans le tempsmeilleure prise en compte p
la conception	- Protection solaire extérieure fixe architecturale = . La première raison étant le cout, il es difficile de jouer sur ce p
Une meilleure information auprès des architectes, un cadre légale	des entrepreneurs mieux sensibilisé à ces techniques,prise en compte dès le départ et remplacement plus aisé en cas
obligation PEB	Qu'elles soient intégrées au verre ! Une volonté du maitre d'ouvrage + un indicateur PEB + sévèr
une garantie de fiabilité dans le temps	Une meilleur sensibilisation des maitres de l'ouvrag nous savons les intégrer mais les entreprises font souvent des v
imposer une limite de surchauffe comme pour les bâtiments neufs.	Sensibiliser le public au fait que la protection à la si Obligation légale
L'architecture sensibilisé	Du temps pour expliquer. meilleur information auprès des clients et entrepreneurs
L'obligation légale serait vraiment l'idéale , seulement l'auvent e	Le coût de construction est tellement élevé, les prote Une vrais communication au niveau Wallonie en relation avec
Une prise de conscience des propriétaires de la nécessité des systè	De meilleures connaissances sur leur mise en oeuvr. La sensibilisation
il faudrait que les architectes le prevois dans la conception global	L'apprentissage du client ?
Plus d'informations, de retour d'expériences....	Plus de budget Principalement réduire les budgets. Beaucoup de propriétaire
L'adaptation des règles urbanistiques (voir obligation) sur les dép	Expliquer davantage l'interet et l'impact de protecti Il faudrait plus sensibiliser les maîtres d'ouvrage et les archite
diminution du prix	Je ne vois pas L'obligation (indicateur de surchauffe plus faible)
-	un cout moins important, un plus bel esthétique pou imposition de la PEB
Une diminution des coûts de manière générale dans la construction	Sauf cas particuliers, il est assez facile d'intégrer de un coût plus accessible
permettre une évaluation rapide et facile de l'impact en terme de co	Une meilleure connaissance : 1. Des nuisances pote Une meilleure prise de conscience des maîtres d'ouvrage
L'information	Diminuer le coût via des primes et sensibiliser les fa Malheureusement, nous avons d'autres priorités
Faire prendre conscience aux donneurs d'ordre et concepteurs de l	Que les protections solaires extérieures (BSO, scree les promoteurs n'aiment pas ces systèmes pour l'entretien de co
obligation	Des exemples simples d'impact(s) chiffrés de la surc /
Un exposé claaire des avantage, inconvénients, cout et amortisseme	Pour ma part, je fais principalement des audits éner Le coût.
Obligation légale et souplesse des règles d'urbanisme	Une mise en avant de l'intérêt et des avantages d'un mieux les valoriser, avoir des personnes compétentes et formée
une obligation	Diminution du coût pour le MO (plus facteur sur le . Pas d'avis sur cette question (pas de blocage particulier sur le
le coût	sensibiliser le publique pour qu'il aie conscience qu Réduire leur coût plus informer de leur utilitéFaciliter leur fon
Une obligation légale et des primes correctes.	Du point de vue de l'encodage dans le logiciel de Re Une plus grande sensibilisation. Les candidats constructeurs n
dans le cas ou des primes seraient accordée ainsi que l'inclusion d	Primes régionales Une meilleure legislation.
Réglementation cohérente	Un module de calcul digne de ce nom n'existe pas d
De la pub vulgarisant les effets T° intérieur avec et sans protection	Plus d'information de la part des pouvoirs publics :
-	Des produits adaptés aux techniques de construction
oui	La première choses à faire est ce convaincre l'urban
Une meilleur sensibilisation des prescripteurs	Un changement dans les méthodologies de calculs r
Comme pour tout, une sensibilisation à l'utilité	primes, rapport monitoré de cas concret
Ils doivent être attractifs au niveau PEB à respecter.Si la demande ?	?
-	Chaque projet est réalisé à la carte. Souvent, une pr
Aucune idée	xx
Des meilleures recommandations et méthodes de conception	prime
Obligation de permis pour certains systèmes	La sensibilisation du maître d'ouvrage et de l'archit
Le coût de la protection (type screen ou claustra) est vraiment imp	C'est presque de "l'imposer" par la région
Est-ce que la question concerne les protections électriques ?	Les pr Normes d'urbanisme trop figées

Selon vous, qu'est-ce qui permettrait de mieux intégrer les protections solaires extérieures dans vos projets de logement(s)[Texte long] - suite

Legal obligation (as in Suisse) and at least a better appreciation of Une meilleure intégration de la surchauffe dans le c
des honoraires plus généreux ;) un système d'évaluation des besoin La sensibilisation du maître d'ouvrage, le PEB qui devrait encourager davantage la conception bioclimatique
Conscientisation de leur efficacité et de leur nécessité auprès du cl. Le Changement climatique : comme il est en cours, les Architectes et les entrepreneurs vont de plus en plus en tenir
La prise de conscience par les utilisateurs de l'importance d'utilise Rien. Je les prévois d'office et en général, elles sont posées.
/
Répondre au problème du coût Avoir une meilleure connaissance des produits, de leur coûts, de l'impact, etc, permettrait de pouvoir mieux conseil
La difficulté chez nous se retrouve surtout au niveau de la rénovation une obligation réglementaire et une intégration dans les chiffres clés tels que la PEB
Une étude des détails exécutés suffisamment aboutie avant mise en œuvre Certaines protections s'intègrent bien
- Les clients sont rarement demandeurs et n'ont pas conscience de l'importance de la gestion de la surchauffe dans le
Méthode de dimensionnement clair permettant de démontrer- la prise de conscience davantage le maître d'ouvrage concernant le risque de surchauffe des bâtiments. Beaucoup de candidatures
Une méthode de calcul simple à utiliser et fiable Une étude spécifique (et pas un simple voyant) dans l'étude PEB
Des primes Mieux informer le public sur les avantages et les différentes alternatives techniques
Pour les promoteurs privés: seule une obligation légale pourrait favoriser la sensibilisation des architectes (à l'importance de la protection ainsi qu'au choix adapté selon l'orientation.) Ne pas pr
Augmenter le "potentiel de séduction" de ce type de dispositifs. Parce que les architectes tiennent compte de la problématique des surchauffes dès les esquisses du projet
Obligation La diminution du coût des screens
Les protections solaires font partie d'un tout et sont intimement liées - Conscientiser les maîtres de l'ouvrage sur l'importance des protections solaires. - Le coût moins importants des dispositifs
Une meilleure connaissance dans le public des techniques envisagées Intégration architecturale dans le projet dès les premières esquisses.
Sans doute que des primes aideraient, car le coût a souvent été un frein à l'obliger via une loi
-
l'habitude L'obligation légale
Des primes parce que le coût est souvent l'obstacle primordial. -
On les prescrit souvent. Il est ensuite au maître d'ouvrage d'en voir Dans les projets PEB, les protections solaires extérieures donnent très peu de résultat quand le bâtiment est équipé
Je ne sais pas La volonté du Maître d'ouvrage
Une prime éventuelle. En PEB, pour les unités de logement mono-orientées on n'a pas le choix de proposer ces solutions parce que le projet est
un coût inférieur, des primes. C'est déjà proposé et bien intégré mais c'est la mise en évidence du risque dans la PEB qui n'est pas correctement intégrée
la prise en compte dès le début de la conception Des primes
Je n'en vois pas l'utilité diminution du coût
Une baisse des coûts Des meilleurs incitatifs législatifs et économiques ainsi qu'une meilleure communication sur leur utilité
Une imposition réglementaire Les prévoir dès la conception
Les projets contemporains permettent de mieux intégrer les protections solaires Education du public et des architectes sur les problèmes de surchauffe en Belgique et le fait que les gains solaires sont
pas de réponse Avoir un architecte compétent et sensibilisé
Responsabilisation des MO une prise de conscience de leur efficacité par les architectes...
L'évaluation du risque de surchauffe dès le début de la conception. Meilleure résistance dans le temps meilleure prise en compte par les architectes

Votre usage des techniques de refroidissement par ventilation

Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Sur ces projets*, avez-vous envisagé les techniques suivantes ? » sous-question

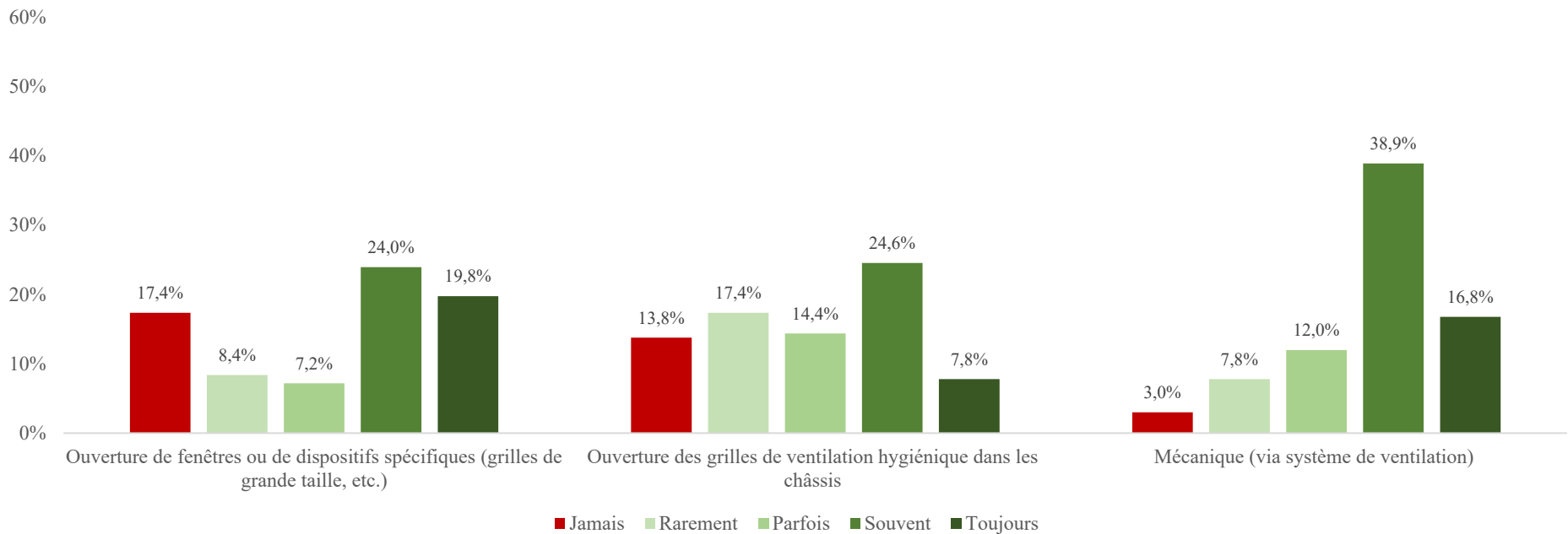
Sur vos projets de logement(s)*, quel(s) type(s) de dispositif(s) permettant la dissipation de chaleur par ventilation avez-vous envisagé(s)** ?

[Choix unique par ligne]

*réalisé au cours des deux dernières années, un projet pouvant contenir un ou plusieurs logements

**même si non réalisé

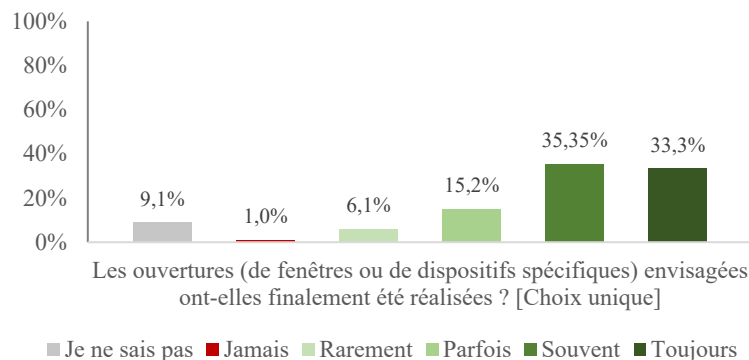
Dispositifs	Jamais		Rarement		Parfois		Souvent		Toujours		Je ne sais pas		Total	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Ouverture de fenêtres ou de dispositifs spécifiques (grilles de grande taille, etc.)	29	17,4%	14	8,4%	12	7,2%	40	24,0%	33	19,8%	4	2,4%	132	89,8%
Ouverture des grilles de ventilation hygiénique dans les châssis	23	13,8%	29	17,4%	24	14,4%	41	24,6%	13	7,8%	2	1,2%	132	89,8%
Mécanique (via système de ventilation)	5	3,0%	13	7,8%	20	12,0%	65	38,9%	28	16,8%	1	0,6%	132	89,8%



Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Sur vos projets de logements, quel(s) type(s) de dispositif(s) permettant la dissipation de

Les ouvertures (de fenêtres ou de dispositifs spécifiques) envisagées ont-elles finalement été réalisées ? [Choix unique]

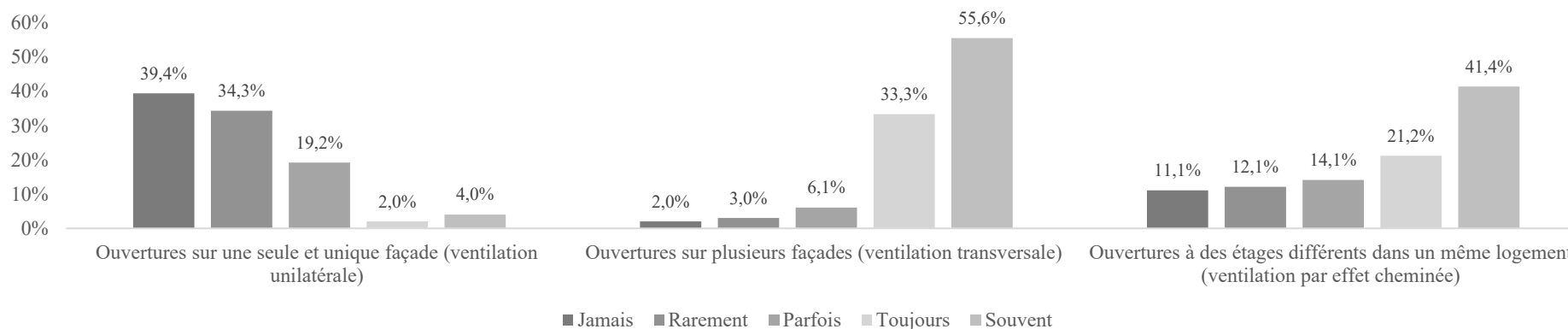
Réponse	n	%
Jamais	1	1,0%
Rarement	6	6,1%
Parfois	15	15,2%
Souvent	35	35,4%
Toujours	33	33,3%
Je ne sais pas	9	9,1%
Total	99	100,0%



Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Sur vos projets de logements, quel(s) type(s) de dispositif(s) permettant la dissipation de

Parmi vos projets comprenant ces possibilités d'ouverture de fenêtres ou de dispositifs spécifiques, quelle(s) stratégie(s) de ventilation avez-vous envisagée(s)* ?

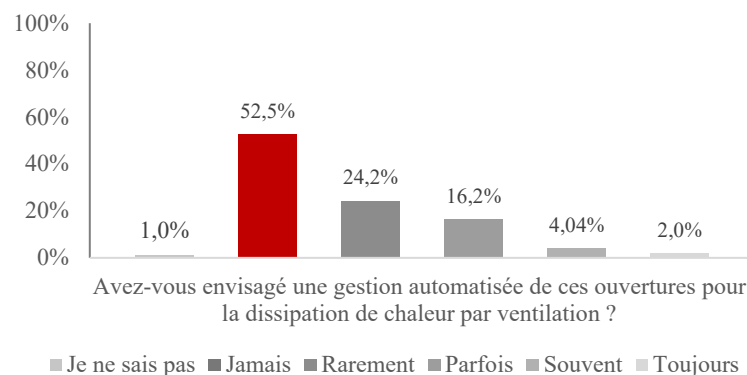
Dispositifs	Jamais		Rarement		Parfois		Souvent		Toujours		Je ne sais pas		Total	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Ouvertures sur une seule et unique façade (ventilation unilatérale)	39	39,4%	34	34,3%	19	19,2%	4	4,0%	2	2,0%	1	1,0%	99	100,0%
Ouvertures sur plusieurs façades (ventilation transversale)	2	2,0%	3	3,0%	6	6,1%	55	55,6%	33	33,3%	0	0,0%	99	100,0%
Ouvertures à des étages différents dans un même logement (ventilation par effet cheminée)	11	11,1%	12	12,1%	14	14,1%	41	41,4%	21	21,2%	0	0,0%	99	100,0%



Conditions : si réponse « rarement » ou « parfois » ou « souvent » ou « toujours » à « Sur vos projets de logements, quel(s) type(s) de dispositif(s) permettant la dissipation de

Avez-vous envisagé une gestion automatisée de ces ouvertures pour la dissipation de chaleur par ventilation ?

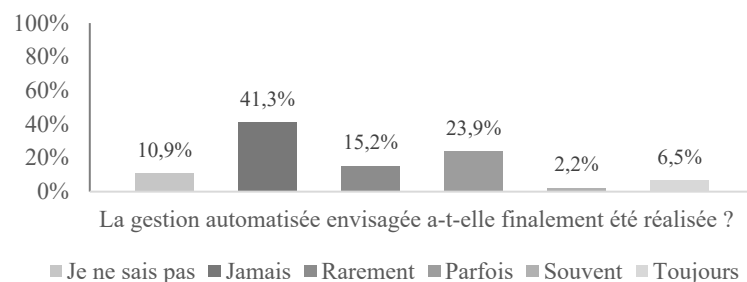
Réponse	n	%
Jamais	52	52,5%
Rarement	24	24,2%
Parfois	16	16,2%
Souvent	4	4,0%
Toujours	2	2,0%
Je ne sais pas	1	1,0%
Total	99	100,0%



La gestion automatisée envisagée a-t-elle finalement été réalisée ?

*présente à la fin du chantier

Réponse	n	%
Jamais	19	41,3%
Rarement	7	15,2%
Parfois	11	23,9%
Souvent	1	2,2%
Toujours	3	6,5%
Je ne sais pas	5	10,9%
Total	46	100,0%



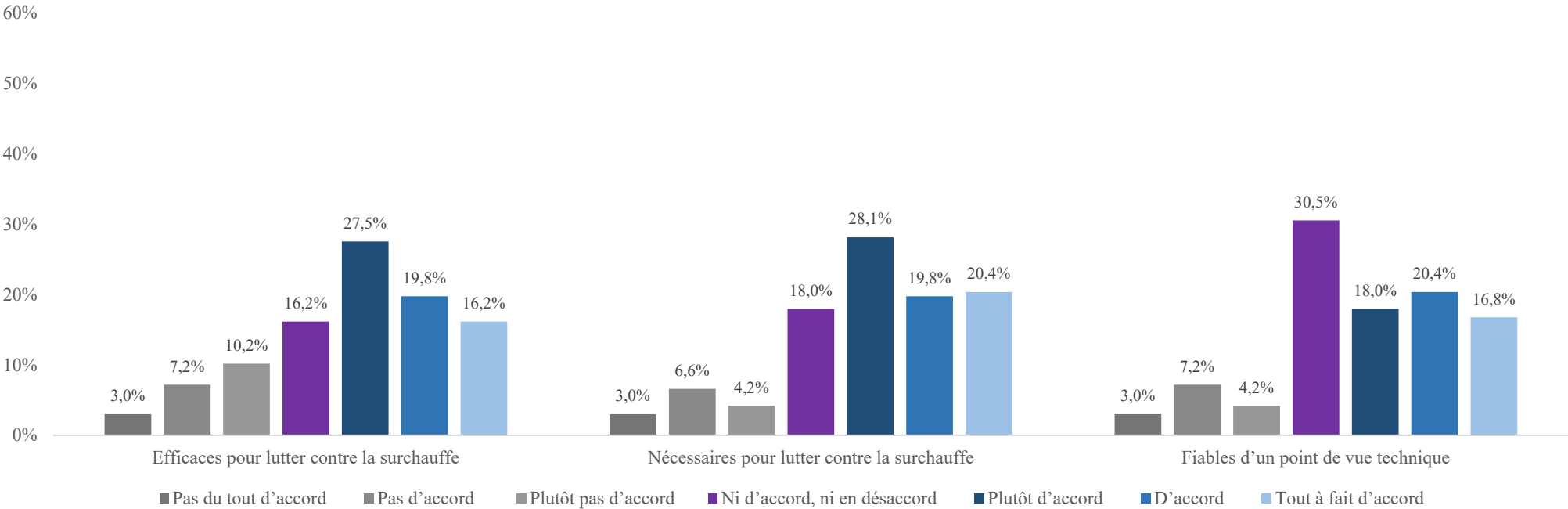
Votre perception des techniques de refroidissement par ouverture de fenêtres

Par technique de refroidissement par ouverture de fenêtres, nous entendons une ventilation réalisée par ouverture de fenêtres provoquant un renouvellement d'air important
Les questions qui suivent se basent sur cette définition et n'interrogent pas la ventilation hygiénique, réalisée pour la qualité de l'air.

Que pensez-vous personnellement des techniques des affirmations suivantes ?

En Belgique, les techniques de refroidissement par ouverture de fenêtres dans les logements sont...

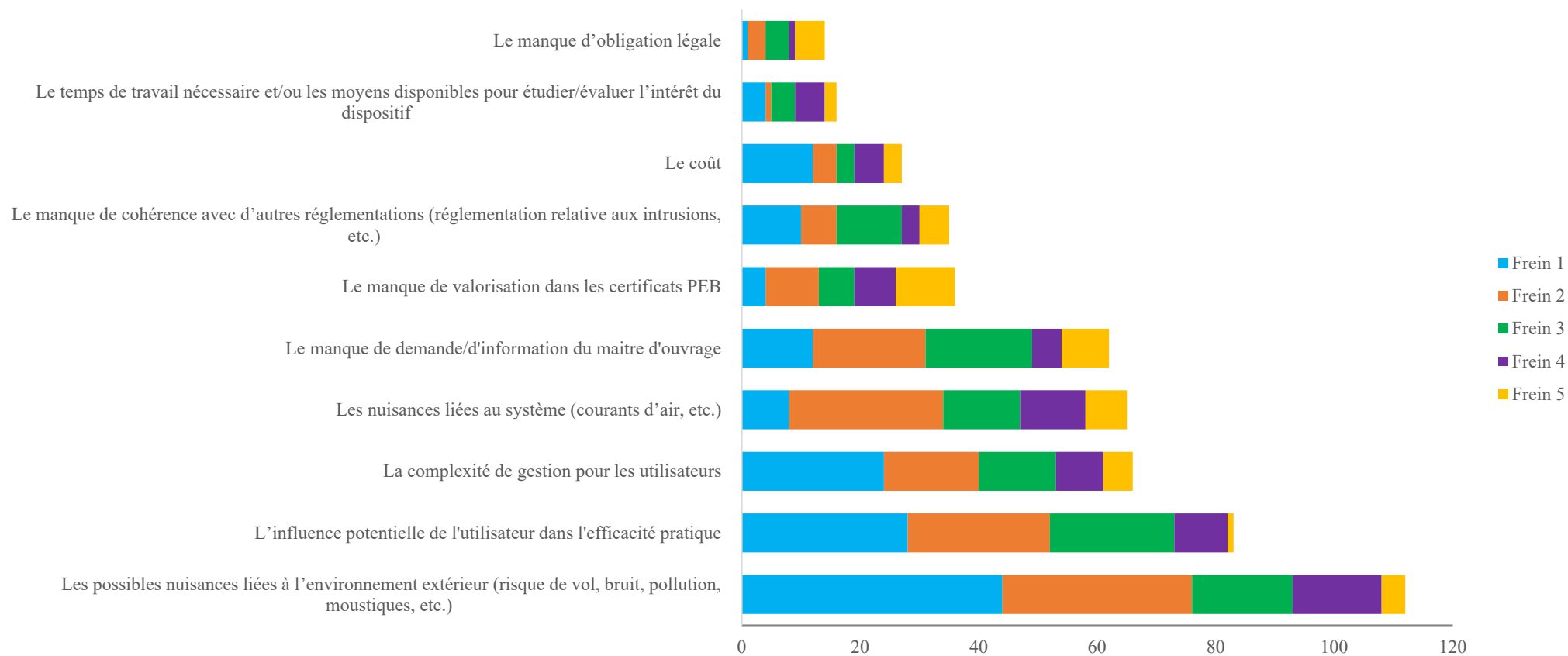
Dispositifs	Pas du tout		Pas d'accord		Plutôt pas		Ni d'accord, ni en		Plutôt d'accord		D'accord		Tout à fait	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Efficaces pour lutter contre la surchauffe	5	3,0%	12	7,2%	17	10,2%	27	16,2%	46	27,5%	33	19,8%	27	16,2%
Nécessaires pour lutter contre la surchauffe	5	3,0%	11	6,6%	7	4,2%	30	18,0%	47	28,1%	33	19,8%	34	20,4%
Fiabiles d'un point de vue technique	5	3,0%	12	7,2%	7	4,2%	51	30,5%	30	18,0%	34	20,4%	28	16,8%



D'après votre expérience professionnelle, qu'est-ce qui empêche le plus d'encourager le refroidissement par ouverture de fenêtres dans vos projets de logement(s) ?
[Classement]

Techniques	Frein 1		Frein 2		Frein 3		Frein 4		Frein 5		Total
	n	%	n	%	n	%	n	%	n	%	n
Les possibles nuisances liées à l'environnement extérieur (risque de vol,	44	26,3%	32	21,3%	17	14,8%	15	20,3%	4	7,3%	112
L'influence potentielle de l'utilisateur dans l'efficacité pratique	28	16,8%	24	16,0%	21	18,3%	9	12,2%	1	1,8%	83
La complexité de gestion pour les utilisateurs	24	14,4%	16	10,7%	13	11,3%	8	10,8%	5	9,1%	66
Les nuisances liées au système (courants d'air, etc.)	8	4,8%	26	17,3%	13	11,3%	11	14,9%	7	12,7%	65
Le manque de demande/d'information du maître d'ouvrage	12	7,2%	19	12,7%	18	15,7%	5	6,8%	8	14,5%	62
Le manque d'efficacité/fiabilité de la technique	20	12,0%	10	6,7%	5	4,3%	5	6,8%	5	9,1%	45
Le manque de valorisation dans les certificats PEB	4	2,4%	9	6,0%	6	5,2%	7	9,5%	10	18,2%	36
Le manque de cohérence avec d'autres réglementations (réglementation relative aux intrusions, etc.)	10	6,0%	6	4,0%	11	9,6%	3	4,1%	5	9,1%	35
Le coût	12	7,2%	4	2,7%	3	2,6%	5	6,8%	3	5,5%	27
Le temps de travail nécessaire et/ou les moyens disponibles pour étudier/évaluer l'intérêt du dispositif	4	2,4%	1	0,7%	4	3,5%	5	6,8%	2	3,6%	16
Le manque d'obligation légale	1	0,6%	3	2,0%	4	3,5%	1	1,4%	5	9,1%	14
Total	167	100,0%	150	100,0%	115	100,0%	74	100,0%	55	100,0%	

D'après votre expérience professionnelle, qu'est-ce qui empêche le plus d'encourager le refroidissement par ouverture de fenêtres dans vos projets de logement(s) ?
[Classement-2]



Selon vous, quels sont les éléments qui permettraient de mieux intégrer le refroidissement par ouverture de fenêtres dans vos projets de logement(s) ? [Texte long]

Une obligation légale	/	Ce ne sont pas nos priorités
c'est moche et pas efficace	l'apprentissage du client	sensibilisation et valorisation plus importante dans
Aucun	Plus de budget	/
aucun	Informé l'occupant	La réduction du risque d'effraction.
sans avis	Pas toujours réaliste à cause du bruit environnant	pas assez valorisé en PEB car trop restrictif
je ne suis pas convaincu de la possibilité de refroidir efficacement un l ?		L'intégrer en amont dans la conception
L'esthétique	Un quartier calme et un moustiquaire	Je ne trouve pas qu'on refroidit en été en ouvrant les
Si vous ouvrez les fenêtres, il faut éviter les fenêtres côté soleil	Une meilleure connaissance des bienfaits du refroid	une meilleure information sur les systèmes automati
la prise de conscience par l'occupant d'une bonne gestion du système.	Meilleure éducation des utilisateurs car cela est sim	
le manque d'information	Peut-être une programmation électronique avec fer	
une meilleure information aux utilisateurs	pas d'opinion.	
La sensibilisation des architectes envers leurs clients	Pour ma part, je fais principalement des audits éner	
?	Meilleure information sur le principe de ventilation	
Education des locataires	Élargissement de la palette des produits châssis pro	
Une meilleure information des locataires. Dans des logements sociaux, c'est un comportement très adopté par les utilisateur		
une méthode d'évaluation facile et simple de l'efficacité	?	
L'information	Sensibilisation/Ouvertures automatiques	
Toutes les études montrent le manque d'efficacité du système. Voir mo	Lorsque l'air extérieur est plus chaud que l'air intéri	
obligation	100,0%	
exposer les avantages et inconvénients clairement. Détailler les coût et rien		
Expliquer une bonne gestion à l'occupant et que celui-ci la respecte	Informé	
Une explication	Une modification de la réglementation PEB	
l'information	information de sensibilisation des occupant via prat	
En été, un A.O.R. amène de la chaleur dans le bâtiment qu'il soit ouvert ?		
La micro ventilation des fenêtres	Système intégré dans un châssis avec grilles RENSC	
Réglementation cohérente	xx	
???	Aucun	
-	La sensibilisation du maître d'ouvrage et de l'archite	
oui	Il faudrait une sécurité et une automatisation.	
Il faudrait pouvoir analyser chaque projet afin de proposer une solutio	Une formation correcte	
Une meilleure compréhension des intérêts et des méthodes efficaces	Avec le réchauffement climatique, les habitants com	
Les ventilations de type c sont plutôt économiques. Il faut cependant sc	Valorisation PEB basée sur la conception et moins s	
-	Entrée et sortie d'air par des ouvertures sécurisées c	

Selon vous, quels sont les éléments qui permettraient de mieux intégrer le refroidissement par ouverture de fenêtres dans vos projets de logement(s) ? [Texte long]- suite 1

<i>Aucune idée</i>	<i>Une meilleure information du public sur la gestion c</i>
<i>Pratique des occupants</i>	<i>Au niveau PEB, ce refroidissement n'est repris que c</i>
<i>Les utilisateurs ne sont pas demandeurs</i>	<i>formation des occupants</i>
<i>Nous ne pratiquons que rarement cela, mais peut-être une meilleure in ?</i>	
<i>A ma connaissance, il n'existe aucun logement sans fenêtre ouvrante (</i>	<i>Si nightcooling, Pas forcément nécessaire. En plus l</i>
<i>A better support by the manufacturers of these devices in the dimension</i>	<i>La plupart des clients n'ont pas conscience du mom</i>
<i>Suite- Selon vous, quels sont les éléments qui permettraient de mieux intégrer le refroidissement par ouverture de fenêtres dans vos projets de logement(s) ? [Texte lon</i>	
<i>sécurité des fenêtres ouverte en oscillo par rapport aux intrusions, pou</i>	<i>Egalement conscientiser davantage le maître d'ouvr</i>
<i>Il me semble difficile de préconiser une ventilation intensive dans du lc</i>	<i>Une étude prouvant les bienfaits.</i>
<i>/</i>	<i>Meilleure information du public</i>
<i>une meilleure compréhension du dispositif par l'utilisateur</i>	<i>Avoir des études paramétriques sur les renouveleme</i>
<i>Question pas très claire pour moi, ou qui manque un peu de nuance...a</i>	<i>Sensibiliser les MO; souvent totalement incompéten</i>
<i>Une prise en compte de l'aspect sécurité lié à l'ouverture de fenetre</i>	<i>La ventilation intensive de nuit lorsque la chaleur es</i>
<i>-</i>	<i>Une demande du maître de l'ouvrage</i>
<i>Idem question précédente</i>	<i>Coordination dès le début du projet avec l'architect</i>
<i>Simulation simple et fiable</i>	<i>un système sécurisé pour les vols</i>
<i>Des primes</i>	<i>.</i>
<i>En général les ouvertures de fenêtres sont très bien intégrées par les a ?</i>	
<i>De manière très concrète, dans des logements sociaux nous n'avons pa-</i>	
<i>Information aux occupants</i>	<i>C'est quasi obligatoire de l' intégrer dans les études</i>
<i>Sensibiliser et "former" le MO de l'ouvrage à la gestion du système en</i>	<i>Diminuer les exigences et contrainte de ventilation l</i>
<i>Le MO doit réfléchir avec l'architecte pour bien gérer le système lors c</i>	<i>Eviter les unités de logement mono-orientées</i>
<i>Il me semble que c'est surtout la législation PEB qui poussent actuelle</i>	<i>Pas l'habitude d'avoir de grands éléments avec grill</i>
<i>-</i>	<i>Informers les occupants</i>
<i>a nouveau, un changement d'habitude des acteurs du secteur comme d ?</i>	
<i>Sensibilisation</i>	<i>Des exemples concrets de réalisation efficace et un</i>
<i>/</i>	<i>Rien</i>
<i>Je ne sais pas</i>	<i>En général mes projets ont pratiquement toujours ui</i>
<i>Il est difficile de contrôler l'usage du bâtiment par les occupants donc</i>	<i>Informers</i>
<i>c'est avant tout lié au programme du projet et sa faisabilité financière. on est malheureusement limité par le climat. S'il fait</i>	
<i>formation de l'utilisateur a bien utiliser la technique.</i>	<i>sans objet</i>
<i>aucun</i>	<i>Conscientisation du public de l'efficacité du disposit</i>
<i>Plus communiquer avec les occupants pour leur faire comprendre com</i>	<i>Je n'ai pas d'idée</i>
<i>Une imposition réglementaire</i>	<i>Un système de suivi de la température</i>

Selon vous, quels sont les éléments qui permettraient de mieux intégrer le refroidissement par ouverture de fenêtres dans vos projets de logement(s) ? [Texte long]- suite 2

Petites fenêtres ou fenêtre très étroite (éviter risque d'intrusion) en par solutions simplifiées et plus claires des fabricants

Une meilleure information auprès du maître de l'ouvrage pas d'éléments qui me viennent à l'esprit

-

Une meilleure sensibilisation des occupants, mais c'est avant tout lié à Une communication claire, avec des outils simples et

Ventilation se faisant naturellement par l'occupant si tant est que la co Prime

sensibilisation au grand public et la démocratisation des systèmes de lu -

La législation et les normes en la matière

une meilleure sensibilisation du grand public

difficile à dire car cette solution doit être couplée à d'autres

le temps pour expliquer et faire comprendre.

?

?

Le problème principal étant la sécurité, il est difficile

Selon moi, l'efficacité de ce système dépend beaucoup

Aucune idée

?

obliger une étude du positionnement des fenêtres par

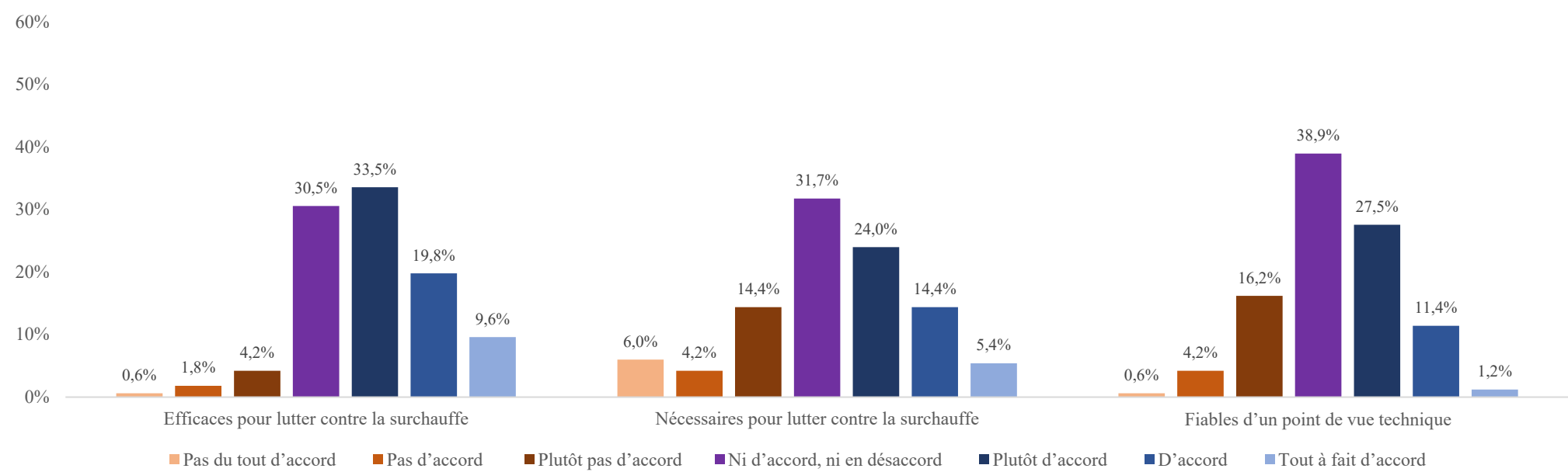
Une meilleure information sur les systèmes d'automatisme

Votre perception de la gestion automatisée

La gestion automatisée est définie dans ce qui suit comme une gestion motorisée et automatique de l’ouverture/fermeture d’un dispositif sur base de paramètres d’ambiance

Que pensez-vous personnellement des affirmations suivantes ?
 En Belgique, les systèmes de gestion automatisée dans les logements sont...

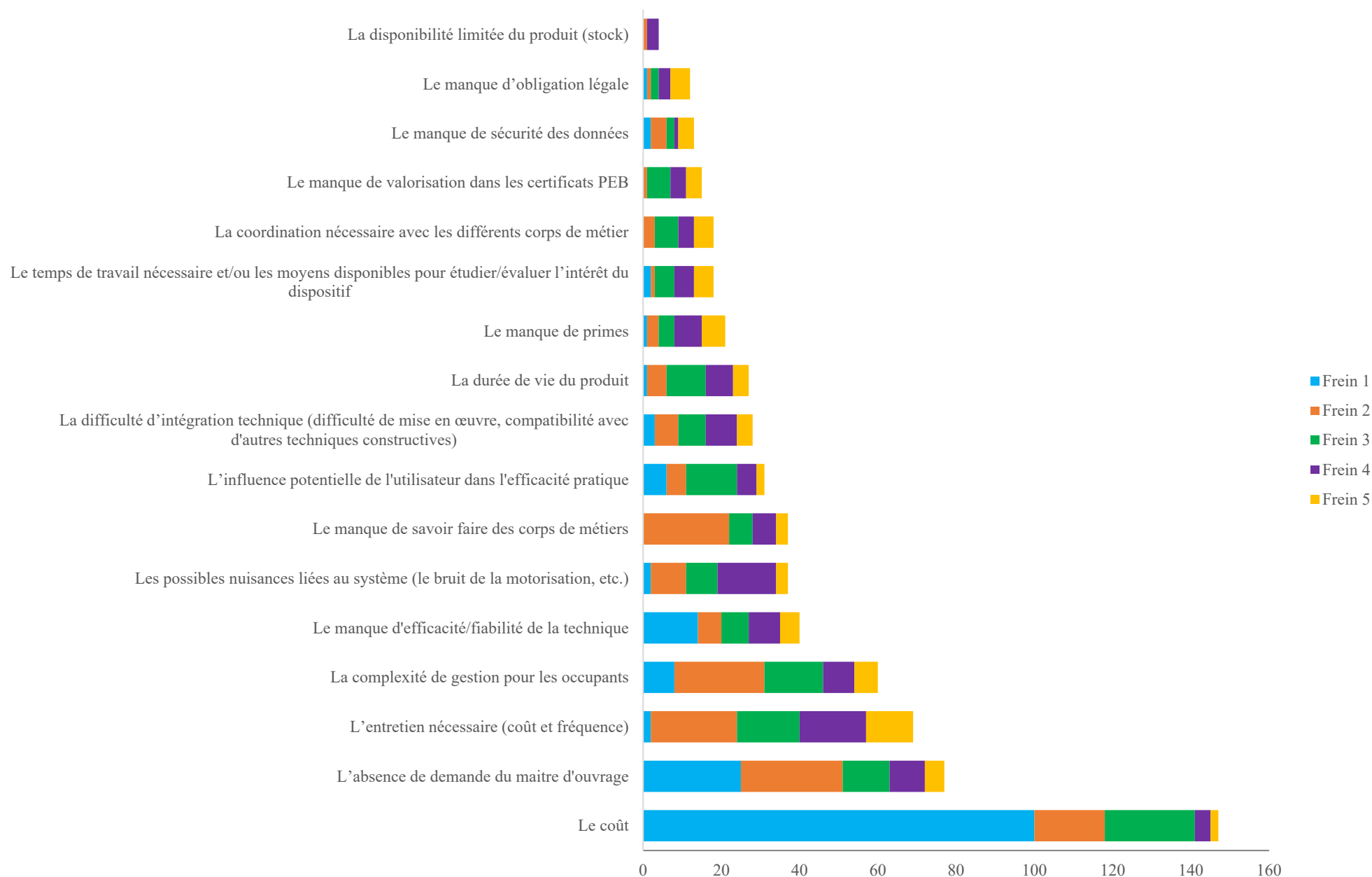
Dispositifs	Pas du tout d'accord		Pas d'accord		Plutôt pas d'accord		Ni d'accord, ni en désaccord		Plutôt d'accord		D'accord		Tout à fait d'accord	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Efficaces pour lutter contre la surchauffe	1	0,6%	3	1,8%	7	4,2%	51	30,5%	56	33,5%	33	19,8%	16	9,6%
Nécessaires pour lutter contre la surchauffe	10	6,0%	7	4,2%	24	14,4%	53	31,7%	40	24,0%	24	14,4%	9	5,4%
Fiables d'un point de vue technique	1	0,6%	7	4,2%	27	16,2%	65	38,9%	46	27,5%	19	11,4%	2	1,2%
Plus fiables que la gestion utilisateur pour garantir le confort estival	6	3,6%	3	1,8%	22	13,2%	50	29,9%	38	22,8%	32	19,2%	16	9,6%



D'après votre expérience professionnelle, qu'est-ce qui limite le plus l'intégration de systèmes de gestion automatisée dans vos projets de logement(s) ? [Classement]

Techniques	Frein 1		Frein 2		Frein 3		Frein 4		Frein 5		Total	
	n	%	n	%	n	%	n	%	n	%	n	
Le coût	100	59,9%	18	11,5%	23	16,2%	4	3,5%	2	2,7%	147	1336,4%
L'absence de demande du maitre d'ouvrage	25	15,0%	26	16,7%	12	8,5%	9	7,9%	5	6,7%	77	700,0%
L'entretien nécessaire (coût et fréquence)	2	1,2%	22	14,1%	16	11,3%	17	14,9%	12	16,0%	69	627,3%
La complexité de gestion pour les occupants	8	4,8%	23	14,7%	15	10,6%	8	7,0%	6	8,0%	60	545,5%
Le manque d'efficacité/fiabilité de la technique	14	8,4%	6	3,8%	7	4,9%	8	7,0%	5	6,7%	40	363,6%
Les possibles nuisances liées au système (le bruit de la motorisation, etc.)	2	1,2%	9	5,8%	8	5,6%	15	13,2%	3	4,0%	37	336,4%
Le manque de savoir faire des corps de métiers	0	0,0%	22	14,1%	6	4,2%	6	5,3%	3	4,0%	37	336,4%
L'influence potentielle de l'utilisateur dans l'efficacité pratique	6	3,6%	5	3,2%	13	9,2%	5	4,4%	2	2,7%	31	281,8%
La difficulté d'intégration technique (difficulté de mise en œuvre, compatibilité avec d'autres techniques constructives)	3	1,8%	6	3,8%	7	4,9%	8	7,0%	4	5,3%	28	254,5%
La durée de vie du produit	1	0,6%	5	3,2%	10	7,0%	7	6,1%	4	5,3%	27	245,5%
Le manque de primes	1	0,6%	3	1,9%	4	2,8%	7	6,1%	6	8,0%	21	190,9%
Le temps de travail nécessaire et/ou les moyens disponibles pour étudier/évaluer l'intérêt du dispositif	2	1,2%	1	0,6%	5	3,5%	5	4,4%	5	6,7%	18	163,6%
La coordination nécessaire avec les différents corps de métier	0	0,0%	3	1,9%	6	4,2%	4	3,5%	5	6,7%	18	163,6%
Le manque de valorisation dans les certificats PEB	0	0,0%	1	0,6%	6	4,2%	4	3,5%	4	5,3%	15	136,4%
Le manque de sécurité des données	2	1,2%	4	2,6%	2	1,4%	1	0,9%	4	5,3%	13	118,2%
Le manque d'obligation légale	1	0,6%	1	0,6%	2	1,4%	3	2,6%	5	6,7%	12	109,1%
La disponibilité limitée du produit (stock)	0	0,0%	1	0,6%	0	0,0%	3	2,6%	0	0,0%	4	36,4%
Total	167	100,0%	156	100,0%	142	100,0%	114	100,0%	75	100,0%		

D'après votre expérience professionnelle, qu'est-ce qui limite le plus l'intégration de systèmes de gestion automatisée dans vos projets de logement(s) ? [Classement]



Selon vous, qu'est-ce qui permettrait de mieux intégrer des systèmes de gestion automatisée dans vos projets de logements ? [Texte long]

Les primes des aides financières pour le client /
pas pour moi Plus de budget ..
Une approche dès le début du projet avec une valorisation et un aperçu de l'information au MO .
aucune Je ne vois pas Selon moi ce n'est pas à intégrer. Cela entraîne une c
convaincre que cela ne rajoute pas en complexité, et convaincre de l'intérêt au par exemple, lorsqu'il s'agit de screen extérieur, si le Réduir le coût Mieux informer sur l'utilité Valoriser
- Cette solution ne peut être qu'en soutien d'autres me: une meilleure information sur les systèmes automati
L'information Une connaissance de l'approche coût/bénéfice et de toujours la législation qui ne prend pas en compte to
Dans ce que vous appeler la gestion automatisée, vous en venez à la do Diminuer le coût
Une bonne connaissance des systèmes de régulation et une prise de conscienc Des systèmes performants plus abordables et bénéfici
une information mieux et plus diffusée aucune idée
une meilleure approche, une meilleure information, Pour ma part, je fais principalement des audits énergi
L'étude de départ par l'architecte Meilleure information des principes de ventilation ai
? Coût élevé Complexité d'un point de vue programm
- Sensibiliser les utilisateurs au fait que ça peut être ass
Encore une fois, une diminution des coûts de manière générale. L'automatisation -
démontrer son intérêt Primes
L'information S'il est démontré par un calcul fiable que cela apport
Former les architectes et bureau d'études à la problématique. (On a toujours d 100,0%
prix moindre une communication plus importante auprès des occup
L'information Je ne suis pas partisane du tout automatique, éduquer
?? Sans avis
une explication préfère sensibiliser l'occupant à comment utiliser son
l'information ?
C'est top ... mais onéreux d'avoir une bonne GTC Plus de fiabilité, moins d'entretien, ... Convient mieu
aucune idée xx
Avoir un système simple pour le plus grand monde p
Une garantie longue durée intervention 24/24 7/7. Je n'ai pas d'avis
- Les prévisions plus souvent et directement dès le début
pui Informations complètes au client, impossible dans le
L'obligation réglementaire est présente, mais les mentalités sont plus dures à Rien, je suis persuadé qu'on doit davantage aller ver
Je ne sais pas Une approche globale, où la gestion automatisée vie
Plus de point de vue et/ou un coût inférieur Je suis pour le low tech. La ventilation naturelle est
- Des primes ? Dans tous les cas, j'essaie de rester le
Aucune idée Meilleure connaissance du produit, fiche technique c
Des systèmes simples plus d'information à ce sujet et une démocratisation
Les utilisateurs ne sont pas toujours demandeurs ... membre si les systèmes c ?
Pas assez d'expérience dans ce domaine. Le prix et le prix lié à coordination
Voir réponses précédentes De tels systèmes de gestion automatisée passent gén
There is a serious lack of knowledge on these kind of solutions at the level of Faire comprendre au maître d'ouvrage qu'un gestion ai
Je ne suis pas du tout adepte de l'augmentation de la dépendance technologique Une baisse des coûts

Selon vous, qu'est-ce qui permettrait de mieux intégrer des systèmes de gestion automatisée dans vos projets de logements ? [Texte long]-suite

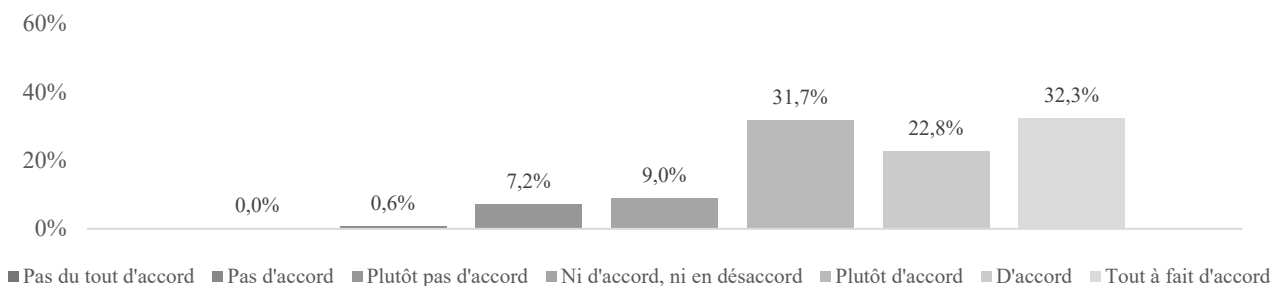
Un promoteur occupant :) (Money, money!)	Pas d'élément spécifique
Un coût et une complexité moins élevées. Mais je ne suis pas convaincue qu'i	régulation basic de stores (vue station météo) ou d'une VMC(by pass, sur ventilation) = a mon sens, para
/	Une intégration plus aisée entre équipements afin de disposer d'un système réellement intelligent.
je travaille essentiellement sur des projets les plus low tech possible. sans mé	pas d'idée
Aucune idée, je n'ai jamais eu à faire à ce type d'équipement.	Que les systèmes soient plus performants
pas d'avis	Connaissance technique des systèmes.
-	un coût moins élevé
Pas d'avisAutomatisation pas une priorite	.
Les systèmes motorisés ne sont pas à mon sens une solution valable; le réflex	Aider les propriétaire financièrement
Des primes	-
Cela nous semble une mesure disproportionnée pour des logements, nous ne c	Difficile à intégrer cette idée aux occupants.Ce type de système est envisagé quand les protections en am
Petit exemple vécu. Chez nous dans notre maison à Ottignies, nous avons un :	Je ne crois pas que ce soit nécessaire de forcément automatiser des comportements qui peuvent être mis c
Sensibili	-
les avantages sont les mêmes que pour une gestion non automatisée. En revan	Coût réduitSystème simple et compatible entre les différents éléments (châssis, protection, ventilation ...)
Le coût d'entretien ne compense pas l'économie environnementale.	Des primes
Des primes...	-
-	Success stories et incitants législatifs, économiques
idem	Conscientisation du client
Campagne d'information et de sensibilisation	Rassurer les différents intervenants sur coût/ durée de vie
/	Informé
Je ne sais pas	un prix plus intéressant
Une prime éventuelle.	...
un coût moindre , des primes	ceci est un ultime recours. Trop de matériel mis en œuvre alors qu'une bonne éducation de l'occupant du l
?	Primes
pas nécessaire	Idem question précédente
Une baisse des coûts	pas d'avis, nous n'avons intégrer que la gestion centralisée de store
Interopérabilité des systèmes et baisse des coûts	Pas sure que ça soit intéressant de mieux intégrer plus ce genre de système.
Une volonté de la part du maître d'ouvrage.	.
Un meilleur information auprès du maitre de l'ouvrage	N'est pas la direction
-	Pas besoin, manuel cela suffit
Une meilleure information des propriétaires sur ce type de produits.	-
Rien et ce n'est pas souhaitable hormis de prévoir des cycles de réglage dans l-	
une gestion plus en accord avec les occupants. souvent les système automatise	Des systèmes automatisés plus simples à installer et à utiliser. Si le système n'est pas programmé correct
L'obligation légale	Le conseil et information concernant les techniques et les prix
je ne m'y connais pas assez sur le sujet que pour pouvoir me prononcer	que cela soit moins cher
je ne connais pas assez ces systèmes	les primes...
Du temps pour expliquer	...
Plus d'information sur ce dispositif.	ce n'est pas notre priorité
/	privilégions les systèmes low tech plutôt que des dispositifs automatiques

Votre avis

Que pensez-vous des affirmations suivantes :

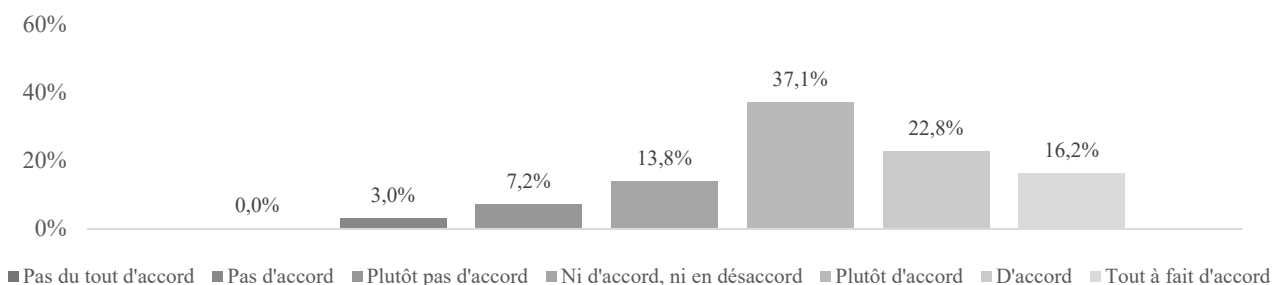
Le confort thermique estival devrait être une priorité dans les bâtiments résidentiels construits aujourd'hui en Belgique

Réponse	n	%
Pas du tout d'accord	0	0,0%
Pas d'accord	1	0,6%
Plutôt pas d'accord	6	3,6%
Ni d'accord, ni en désaccord	15	9,0%
Plutôt d'accord	53	31,7%
D'accord	38	22,8%
Tout à fait d'accord	54	32,3%
Total	167	100,0%



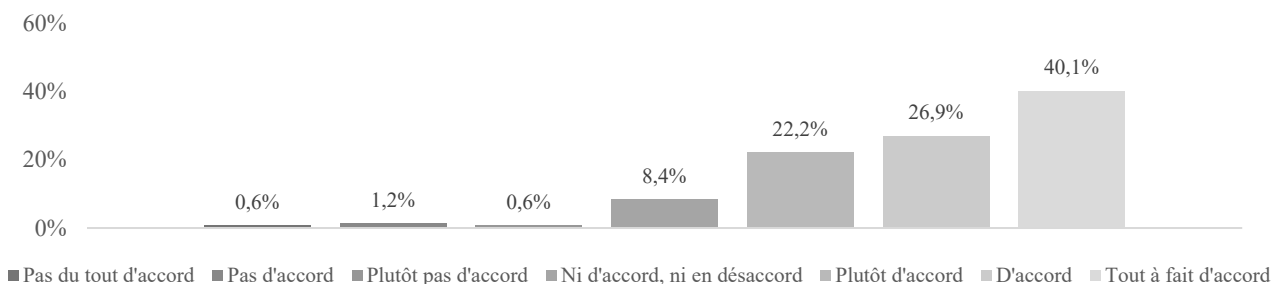
La surchauffe estivale dans les bâtiments résidentiels récemment construits en Belgique est problématique

Réponse	n	%
Pas du tout d'accord	0	0,0%
Pas d'accord	5	3,0%
Plutôt pas d'accord	12	7,2%
Ni d'accord, ni en désaccord	23	13,8%
Plutôt d'accord	62	37,1%
D'accord	38	22,8%
Tout à fait d'accord	27	16,2%
Total	167	100,0%



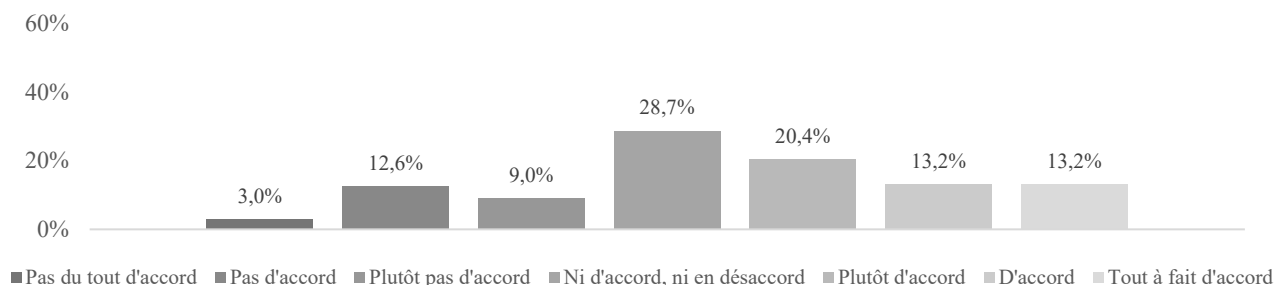
La surchauffe estivale dans les bâtiments résidentiels pourrait devenir problématique en Belgique d'ici à 2050

Réponse	n	%
Pas du tout d'accord	1	0,6%
Pas d'accord	2	1,2%
Plutôt pas d'accord	1	0,6%
Ni d'accord, ni en désaccord	14	8,4%
Plutôt d'accord	37	22,2%
D'accord	45	26,9%
Tout à fait d'accord	67	40,1%
Total	167	100,0%



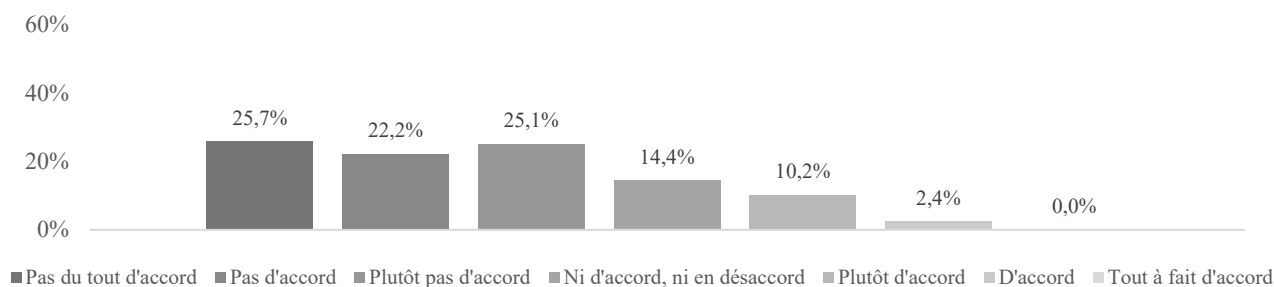
Les nouvelles constructions ou rénovations empirent le phénomène de surchauffe

Réponse	n	%
Pas du tout d'accord	5	3,0%
Pas d'accord	21	12,6%
Plutôt pas d'accord	15	9,0%
Ni d'accord, ni en désaccord	48	28,7%
Plutôt d'accord	34	20,4%
D'accord	22	13,2%
Tout à fait d'accord	22	13,2%
Total	167	100,0%



La climatisation est la solution pour garantir le confort estival dans les logements

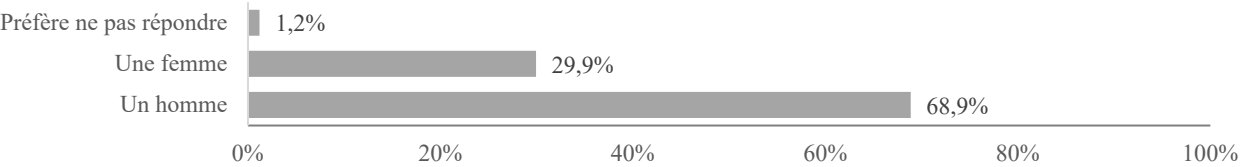
Réponse	n	%
Pas du tout d'accord	43	25,7%
Pas d'accord	37	22,2%
Plutôt pas d'accord	42	25,1%
Ni d'accord, ni en désaccord	24	14,4%
Plutôt d'accord	17	10,2%
D'accord	4	2,4%
Tout à fait d'accord	0	0,0%
Total	167	100,0%



Votre profil

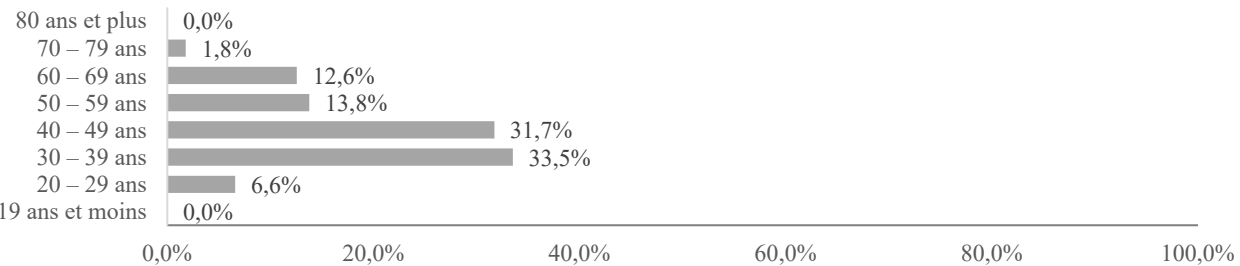
Vous êtes... [Choix unique]

Réponse	n	%
Un homme	115	68,9%
Une femme	50	29,9%
Préfère ne pas répondre	2	1,2%
Total	167	100,0%



Dans quelle tranche d'âge vous situez-vous [Choix unique] ?

Réponse	n	%
19 ans et moins	0	0,0%
20 – 29 ans	11	6,6%
30 – 39 ans	56	33,5%
40 – 49 ans	53	31,7%
50 – 59 ans	23	13,8%
60 – 69 ans	21	12,6%
70 – 79 ans	3	1,8%
80 ans et plus	0	0,0%
Total	167	100,0%



Appendix F. Analysis of climate datasets

Appendix F presents a preliminary analysis of the climate datasets available for historical conditions and future projections under high-emission scenarios in the Belgian context. Conducted by the author of this thesis, the analysis aims to position the ALARO climate model used in Chapter V in relation to ERA5 meteorological reanalysis data and other recently available future climate models (see Table IX.2 p.254 for further details).

Climate models and scenarios: Historical (1976-2005 or 2001-2020) and long-term future periods (2081-2100) under high-emission scenarios (RCP8.5 and SSP5-8.5).

- Multi-year climate datasets: ERA5, MAR, REMO15 and ALARO.
- Reference-year climate files: MAR Typical Meteorological Year (TMY), and COSMO Extreme Warm Year (EWY) and Typical Downscaled Year (TDY).

Number of Summer Days ($T_{\max} > 25^{\circ}\text{C}$) per year

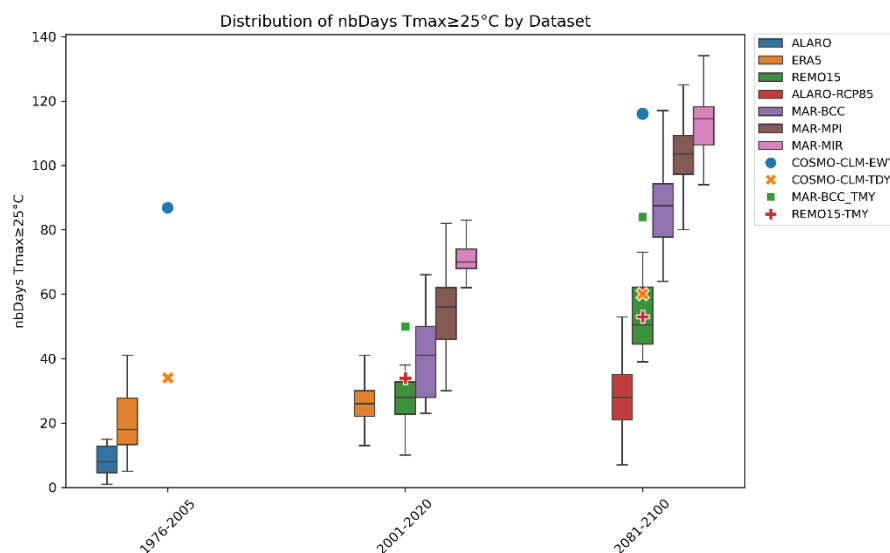


Figure iii. Number of summer days ($T_{\max} > 25^{\circ}\text{C}$) per year, by period and climate dataset

Number of Heatwave Days ($T_{\max} > 30^{\circ}\text{C}$) per year

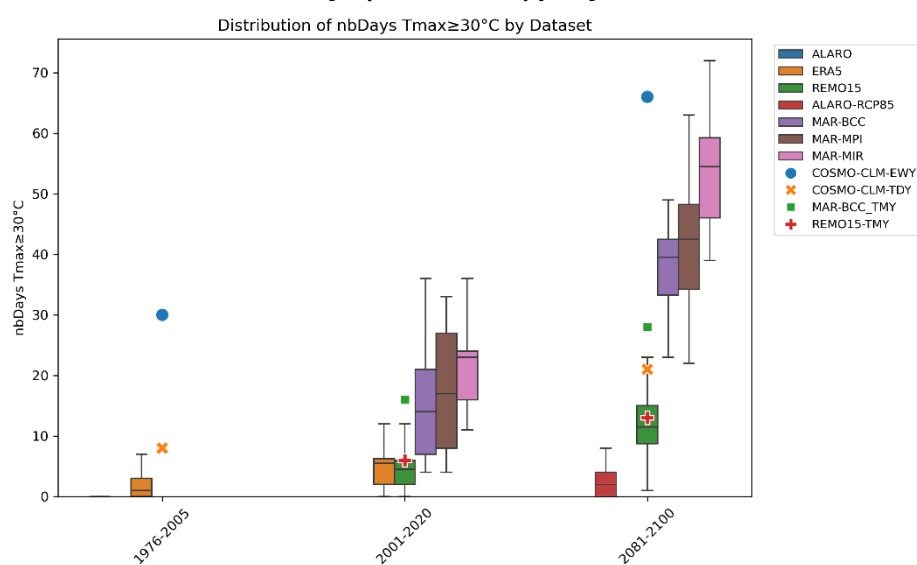


Figure iv. Number of heatwave days ($T_{\max} > 30^{\circ}\text{C}$) per year, by period and climate dataset

Number of Tropical nights ($T_{min} > 20^{\circ}\text{C}$) per year

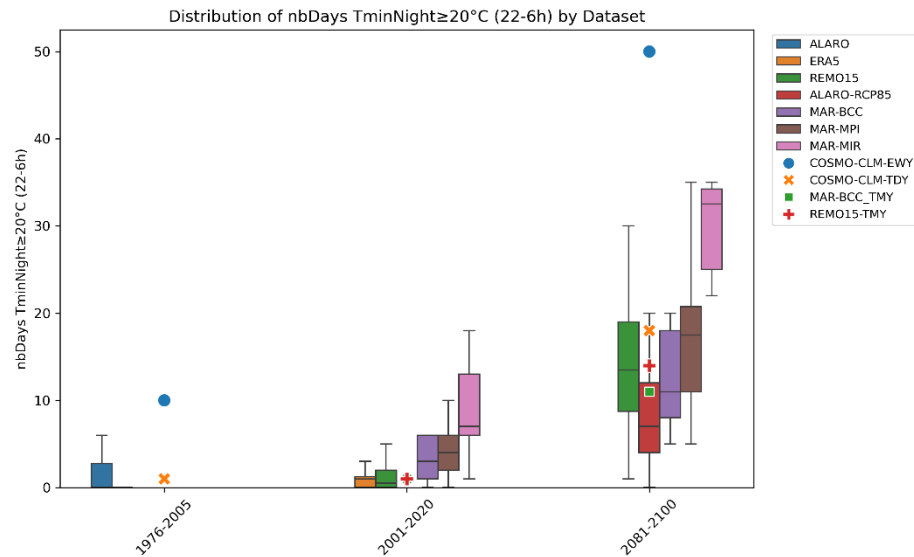


Figure v. Number of tropical nights ($T_{min} > 20^{\circ}\text{C}$) per year, by period and climate dataset

Number of Heatwave periods per year

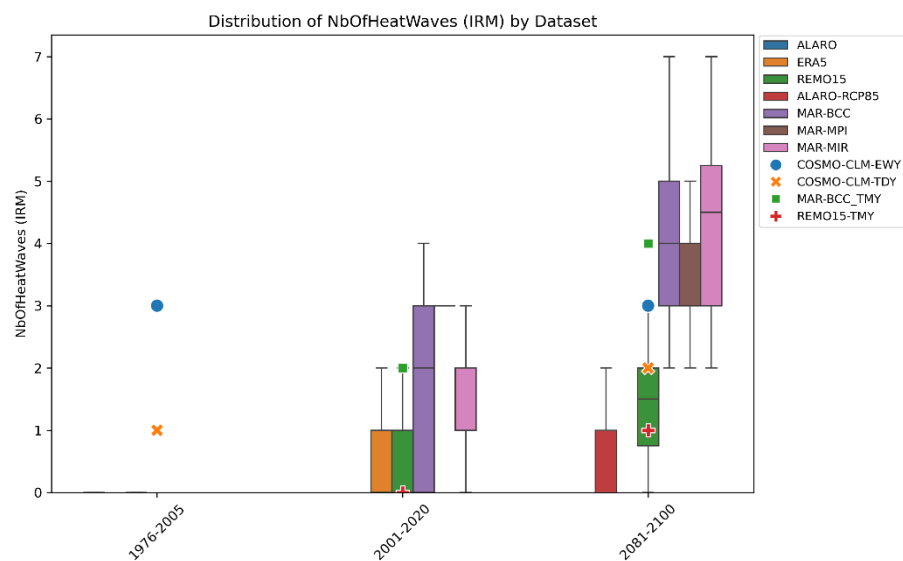


Figure vi. Number of heatwave periods per year, by period and climate dataset. A heatwave is here defined as at least five consecutive days with $T_{max} \geq 25^{\circ}\text{C}$, including at least three days with $T_{max} \geq 30^{\circ}\text{C}$.

Global horizontal irradiation [kWh/m².year]

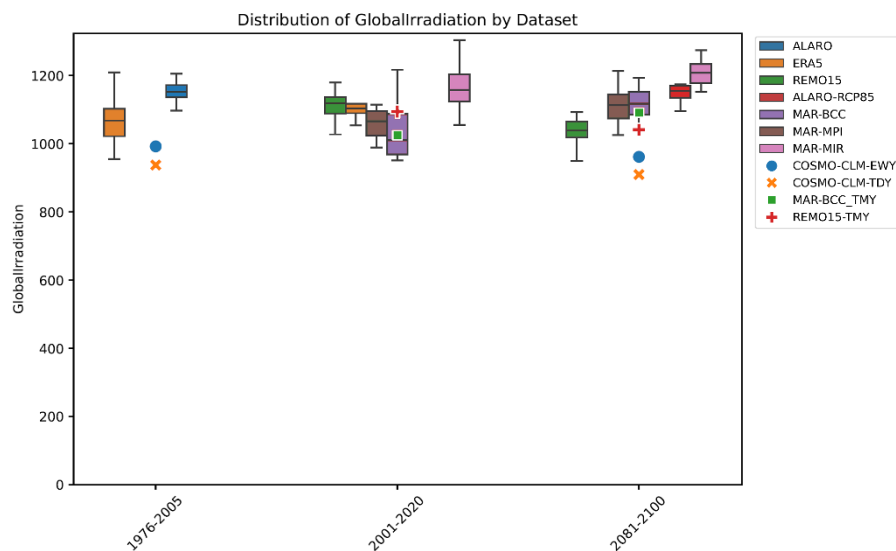


Figure vii. Annual global solar irradiation received by a 1 m² horizontal surface, by period and climate dataset.

Key findings:

The comparison highlights substantial differences among the climate datasets in their representation of summer conditions:

- ALARO produces the coolest summer conditions but present slightly higher solar irradiation.
 - It presents the lowest median number of summer days, with 8 days per year, compared with 18 days in the ERA5 reanalysis. This tendency is also reflected in the number of days with outdoor temperatures above 30°C, and no heatwave is identified during the historical period.
 - It remains the coolest model even under future high-emission scenarios.
 - This model presents a slightly higher median annual solar irradiation of 1152 kWh/m², compared with 1068 kWh/m² for ERA5.

- MAR produces the most severe summer conditions.
 - For the historical period 2001–2020, the median number of summer days ranges from 26 to 51 days per year, depending on the driving model, compared with 18 days in ERA5. This tendency is also reflected in the number of heatwave days and tropical nights.
 - This tendency persists under future high-emission scenarios, in which the number of heatwave periods reaches between two and seven per year.
 - The number of summer days reaches approximately 88 days per year (median value) for the BCC-driven simulation and 115 days for the MIR-driven simulation.
 - The median number of tropical nights reaches 11 days per year for BCC and 33 days for MIR.
- The COSMO reference years also represent relatively severe conditions.
 - The Typical Downscaled Year (TDY) is broadly aligned with the 75th percentile of the REMO15 distribution.
 - The Extreme Warm Year (EWY) is closer to the median of the most severe model. However, it presents a substantially higher number of tropical nights, reaching approximately 50 occurrences per year.
- REMO15 provides the closest agreement with ERA5.
 - For the historical period, REMO15 reproduces the ERA5 reanalysis more closely than the other models.
 - This agreement is likely attributable to the quantile delta mapping (QDM) bias-correction procedure.
 - REMO15 therefore appears to provide more realistic values, at least for the historical period.
 - It is however the only model that projects a decrease in solar irradiation during future periods (~7%).

More generally, these results:

- illustrate the crucial importance of calibration and bias-correction procedures in producing realistic climate data, at least for historical periods;
- explain why REMO15 was preferred over ALARO for the subsequent analyses, despite ALARO having been used in the preliminary analysis presented in Chapter III; and
- call for further investigation considering not only temperature-based indicators, but also the full range of weather variables influencing whole-building energy simulations.

Appendix G. Sensitivity analysis of passive-control characteristics

Appendix G presents the results of additional whole-building energy simulations conducted using the calibrated model of the typical nZEB house (Subsample A.3 see Section II.3.1 p.83) developed in Chapter V. These simulations aim to investigate the effects of various technical and operational characteristics associated with the implementation of passive controls in this house.

Climate files and scenarios: Typical Meteorological Year (TMY) files and heatwave events (HW) for the historical (2001–2020) and long-term future (2081–2100) periods, derived from the REMO15 regional climate model under the high-emission RCP8.5 scenario (see Table IX.2 p.254 for further details).

Operational strategy scenarios: Table ii presents the technical and operational strategies considered in the simulations.

Table ii. Simulated technical and operational characteristics of passive controls.

Property ID	Description	Value 1 = Lower value considered	Value 2 = Higher value considered
Technical characteristics			
VC AchValue	Ventilative Cooling Air Change per hour [h-1]	2	6
SS SFValue	Solar Shading Factor Value [-]	0.42 White internal screen	0.83 Black external screen
TM	Building Thermal Mass Type (according to ISO 52016) Building Thermal Capacity [kJ/K]	Light 20324	Heavy 61335
Operational strategies			
Op1	Building-level Operation	Off Main rooms only*	On
Op2	Non Occupancy Based Operation	Off Occupancy only	On
Op3	Discomfort Anticipated Operation	Off Reactive to discomfort Tcomf+2°C	On Tcomf as threshold
Op4	Outdoor Temperature restricted Operation for Ventilative Cooling (Tin>Tout)	Off	On
Op5	Overcooling Tolerated Operation (Ventilative Cooling)	Off Tcomf as lower threshold	On

*Main rooms are here the main double bedroom and the living room

Number of simulation runs: 1536 performed using the TRNSYS 18 simulation engine.

Sobol Sensitivity analysis

Sobol' variance-based sensitivity analysis is a global sensitivity analysis method that quantifies the contribution of each input variable, and combinations of variables, to the output variance of a model. It decomposes the total output variance into fractions attributed to individual input factors (first-order effects), their interactions (higher-order effects), and their total combined influence (total-order indices). This sensitivity analysis method has been here used to study the effect of various technical and operational properties of passive strategies implementation on the *Indoor Overheating Degree metric*, which is a time-integrated metric that quantifies the positive deviation (asymmetric index) of indoor operative temperature (T_{op}) from a predefined upper threshold (T_{up}) during occupied hours (H_{occ}). First introduced by Hamdy et al. [94], it was subsequently proposed by IEA EBC Annex 80 as a key indoor performance indicator for assessing building resilience [111]. When extended to multiple thermal zones (Z), it could provide an aggregated assessment capturing similarly the intensity and duration of high indoor temperatures (see equation below). This approach also allows for considering different comfort criteria (T_{up}) according to the cooling strategy (e.g., naturally ventilated vs. air-conditioned) and/or use of the zone (e.g., living areas vs. bedrooms).

$$IOhD \equiv \frac{\sum_{i=1}^{H_{occ}} \left[\sum_{Z=1}^Z (T_{op,z,i} - T_{up,z,i})^+ \cdot h_i \right]}{\sum_{i=1}^{H_{occ}} h_i}$$

The calculation has been here made focusing on the living room and the main double bedroom considering adaptive (Cat II.) and static (26°C) T_{up} thresholds (=Tcomf+2°C) respectively, considering a period of analysis covering May to September.

The results of this analysis are presented in Table iii.

Table iii. Sensitivity analysis results: First and Total order Sobol indices.

Variable	TMY				Most Severe and Longest HW				Most Intense HW			
	2001-2020		2081-2100		2002		2090		2020		2097	
	First-Order [%]	Total-Order [%]	First-Order [%]	Total-Order [%]	First-Order [%]	Total-Order [%]	First-Order [%]	Total-Order [%]	First-Order [%]	Total-Order [%]	First-Order [%]	Total-Order [%]
VC_AchValue	10.9	32.1	14.3	28.3	12.3	19.3	16.7	21.5	5.1	11.5	15.4	21.2
VC_Op1	19.4	51.1	34.5	56.9	33.2	51.6	46.0	58.4	12.3	30.6	44.7	58.6
VC_Op2	3.1	13.0	2.7	8.8	1.4	4.3	2.2	5.2	0.4	2.1	2.0	5.1
VC_Op3	0.2	0.3	0.1	0.2	0.1	0.1	0.0	0.1	0.0	0.1	0.0	0.1
VC_Op4	0.0	0.1	0.2	0.3	0.4	0.7	0.2	0.4	0.6	1.3	0.4	0.6
VC_Op5	0.1	0.4	0.1	0.2	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1
SS_SFValue	1.1	4.4	1.5	4.1	0.8	2.6	1.0	2.6	0.9	2.9	1.0	2.6
SS_Op1	4.4	16.4	5.1	12.9	3.3	8.5	3.6	7.6	2.4	7.1	3.7	8.1
SS_Op2	1.5	5.5	2.0	5.1	1.1	3.2	1.5	3.7	1.1	3.9	1.5	3.7
SS_Op3	0.3	0.8	0.3	0.6	0.2	0.6	0.2	0.4	0.3	0.4	0.2	0.4
TM	13.9	32.4	10.6	15.0	22.1	38.1	11.9	18.8	48.6	72.1	12.6	20.6

Key findings:

- Considering both first- and total-order sensitivity indices (see Table iii), the three most influential parameters are VC_Op1 (whole-building implementation of ventilative cooling), TM (building thermal-mass capacity), and VC_AchValue (ventilative-cooling air-change capacity). VC_Op1 is generally the dominant parameter, except during the short and intense 2020 heatwave, when TM becomes the most influential owing to its strong interactions with the other passive strategies (total-order index: 72.1%).
- Solar shading (SS_SFValue) has a comparatively limited influence in the analysed case study, partly owing to the building's small, glazed area and the use of selective glazing (SHGC = 0.35). Its slightly lower influence under future climatic conditions may also reflect the projected decrease in solar irradiance, although this trend is specific to the REMO15 model (see Appendix F.) and should not be generalised.
- Ventilative cooling (VC_AchValue) plays a crucial role in the analysed case study. Its relative importance increases under future climatic conditions, likely because heat dissipation is required over longer periods, particularly in the absence of complementary passive strategies.

- The influence of thermal mass (TM) decreases under future climatic conditions. Although it remains particularly effective during short, intense heatwaves, its relative contribution diminishes as overheating becomes more persistent.
- Whole-building implementation of passive strategies (Op1) has a greater influence than improving the intrinsic performance of individual devices. For both ventilative cooling ($VC_Op1 > VC_AchValue$) and solar shading ($SS_Op1 > SS_SFValue$), the spatial extent and practical deployment of strategies are more influential than device performance alone.
- The operation of passive strategies during unoccupied periods (Op2) also contributes to performance, although to a lesser extent. For solar shading, maintaining protection while occupants are absent is at least as influential as improving the shading performance itself, whereas for ventilative cooling, achievable air-change rates remain more influential than unoccupied operation.
- Anticipatory control (Op3) is more beneficial for solar shading than for ventilative cooling, particularly during heatwaves, because solar gains can be prevented before indoor temperatures rise. Nevertheless, this optimisation strategy has a secondary influence compared with whole-building implementation, thermal mass, and ventilative-cooling capacity.
- Outdoor-temperature-based control (Op4) and overcooling strategies (Op5) have positive but limited effects. Outdoor-temperature-based control becomes slightly more influential during heatwaves, while overcooling has a somewhat greater influence over longer climatic periods.

Overall, the analysis shows that operational and implementation-related factors are generally more influential than the intrinsic technical performance of passive-control devices. Extending strategies throughout the building and enabling their operation during unoccupied periods provide greater benefits than improvements in device efficiency, while thermal mass could play an important role during short and intense heatwaves.

Appendix H. Exploring the feasibility of thermal autonomy under current and future climate conditions

Appendix H presents the results of additional whole-building energy simulations conducted using the calibrated model of the typical nZEB house (Subsample A.3, see Section II.3.1 p.83) developed in Chapter V. These simulations aim to assess the extent to which combinations of passive operational strategies can maintain comfortable indoor conditions without active cooling under future climatic conditions.

Climate files and scenarios: Typical Meteorological Year (TMY) and Heatwave Year (HWY) files for the historical (2001–2020) and long-term future (2081–2100) periods, derived from the REMO15 regional climate model under the RCP8.5 scenario (see Table IX.2 p.254). For the heatwave years, the most intense event (here highest maximum daily mean temperature), the longest event (duration in days), and the most severe event ($^{\circ}\text{C}\cdot\text{day}$) were selected according to the methods and data provided by Machard et al. [21]. Here, the most severe events also correspond to the longest.

Key Performance Indicator: Thermal Autonomy (TA) is here used as Key Performance Indicator (KPI). It is defined as “*the percentage of the occupied time over a period where a thermal zone meets or exceeds a given set of thermal comfort acceptability criteria through passive means only* [278]”. Its evaluation could be conducted either at the zone level or for several thermal zones based on the following formula:

$$TA = \frac{\sum_{i=1}^{Hocc(z)} \min(wf_{\{i,Z1\}}, \dots, wf_{\{i,Zn\}})}{\sum_{i=1}^{Hocc(z)} h_i}$$

Where:

$$wf_{i,Zx} = 1 \text{ if } T_{in,Zx} \leq T_{up,Zx}$$

$$wf_{i,Zx} = 0 \text{ if } T_{in,Zx} > T_{up,Zx}$$

For the present study, the calculation focuses on the thermal autonomy of the living room and the main double bedroom, assessed using an adaptive Category II upper temperature threshold ($= T_{comf} + 2^{\circ}\text{C}$) and a static upper temperature threshold of 26°C , respectively.

Operational strategy scenarios:

Table iv presents the technical characteristics and operational strategies considered in the simulations, which are identical to those examined through the sensitivity analysis presented in Appendix G.

Table iv. Simulated improvements to the technical characteristics and operational strategies of passive controls.

Property ID	Description	Value 1 = Lower value considered	Value 2 = Higher value considered
Technical characteristics			
VC AchValue	Ventilative Cooling Air Change per hour [h ⁻¹]	2	6
SS SFValue	Solar Shading Factor Value [-]	0.42 White internal screen	0.83 Black external screen
TM	Building Thermal Mass Type (according to ISO 52016) Building Thermal Capacity [kJ/K]	Light 20324	Heavy 61335
Operational strategies			
Op1	Building-level Operation	Off Main rooms only*	On
Op2	Non Occupancy Based Operation	Off Occupancy only	On
Op3	Discomfort Anticipated Operation	Off Reactive to discomfort T _{comf} +2°C	On T _{comf} as threshold
Op4	Outdoor Temperature restricted Operation for Ventilative Cooling (T _{in} >T _{out})	Off	On
Op5	Overcooling Tolerated Operation (Ventilative Cooling)	Off T _{comf} as lower threshold	On

*Main rooms are here the main double bedroom and the living room

Number of simulation runs: 216 performed using the TRNSYS 18 simulation engine.

Results:

Table v. presents the results obtained for several combinations of technical characteristics and operational control strategies (see Table iv). The main values refer to the entire summer period, from May to September inclusive, while the values in parentheses refer specifically to the heatwave period. Results complying with the CIBSE recommendation that discomfort should occur during less than 1% of occupied hours [53] are highlighted in the table.

	2001-2020 REMO15 TMY										2081-2100 REMO15 TMY									
	Operational strategies										Operational strategies									
	1. Localised	2. Generalised	3. NonOccup	4. Discomfort	5. ToutConsid	6. Overcooling	7. Anticipated	8. Overcooling	9. Anticipated	10. Overcooling	1. Localised	2. Generalised	3. NonOccup	4. Discomfort	5. ToutConsid	6. Overcooling	7. Anticipated	8. Overcooling	9. Anticipated	10. Overcooling
Technical characteristics	Op1-Off	Op1-On	Op2-On	Op3-On	Op4-On	Op5-On	Op6-On	Op7-On	Op8-On	Op9-On	Op1-Off	Op1-On	Op2-On	Op3-On	Op4-On	Op5-On	Op6-On	Op7-On	Op8-On	Op9-On
	87.3	91.4	93.6	97	98.5	✓ 99	✓ 99.8	✓ 100	✓ 100	✓ 100	81.1	86.5	87.9	92.6	95	96.5	96.5	96.5	96.5	96.5
	89.1	92.6	95.2	98.9	✓ 99.8	✓ 100	✓ 99.8	✓ 100	✓ 100	✓ 100	83.1	87.8	90.4	95.8	97.6	98.1	98.1	98.1	98.1	98.1
	95.4	96.1	96.9	98.3	✓ 99.8	✓ 100	✓ 99.8	✓ 100	✓ 100	✓ 100	90.9	92.2	92.4	94.5	97.5	98.3	98.3	98.3	98.3	98.3
	95.9	98.3	98.1	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	88.4	92.5	92	97.6	98.8	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100
	95.6	96.4	97.5	✓ 99.2	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	91.2	92.6	93.2	96.6	✓ 99	✓ 99.3	✓ 99.3	✓ 99.3	✓ 99.3	✓ 99.3
Technical characteristics	89.8	98.6	✓ 99	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	96.6	97.2	96.8	98.3	✓ 99.4	✓ 99.4	✓ 99.4	✓ 99.4	✓ 99.4	✓ 99.4
	97.3	✓ 99	✓ 99	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	90.3	93.5	93.8	98.9	✓ 99.7	✓ 99.7	✓ 99.7	✓ 99.7	✓ 99.7	✓ 99.7
	✓ 99.2	✓ 99.3	✓ 99.3	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	96.8	97.2	97.1	✓ 99.1	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100	✓ 100
	2090 REMO15 HWY-MostSevere Longest										2090 REMO15 HWY-MostSevere Longest									
	1. Localised	2. Generalised	3. NonOccup	4. Discomfort	5. ToutConsid	6. Overcooling	7. Anticipated	8. Overcooling	9. Anticipated	10. Overcooling	1. Localised	2. Generalised	3. NonOccup	4. Discomfort	5. ToutConsid	6. Overcooling	7. Anticipated	8. Overcooling	9. Anticipated	10. Overcooling
	Op1-Off	Op1-On	Op2-On	Op3-On	Op4-On	Op5-On	Op6-On	Op7-On	Op8-On	Op9-On	Op1-Off	Op1-On	Op2-On	Op3-On	Op4-On	Op5-On	Op6-On	Op7-On	Op8-On	Op9-On
Technical characteristics	86.4 (27.5)	88.8 (39.4)	89.5 (44.5)	92.2 (53.1)	94.4 (66.2)	95.5 (70.1)	96.3 (79.4)	97.3 (84.1)	98.5 (91.4)	99.8 (98.9)	72 (24)	76.5 (34.5)	78.1 (38.7)	83.5 (47.1)	86.3 (54.8)	88.6 (59.1)	88.6 (59.1)	88.6 (59.1)	88.6 (59.1)	88.6 (59.1)
	87.2 (31.8)	89.1 (42.4)	90.4 (48.2)	94.5 (65.8)	96.3 (79.4)	97.3 (84.1)	98.5 (91.4)	99.8 (98.9)	99.8 (98.9)	99.8 (98.9)	74.3 (29)	77.8 (39)	80.4 (46.4)	88.3 (61.3)	90.8 (68.5)	93 (75.4)	93 (75.4)	93 (75.4)	93 (75.4)	93 (75.4)
	92.6 (57.6)	93.3 (63)	93.3 (62.4)	94.6 (68.6)	97.9 (86)	98.8 (91.4)	99.8 (98.9)	99.8 (98.9)	99.8 (98.9)	99.8 (98.9)	84.5 (54.7)	86.8 (59.8)	86.9 (60)	89.5 (64.5)	94.1 (78.9)	94.8 (81.8)	94.8 (81.8)	94.8 (81.8)	94.8 (81.8)	94.8 (81.8)
	90.8 (58.7)	92 (59.8)	92.5 (61.1)	94.9 (71.6)	96.2 (79.6)	97.3 (88.2)	98.5 (91.4)	99.8 (98.9)	99.8 (98.9)	99.8 (98.9)	79.9 (46.4)	83.8 (54.4)	84.6 (54.4)	87.5 (58.2)	88.8 (62)	90.9 (67.8)	90.9 (67.8)	90.9 (67.8)	90.9 (67.8)	90.9 (67.8)
	92.8 (59.8)	93.4 (62.8)	93.6 (63.4)	95.7 (72.9)	98.5 (91.2)	✓ 99.2 (95.3)	✓ 99.8 (98.9)	✓ 99.8 (98.9)	✓ 99.8 (98.9)	✓ 99.8 (98.9)	85.2 (56.2)	87.5 (61.9)	88 (62.7)	91.9 (72)	94.7 (81.5)	95.5 (84.4)	95.5 (84.4)	95.5 (84.4)	95.5 (84.4)	95.5 (84.4)
	96.2 (78.9)	96.8 (83)	96.7 (82.2)	97.4 (84.7)	✓ 99.3 (96.6)	✓ 99.8 (98.9)	✓ 99.8 (98.9)	✓ 99.8 (98.9)	✓ 99.8 (98.9)	✓ 99.8 (98.9)	89.1 (65)	91 (70.2)	91.4 (72.3)	93 (75.9)	95.8 (86.4)	97.1 (90.8)	97.1 (90.8)	97.1 (90.8)	97.1 (90.8)	97.1 (90.8)
Technical characteristics	91.4 (59.8)	92.2 (60.6)	92.5 (64.1)	97.1 (82.2)	98.9 (93.3)	✓ 99.3 (98.5)	✓ 99.3 (98.5)	✓ 99.3 (98.5)	✓ 99.3 (98.5)	✓ 99.3 (98.5)	82.9 (51.9)	84.2 (53.8)	85.5 (56.1)	89.7 (65)	91.3 (71.2)	94.5 (80.1)	94.5 (80.1)	94.5 (80.1)	94.5 (80.1)	94.5 (80.1)
	96.3 (80.2)	96.9 (83)	96.8 (82.6)	98.3 (88.2)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	89.2 (64.8)	91.3 (71.2)	91.9 (73.7)	93.9 (79.2)	97.3 (91.4)	97.8 (94.4)	97.8 (94.4)	97.8 (94.4)	97.8 (94.4)	97.8 (94.4)
	2097 REMO15 HWY-MostIntense										2097 REMO15 HWY-MostIntense									
	1. Localised	2. Generalised	3. NonOccup	4. Discomfort	5. ToutConsid	6. Overcooling	7. Anticipated	8. Overcooling	9. Anticipated	10. Overcooling	1. Localised	2. Generalised	3. NonOccup	4. Discomfort	5. ToutConsid	6. Overcooling	7. Anticipated	8. Overcooling	9. Anticipated	10. Overcooling
	Op1-Off	Op1-On	Op2-On	Op3-On	Op4-On	Op5-On	Op6-On	Op7-On	Op8-On	Op9-On	Op1-Off	Op1-On	Op2-On	Op3-On	Op4-On	Op5-On	Op6-On	Op7-On	Op8-On	Op9-On
Technical characteristics	92.9 (25.5)	94.1 (37.9)	94.7 (42.2)	97.3 (58.4)	97.9 (67.1)	98.3 (71.4)	98.7 (83.2)	99.3 (87.7)	99.8 (91.9)	99.8 (91.9)	74.3 (29.2)	79 (39.8)	81.8 (45.5)	87.3 (58.4)	89.6 (65.3)	91.9 (72.4)	91.9 (72.4)	91.9 (72.4)	91.9 (72.4)	91.9 (72.4)
	93.6 (34.2)	94.8 (42.2)	95.7 (44.1)	98 (68.3)	98.5 (75.8)	98.7 (83.2)	99.3 (87.7)	99.8 (91.9)	99.8 (91.9)	99.8 (91.9)	75.6 (32.6)	80.7 (44.9)	84.5 (53.6)	90.8 (70)	93.2 (77.1)	94.8 (81.2)	94.8 (81.2)	94.8 (81.2)	94.8 (81.2)	94.8 (81.2)
	96 (47.2)	97.3 (53.4)	97.4 (53.4)	98.1 (64.6)	✓ 99 (82.6)	✓ 99.3 (87.7)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	88.2 (64.2)	90.1 (69.3)	90.3 (70.8)	92.2 (74.6)	95 (82.3)	96.3 (85.7)	96.3 (85.7)	96.3 (85.7)	96.3 (85.7)	96.3 (85.7)
	96.6 (81.4)	97.6 (81.4)	97.8 (81.4)	98.4 (81.4)	98.8 (100)	✓ 99 (100)	✓ 99.3 (87.7)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	78.6 (49.7)	85.4 (58.8)	87 (60.1)	90.5 (65.2)	91.4 (67.1)	93 (75.4)	93 (75.4)	93 (75.4)	93 (75.4)	93 (75.4)
	96.5 (49.7)	97.4 (54.7)	97.5 (57.1)	98.4 (72)	✓ 99.3 (87.7)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	✓ 99.8 (91.9)	86.6 (66)	90.5 (70.9)	90.8 (71.7)	93.3 (77.8)	96.7 (87.4)	97.1 (88.9)	97.1 (88.9)	97.1 (88.9)	97.1 (88.9)	97.1 (88.9)
	98.4 (87)	98.4 (85.7)	98.4 (83.9)	98.9 (83.2)	✓ 99.9 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	91.6 (69.5)	93.9 (78.2)	93.6 (77.4)	94.8 (80.1)	97.3 (89.4)	98.1 (92.7)	98.1 (92.7)	98.1 (92.7)	98.1 (92.7)	98.1 (92.7)
Technical characteristics	96.5 (81.4)	97.6 (81.4)	97.8 (81.4)	98.9 (89.4)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	80.6 (54.6)	86.4 (60.6)	88.2 (61)	91.6 (68.2)	93.8 (76.5)	95.9 (87)	95.9 (87)	95.9 (87)	95.9 (87)	95.9 (87)
	98.3 (87)	98.4 (86.3)	98.5 (83.9)	✓ 99.1 (83.2)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	✓ 100 (100)	92.4 (71.9)	94.1 (78.9)	93.9 (79.4)	96.5 (83)	98.1 (93)	98.8 (94.5)	98.8 (94.5)	98.8 (94.5)	98.8 (94.5)	98.8 (94.5)
	2097 REMO15 HWY-MostIntense										2097 REMO15 HWY-MostIntense									
	1. Localised	2. Generalised	3. NonOccup	4. Discomfort	5. ToutConsid	6. Overcooling	7. Anticipated	8. Overcooling	9. Anticipated	10. Overcooling	1. Localised	2. Generalised	3. NonOccup	4. Discomfort	5. ToutConsid	6. Overcooling	7. Anticipated	8. Overcooling	9. Anticipated	10. Overcooling
	Op1-Off	Op1-On	Op2-On	Op3-On	Op4-On	Op5-On	Op6-On	Op7-On	Op8-On	Op9-On	Op1-Off	Op1-On	Op2-On	Op3-On	Op4-On	Op5-On	Op6-On	Op7-On	Op8-On	Op9-On
	92.9 (25.5)	94.1 (37.9)	94.7 (42.2)	97.3 (58.4)	97.9 (67.1)	98.3 (71.4)	98.7 (83.2)	99.3 (87.7)	99.8 (91.9)	99.8 (91.9)	74.3 (29.2)	79 (39.8)	81.8 (45.5)	87.3 (58.4)	89.6 (65.3)	91.9 (72.4)	91.9 (72.4)	91.9 (72.4)	91.9 (72.4)	91.9 (72.4)

Table v. Summer thermal autonomy, expressed in percentage of the occupancy time [%] resulting from the implementation passive control strategies (results of Whole Building Energy Simulation).

Key findings:

- Under the historical TMY, operational improvements alone can achieve high summer thermal autonomy, but the required level depends strongly on the technical configuration.
- During the intense but shorter historical heatwave of 2020 (Intensity: 28.9°C; Duration: 10 days; Severity: 12.1°C.days), thermal mass appears to play an important role, providing a baseline heatwave autonomy of 81.4% without any other improvement and enabling 100% autonomy when combined with one or more additional improvements, whether technical or operational.
- During the longest and most severe historical heatwave of 2002 (Intensity: 28.4°C; Duration: 26 days; Severity: 29.1°C.days), a full combination of technical and operational improvements is required to maintain complete thermal autonomy throughout the heatwave.
- Under the future TMY, technical improvements become necessary, and operational optimisation alone is insufficient.
- For the intense future heatwave year of 2097 (Intensity: 31.5°C; Duration: 42 days; Severity: 49.6°C.days), the best-performing configuration (SS2–TM2–VC2 combined with optimised control and overcooling) achieves 98.8% summer thermal autonomy annually and 94.5% during the heatwave.
- For the longest and most severe future heatwave of 2090 (Intensity: 29.32°C; Duration: 45 days; Severity: 62.9°C.days), no configuration complies with the CIBSE criteria. Nevertheless, the best-performing configuration (SS2–TM2–VC2 with optimised operational strategies allowing overcooling) achieves 97.8% summer thermal autonomy annually and 94.4% during the heatwave.
- Among the operational strategies, whole-building generalisation and continuous operation produce the first major improvements, while discomfort anticipation, outdoor-temperature-based restrictions, and overcooling are required to achieve the highest performance.

Overall, the results indicate a progressive increase in the level of technical and operational improvement required. Operational optimisation may be sufficient under historical typical conditions, whereas heatwaves and future typical summers require combined operational and technical improvements. This demonstrates that, under future climates, technical and operational improvements will be complementary rather than interchangeable.

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Short bio

Olivier Dartevelle is a civil engineer–architect, graduated from the École Polytechnique de Louvain (Belgium) after completing an exchange year at the Politecnico di Torino (Italy). He also holds a specialized master’s degree in bioclimatic architecture from Ricardo Palma University (Peru). He has both practical and academic expertise in issues related to energy, comfort, and indoor environmental quality in the built environment. Over the past ten years, in parallel with his teaching and professional activities, he has contributed to research projects in these fields within the *Architecture et Climat* research unit, part of the Louvain Research Institute for Landscape, Architecture, and Built Environment (LAB – UCLouvain).

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Rising temperatures and more frequent heatwaves increasingly challenge our built environment. Understanding how buildings and occupants can adapt to these changing conditions has become a critical research and policy priority. Focusing on low-energy single-family houses in Wallonia, this thesis critically examines how design practices can evolve to more effectively support summer thermal adaptation through passive strategies in a context where such adaptation has not historically been culturally embedded.

Drawing on monitoring data, field surveys, and whole-building energy simulations, the research highlights the extent of summer thermal discomfort currently experienced and its expected intensification under climate change. It also identifies the sociotechnical dimensions that shape current practices through surveys and interviews conducted with occupants, building professionals, and public policymakers.

The thesis shows that summer thermal adaptation in buildings cannot be addressed as a purely technical challenge, but must also be understood as part of evolving social practices. It therefore advocates for paradigm shifts grounded in transdisciplinary perspectives, linking building engineering with the social, climate, and health sciences, and calls for new design approaches that better support adaptation processes, with the aim of fostering more effective and socially embedded practices.

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