MITIGATING SUMMERTIME OVERHEATING IN AFFORDABLE HOUSING (SEASON)

Final Report for the Low Carbon Built Environment Programme

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Summary

Global heating is resulting in increasing average temperatures, and more frequent, severe, and long heatwave events. Many Finnish apartment buildings are not well adapted to heat, with high rates of self-reported and observed overheating during periods of hot weather, causing occupant discomfort and potential negative health outcomes, particularly for the more heat-vulnerable members of society. Passive measures, such as window interventions, can help reduce indoor temperatures without consuming additional energy, or can help reduce the energy demands of active cooling systems.

The SEASON project examined the potential for window interventions to reduce indoor temperatures in affordable housing in Tampere, Finland, using a sociotechnological approach that includes both a resident survey and building physics modelling. In collaboration with VTS-kodit, a survey was sent to residents of affordable apartment buildings asking respondents about their experiences with high indoor temperatures, the actions that they take to reduce these temperatures, and their preferences for different window and technological solutions. The answers from this survey were used to inform the dynamic thermal building physics simulation of a selected VTS apartment building that is scheduled to undergo an energy efficient retrofit in the near future, examining space heating energy consumption, daylighting levels, and overheating under current and future climates.

The survey results indicated a high degree of overheating in apartments, with 92% responding that apartments were too warm or hot, with the rates of overheating highest in south, east, or west-facing apartments. Actions taken to reduce temperatures included closing blinds and opening balcony doors to ventilate the apartment. Building simulation models confirmed the high rates of overheating by orientation. The modelled window interventions found that windows with openable areas and solar protection were able to substantially reduce overheating in most apartments in the modelled building, demonstrating the potential for natural ventilation and reduced solar gains on heat mitigation. Combined with the results of the survey, this evidence can be used to inform the energy efficiency renovations in apartments in the future.

Ilmaston lämpeneminen tulee johtamaan kohoaviin keskilämpötiloihin sekä yhä yleistyviin, pidempikestoisiin ja vakavampiin helleaaltoihin. Useat suomalaiset asuinrakennukset eivät ole sopeutuneet lämpimään ilmastoon, ja kuumina aikoina esiintyvää ylikuumenemista havaitaan ja raportoidaan runsaasti. Tämä aiheuttaa asukkaille, erityisesti lämmölle herkille erityisryhmille, epämukavuutta ja mahdollisia negatiivisia terveysvaikutuksia. Passiiviset toimenpiteet, kuten erilaiset ikkunaratkaisut, voivat auttaa alentamaan sisälämpötiloja kuluttamatta ylimääräistä energiaa tai vähentämään aktiivisten jäähdytysjärjestelmien energiantarpeita.

SEASON-hankkeessa tutkittiin ikkunoihin kohdistuvien toimenpiteiden mahdollisuuksia alentaa sisälämpötiloja kohtuuhintaisissa asunnoissa Tampereella. Hankkeessa hyödynnettiin sosioteknologista lähestymistapaa pitäen sisällään asukaskyselyn ja rakennusfysikaalista mallinnusta. Kysely lähetettiin kohtuuhintaisten asuntojen asukkaille yhteistyössä VTS-kotien kanssa, ja sillä kartoitettiin asukkaiden kokemuksia korkeista sisälämpötiloista, tietoja käytetyistä keinoista korkeiden lämpötilojen alentamiseen, sekä asukkaiden näkemyksiä eri ikkunaratkaisuista sekä muista lämpötilan hallintaan liittyvistä teknisistä ratkaisuista.

Kyselyn vastauksia käytettiin lähtötietoina rakennuksen dynaamiselle lämpötasesimuloinnille. Simulointi toteutettiin valitulle VTS-kotien asuinrakennukselle, johon on tarkoitus tehdä energiatehokkuutta parantava saneeraus lähitulevaisuudessa. Simuloinnin avulla tutkittiin lämmitysenergian kulutusta, päivänvalon määrää ja ylilämpenemistä nykyisessä ja tulevaisuuden ilmastossa. Kyselyn tulokset indikoivat korkeaa ylikuumenemisastetta asunnoissa. Vastaajista 92% ilmoitti asuntojen olevan liian lämpimiä tai kuumia ja ylikuumenemisasteen olleen suurin etelään, itään tai länteen suuntautuvissa asunnoissa. Lämpötilan alentamiseen käytetyt keinot pitivät sisällään kaihtimien sulkemisen ja asunnon tuulettamisen avaamalla parvekkeen oven. Rakennussimulaatiomallit vahvistivat korkean ylikuumenemisasteen asunnon sijoittumisen mukaan. Mallinnetut toimenpiteet liittyen ikkunoihin osoittivat, että avattavat ja aurinkosuojatut ikkunat kykenivät oleellisesti vähentämään ylikuumenemista suurimmassa osassa mallinnetun rakennuksen asuntoja osoittaen luonnollisen ilmanvaihdon ja auringonvalon suodattamisen potentiaalin lämmön alentamisessa. Yhdessä kyselyn tulosten kanssa simulaatiotuloksia voidaan hyödyntää asuntojen energiatehokkuussaneerauksia suunniteltaessa

1. Background and objectives of the project

The changing climate means that periods of hot weather and heatwaves are becoming more frequent and extreme in Finland. By 2100, it is projected that average yearly temperatures in Finland will increase by 2-6 °C, with heatwaves becoming hotter, longer, and more frequent in the future[1]. Hot weather and heatwaves are associated with a number of health and wellbeing issues. Humans have an internal body temperature of 36-38 °C at rest, regulating temperatures within this narrow range given metabolic heat production, heat loss from the body, and heat gain from the surrounding environment. When the body accumulates heat, heat stress can occur leading to acute illnesses such as cramps and heat stroke. Heat exposure can lead to decreased cognitive performance and reduced sleep quality and an increased strain on the body. Periods of hot weather are associated with a noticeable increase in all-cause mortality, including cardiovascular causes[2],[3] and increased mental health problems[4]. The heatwave in Finland from 9th July to 12th August 2018 is estimated to have caused 380 excess deaths in Finland[5], for example, while the 2022 European heatwave is thought to have resulted in over 15,000 excess deaths[6]. The health risks from heat exposure are not equally shared. Older adults, the very young, those with pre-existing health issues, and the socially isolated are more at risk of negative health outcomes[7].

In Finland, as in most other countries, the population spends around 90% of their time indoors[8], the majority of which is spent in their own homes. This is likely higher still for the most heat-vulnerable such as older adults and those with health concerns. Housing is therefore an important environment for summertime heat exposure and has increased in awareness in policy and building design, both within Finland and the European Union (EU). Finnish housing has been constructed for cold winters and mild summers rather than high temperatures, and while Finland has one of the coolest climates in Europe, national surveys in 2007 and 2010 showed that 29% and 45% of Finns, respectively, considered their homes to be too hot during summer[9]

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[1] Pilli-Sihvola, K., Halonen, J., … Sorvali, J. (2023, December 4). *Ilmastonmuutokseen liittyvät riskit ja haavoittuvuudet Suomessa: Tarkastelu kansallisen ilmastonmuutoksen sopeutumissuunnitelman 2030 taustaksi* [Sarjajulkaisu]. Valtioneuvosto
[2] Naumann G, et al. Global warming and human impacts of heat and cold extremes in the EU. In: Publications Office of the European Union. Luxembourg; 2020. Available from: https://ec.europa.eu/jrc
[3] Feyen L, et al, editors. Climate change impacts and adaptation in Europe. JRC PESETA IV final report. In Luxembourg: Publications Office of the European Union; 2020
[4] Thompson R, et al. Associations between high ambient temperatures and heat waves with mental health outcomes: a systematic review. Public Health. 2018 Aug 1;161:171–91.
[5] https://thl.fi/en/web/thlfi-en/-/last-summer-s-heat-wave-increased-the-mortality-of-older-people-prepare-for-hot-weather-in-time
[6] https://www.who.int/europe/news/item/07-11-2022-statement---climate-change-is-already-killing-us--but-strong-action-now-can-prevent-more-deaths
[7] Kollanus V, Tiittanen P, Lanki T. Mortality risk related to heatwaves in Finland – Factors affecting vulnerability. Environmental Research. 2021 Oct 1;201:111503
[8] Schweizer C, et al. Indoor time-microenvironment-activity patterns in seven regions of Europe. Journal of exposure science & environmental epidemiology. 2007 Mar 17;17(2):170–81.
[9] https://www.julkari.fi/bitstream/handle/10024/110434/URN_ISBN_978-952-245-976-3.pdf?sequence=1&isAllowed=y

while a recent monitoring study indicated that 96% of apartments exceeded 27 ° C during the hot summer of 2021[10]. Finnish buildings may be at an increased risk of overheating, as they have not historically been designed for a hot climate, and highly insulated and airtight building fabrics may trap heat inside during hot weather, while passive solar architecture can increase solar gains[11]. Of particular importance are windows due to the long summertime daylight hours with extended periods of low solar angles during morning and evening.

Due to the increasing frequency and severity of hot summers and heatwaves, there is a need to adapt buildings to improve their resilience to hot summer weather, while at the same time reducing energy consumption by making housing more energy efficient and reducing the need for active cooling systems. Given the relative importance of solar exposure on indoor overheating in Finland, and the relatively low cost of window adaptations compared to external shading or mechanical cooling, windows are a logical area of buildings to adapt. There are also opportunities to target adaptation measures towards buildings with higher-than-average numbers of vulnerable occupants, combining adaptations with scheduled building renovations. One possibility is affordable housing, which can house vulnerable occupants and where providers and occupants are limited in terms of the installation of specialized building services equipment such as air conditioning (which may also be costly to maintain and operate), and instead require low-cost retrofit and adaptation measures. However, there is a need to understand the effectiveness of different adaptations, occupants understanding of heat risk, and what heat-mitigating adaptations are most acceptable.

The aim of the SEASON project was to understand how different window and shading designs can reduce overheating in affordable housing apartments. To do so, we survey residents of affordable housing in Tampere, Finland, and – using a representative apartment building as a case study – we model indoor temperatures and overheating risk under current and a range of future climate and window adaptation scenarios to understand the energy, daylighting, and overheating implications of these adaptations.

2. Project partners and methods

The project is a collaboration between the Urban Physics Research Group and the Department of Architecture, Tampere University (TAU), the affordable housing provider VTS-kodit, a social landlord in Tampere that provides low-cost rental homes to around 17,000 residents, and Pihla Group Oy, Finland largest window manufacturer, and regularly undertakes window renovations in housing companies throughout Finland.

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[10] Farahani AV, et al. Overheating assessment for apartments during average and hot summers in the Nordic climate. Building Research & Information. 2023 Sep 5;1–19.

[11] Taylor J, et al. Ten questions concerning residential overheating in Central and Northern Europe. Building and Environment. 2023 Apr 15;234:110154.

2.1. Methods

The study used a socio-technological approach to understand both the current extent of overheating, occupants' behaviours to mitigate and adapt to heat, as well as modelling indoor overheating under a range of climate and housing adaptations. To do this, we surveyed occupants in order to understand their behaviour in warm weather and identify their preferences for different window and shading adaptations. We then modelled a case study apartment in an affordable housing apartment building using the dynamic energy modelling program IDA Indoor Climate and Energy (IDA-ICE) under current and future climate scenarios. Using this building physics model, we tested a range of different window and shading adaptations for their ability to reduce summertime overheating as well as impacts on energy consumption.

Survey

A survey was developed and sent to residents of VTS-kodit residential buildings in Tampere. The survey was designed to evaluate how well they understand heat risks, what types of actions they take to reduce indoor temperatures, and how they would accept and use the different window adaptations modelled. The survey consisted of 17 questions clustered into four main groups: (1) a descriptive analysis to understand the number of people living in the households, general location of the apartment in the building, and type of ventilation system (if any); (2) the occupants' behaviour during hot weather; (3) the occupants' window preferences; and (4) the occupants' shading preferences. To safeguard the rights and freedoms of data subjects, we did not collect personal data. We used descriptive statistics to describe and analyse single variables, followed by ordinal logistic regressions to assess for differences in self-reported overheating risk between apartment and household characteristics. Analysis was carried out using R.

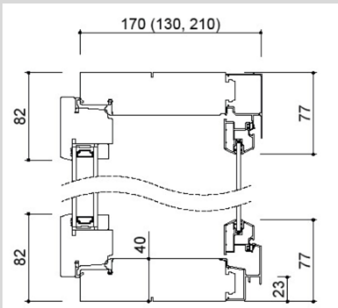
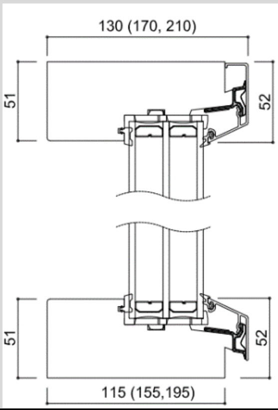
Simulation

A specific VTS apartment was modelled IDA ICE 5.0, a dynamic building simulation tool regularly used to assess energy and overheating performance of buildings at the design-stage in Finland. The modelled apartment was an 8-story apartment building located in Hervanta, Tampere, which was constructed in the 1970's and has upcoming energy efficiency renovations to the windows planned. Currently, windows are triple-glazed (u-value 1.9 W/m²K) with blinds or curtains on the inside. Bedroom windows can be opened via an openable side window, while living rooms have balcony doors which can be opened. Floorplans and building data was provided by VTS-kodit.

The building was modelled with all apartments at the top and bottom levels as-is, and with adaptations to windows and shading. The modelling approach differed from that of the guidelines for design-stage overheating modelling which allow for increased mechanical extract ventilation, the closing of integrated blinds, and closed internal doors. This is because this is an as-built simulation, while the existing building does not have integrated blinds in the windows and has only constant exhaust ventilation. Instead, we modelled occupant behaviours as per the outcomes of the survey, which indicate that internal blinds and balcony doors are used by residents during periods of hot weather. Balcony doors were opened when indoor temperatures exceeded 24 °C and outdoor temperatures were less than indoor temperatures, internal blinds were closed in response to sunlight levels, and doors inside the apartments were left open to ensure airflow. We assumed balcony glass was opened during the summer to prevent high balcony temperatures and ensure sufficient airflow. While adaptations to balcony glass, such as blinds, could have further reduced indoor temperatures, we did not model this as the focus was on window replacements.

The modelled adaptations to the windows are described in Table 1. Replacement windows offered increased energy efficiency, greater openable area, and reduced g-values. These windows were modelled with integrated blinds which, similar to the base-case, closed in response to sunlight levels. Window adaptation also included variants with solar protective film to reduce the amount of solar gains entering the apartments.

Table 1. Characteristics of base case and window interventions and ventilation.

Window	U-value (W/m²K)	G-Value (-)	Frame width (mm)	Description	
Base	1.9	0.76	82	Base case window with an openable side window in the bedrooms and openable balcony door in living rooms	
Window A	1.0	0.58	82	All windows are replaced with Window A that has an openable size window. The side window is has the maximum allowable width for the window height (590mm). For windows larger than 2m wide, two side windows were installed on either side of the window. Balcony doors are replaced with energy efficient glass doors (U-value 1,0, with or without protective solar foil)	
Window A with Solar Protection	1.0	0.38	82		
Window B	1.0	0.53	52	All windows are replaced with Window B, an energy efficient window without a side window. Balcony doors are replaced with with energy efficient glass doors (U-value 1,0, with or without protective solar foil)	
Window B with Solar Protection	1.0	0.35	52		

Simulations were performed for summertime overheating (June - August) using weather files from the Finnish Meteorological Institute (FMI) representative of 2020, 2050, and 2080 climates for Tampere (Jokoinen) according to RCP4.5 [12]. Energy consumption was estimated for the calendar year using the 2020 weather file.

Model space heating energy consumption and daylighting was taken directly from the results of the IDA ICE models, while thermal comfort were aggregated and calculated using a postprocessing script run in R Studio. For energy, the space heating energy consumption per unit area was obtained for the building. Daylighting (specifically, the daylight factor for the International Commission on Illumination (CIE) standard for an overcast sky) was simulated separately, estimating the daylight factor at a height of 0.8 on a horizontal surface with no blinds drawn. For daylighting, the median was taken for all rooms.

Thermal comfort was calculated according to Finnish overheating standards from the Ministry of Environment, which requires a maximum of 150 degree hours (Kh) above 27°C during summer for the new apartment buildings according to simulations performed according to their guidelines. We calculate the same metric for the different years simulated, as well as the European thermal adaptive comfort standard BS EN 16798-1, which is widely used for free-running buildings (or buildings without mechanical heating or cooling, such as the building modelled here) and which allows for the fact that individuals can physiologically adapt to high temperatures over time. This adaptive model was estimated for three different categories:

- Category I: A high level of expectation, for vulnerable persons, with a range ±2 °C of the calculated comfort temperature
- Category II: A normal expectation for new buildings and renovations, with a range ±3 °C of the calculated comfort temperature
- Category III: A moderate expectation for existing buildings, with a range ±4 °C of the calculated comfort temperature

The thermal comfort calculations were performed for each of the modelled rooms in the building and aggregated. To make this metric somewhat comparable with the Ministry of Environment metric, we estimate degree-hours of exceedance rather than reporting the number of hours only.

3. Project results

Survey

Additional results from the survey can be seen in Appendix 1. There were 136 responses to the survey, with respondents from 49 different VTS apartment buildings. The majority of respondents lived in the top or second top (36%) or middle (35%) floors of their buildings. Most apartments were oriented towards south (22%) or west (21%). The apartments represented residences for 680 people, the age distribution of which can be seen in Figure 1. The apartments were consistently occupied throughout the day, particularly on weekends.

[12] https://www.ilmatieteenlaitos.fi/energialaskenta-try2020

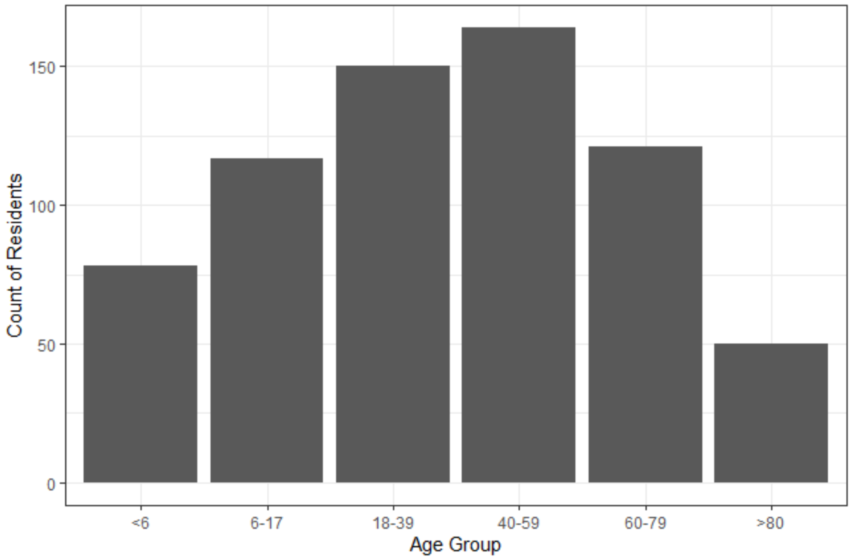


Figure 1. Age distribution of responding households.

Respondents indicated that apartments had a significant overheating risk (Figure 2), with 62% responding that their living rooms were hot during the day, and 92% responding that they were too warm or hot. Rates of uncomfortable nighttime bedroom temperatures were also found to be very high, with 49% responding that temperatures were hot and 39% responding that they were too warm. The ordinal logistic regression indicates a significant increase in self-reported indoor temperatures by floor level (top floors with the greatest rates of self-reported overheating) and orientation (North-facing having significantly lower amounts of self-reported overheating).

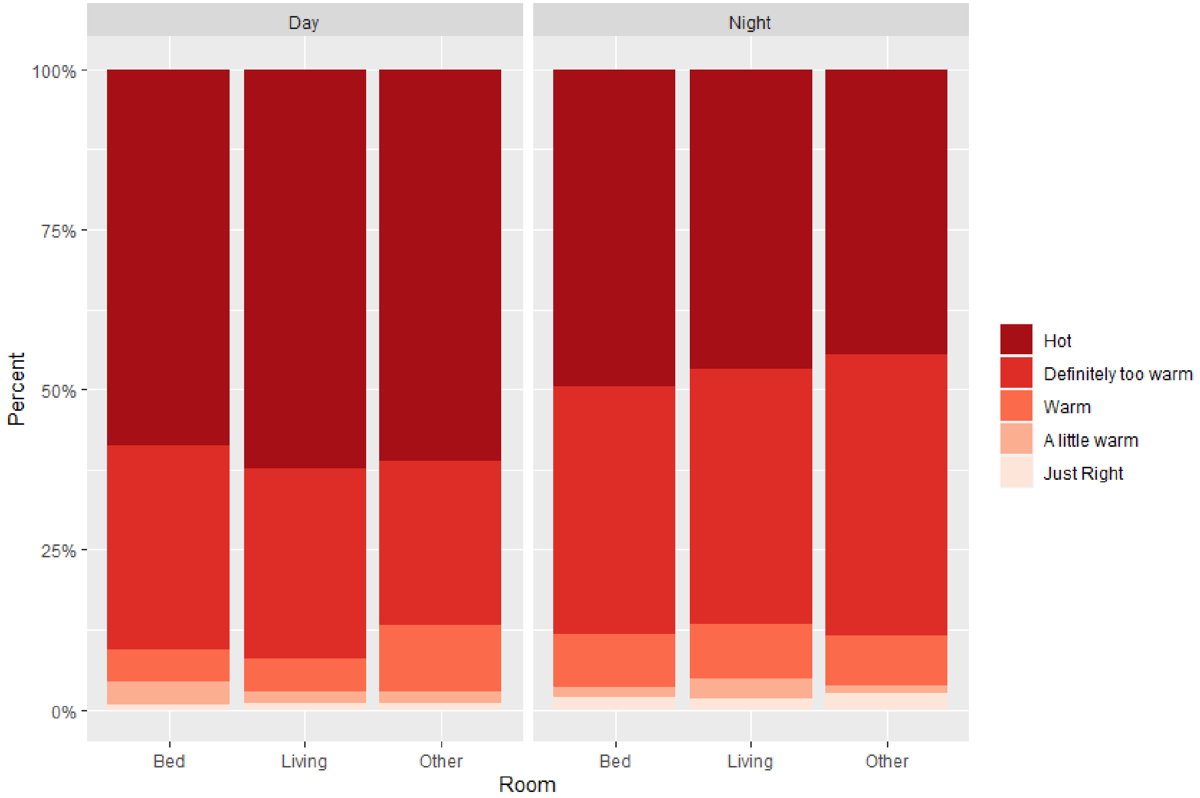


Figure 2. Subjective overheating in respondent apartment buildings (bedroom, living room, some other room) when outdoor daytime temperatures exceed 25 °C.

During periods of hot weather, occupants reported using a variety of adaptations to reduce indoor temperatures (Figure 3), including using window blinds and curtains, opening or closing windows, and using electric fans. Many residents were interested in using mechanical cooling in the future, while windows with solar protection, a ventilation side window, and with integrated blinds were the most popular window option. Common personal adaptations to heat included taking a shower, changing clothes, and drinking cold water.

When asked to mark when and how they ventilate their homes during hot weather, respondents showed rates of ventilation of around 25% suggesting that this is an underutilized means of cooling the apartments (Figure 4). Residents increased their use of natural ventilation while at home, with diurnal patterns indicating that balcony doors and windows are left open overnight. Outdoor noise and insects were primary reasons for keeping ventilative openings closed, while free-text answers indicated that household pets were another important reason.

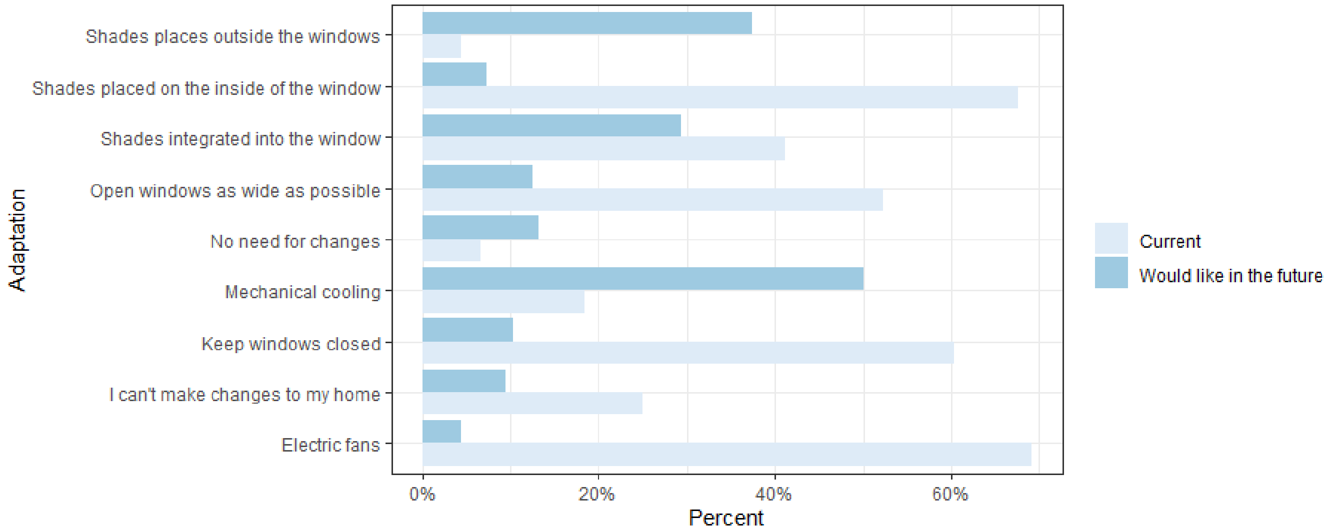


Figure 3. Respondent actions to cool their apartments by the % of households

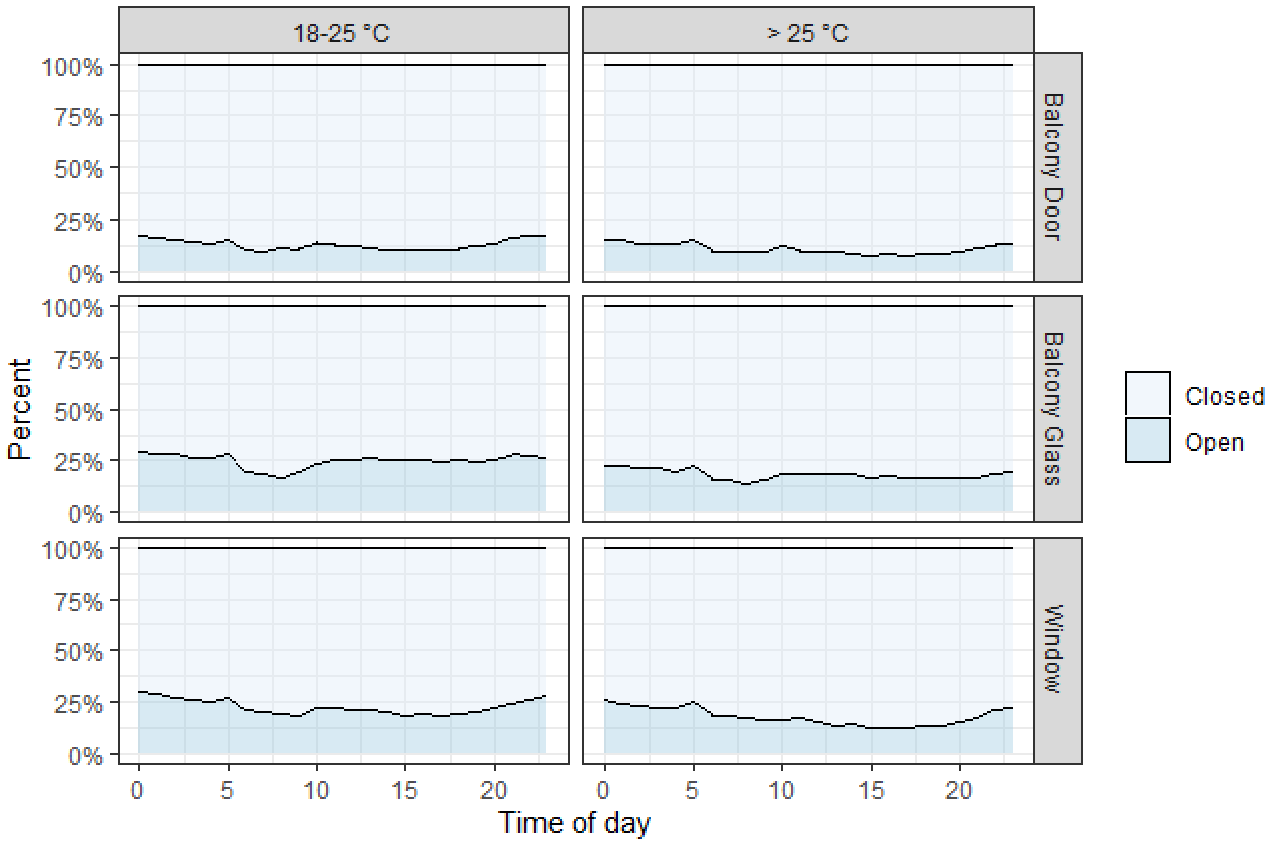


Figure 4. Occupant ventilation patterns during the day.

Building Simulation

Building simulation results can be seen in Figures 5-6. Under the base case scenario, there was a much higher risk of overheating in south-facing apartments compared to north-facing (Figure 5), with much of the difference between apartments attributable to the orientation. For the many 2 room (or 1 bedroom) apartments, the greater heat risks can be seen in the location with the larger south-facing windows. Modelling results reflected the survey answers, with apartments facing south and top floor apartments experiencing greater levels of overheating. A clear difference in the heat risk can be seen between the different standards used, with the adaptive standard showing a low number of degree hours due to the assumption of physiological adaptation. In the case of the degree-hours over 27 °C commonly used for design-stage analysis in Finland, the majority of apartments exceeded the 150 K-h guideline limit for overheating, with the exceptions being a selection of north-facing apartments under the 2020 climate.

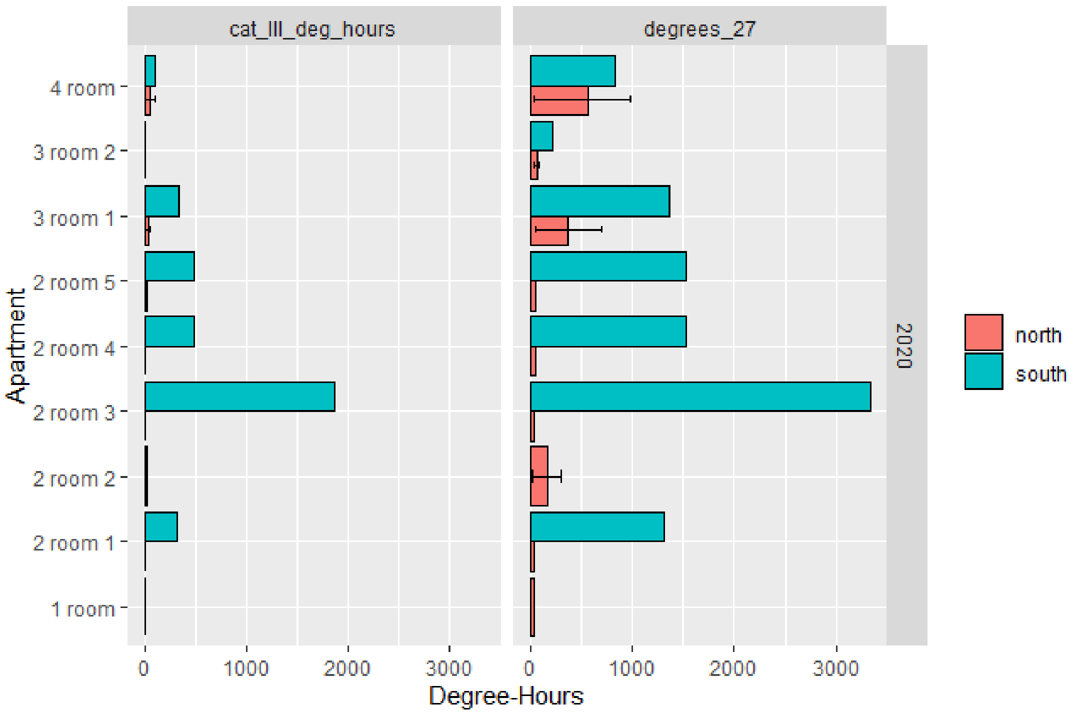


Figure 5. Overheating by apartment, by the orientation of the rooms under the 2020 climate for different overheating metrics.

Heat exposures increase as the climate warms (Figure 6), but the modelled adaptations are able to significantly reduce the degree hours of overheating. Window adaptations that increase ventilation were more effective than solar protection foil alone, illustrating the benefits of allowing for airflow throughout apartments. The low levels of overheating using the adaptive standard versus the static threshold indicate the sensitivity of overheating risk assessments to the metric used. By 2080, the windows with additional ventilation and solar protective foil were able to reduce overheating to below regulation levels in the majority of simulated rooms.

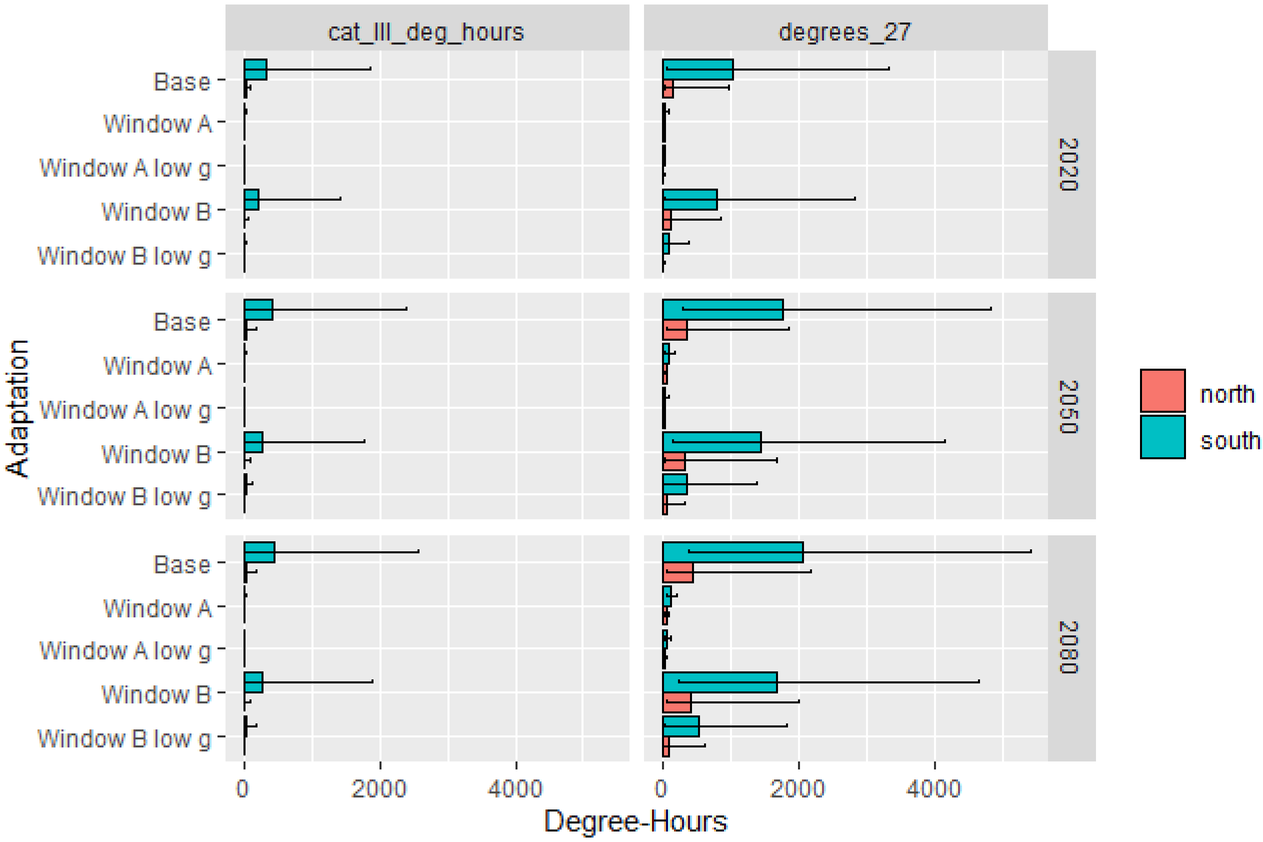


Figure 6. Degree hours above BS EN 16798-1 (left) and above 27C (right) under the base and adaptation windows. Bars represent the average degree hours in the apartment, while error bars represent the minimum and maximum within the rooms of the apartment. Results are grouped by window orientation.

In all cases, the energy efficient retrofit of windows led to a decrease in energy consumption in the building relative to the current baseline. The application of solar control foil on the windows led to a marginal increase in space heating energy consumption compared to the equivalent window without foil, presumably because of the reduction in winter solar gains. There were no impacts on daylighting levels by applying the solar foil as transmittance was not changed, although the frame sizing did lead to a minor decrease in daylighting from the new windows.

Collated results can be seen in Table 2, including the energy, overheating, and daylight performance derived from the simulations, the occupant preferences from the survey, and an indicative cost per m2. These results indicate that windows with an openable side aperture are a strong choice for the renovation of the building, offering reduced overheating risk and space heating energy consumption, while having lower costs and high occupant preference. Installing solar film on south facing windows can help to offset overheating further, while this may not be necessary on the north face of the building.

Table 2. Simulation and survey results for modelled window variants.

Window	Whole Building Space Heating Energy (2020) (kWh/m2)	Apartment room-average degree-hours above 27 °C (2080)	Apartment room median daylight factor (%) (CIE)	Resident preference (rank)	Illustrative Cost (€/m2)
Base	131.0	979	0.91	(-)	(-)
Window A	116.4	68	0.87	2	190
Window A with Solar Protection	122.6	32	0.87	1	215
Window B	118.0	846	0.88	4	210
Window B with Solar Protection	123.9	242	0.88	3	235

4. Impact of the project

Recent studies have suggested that mechanical cooling is the only way to ensure that indoor temperatures are able to meet existing thermal comfort guidelines in Finland in the future[13]. However, these studies were performed according to the design guidance, and does not account for occupant capacity to adapt. Mechanical cooling has significant energetic costs, and depending on the source of energy, it can lead to substantial Greenhouse Gas emissions. Evidence also shows that air conditioning can contribute to increased local outdoor temperatures due to the heat removal from buildings[14], thus worsening the Urban Heat Island effect. In hotter climates, the availability of active cooling systems is an issue of equity, with exposures higher for those not in conditioned spaces such as outdoor workers or those living in homes without A/C [15]. A reliance on active systems means that heatwave mortality can be amplified during energy blackouts [16], meaning buildings should also be designed to for passive survivability – or the ability to remain safe without an energy supply. Due to these issues, various EU and national policies advocate for the prioritisation of passive measures to reduce indoor overheating [17].

Scheduled energy efficiency renovations provide opportunities to reduce indoor overheating and building space heating and cooling energy consumption, and this study demonstrates how window interventions can help mitigate overheating. Passive measures such as window alterations do does not exclude active cooling systems, which may be required to reduce

[13] Farahani, A. V. et al. (2024). Simulation analysis of Finnish residential buildings' resilience to hot summers under a changing climate. *Journal of Building Engineering*, *82*, 108348.
[14] Brousse, O., et al., 2023. Cool roofs could be most effective at reducing outdoor urban temperatures in London compared with other roof top and vegetation interventions: a mesoscale urban climate modelling study. Authorea Preprints.
[15] Huang, L., et al. Inequalities across cooling and heating in households: Energy equity gaps. *Energy Policy*, *182*, p.113748.
[16] Stone Jr, B., et al., 2023. How blackouts during heat waves amplify mortality and morbidity risk. *Environmental Science & Technology*.
[17] Taylor, J., et al., 2023. Ten questions concerning residential overheating in Central and Northern Europe. Building and Environment, 234, p.110154.

exposures for the most vulnerable or that can operate when adaptive thresholds are exceeded, but can help to reduce energy demand, minimise the negative impacts of active cooling, and provide passive survivability.

Results of this study indicates that, through a combination of window adaptations and physiological adaptations, the overheating performance of these 'free-running' buildings can be reduced substantially through additional ventilation openings that allow ventilation through the apartment. Given scheduled energy efficiency upgrades of the windows in the VTS apartments, there are opportunities to implement new windows that can help reduce indoor overheating, working with existing occupant adaptation actions and preferences, and so save energy. Choosing the correct intervention (i.e., passive solutions that facilitate occupants' behaviour change) can help extend the lifespan of the buildings. The results also illustrate the potential for 'sufficiency' in indoor temperatures, where energy use is avoided and indoor temperatures are allowed to vary.

Finally, this project also provides a better understanding of how occupant preferences for window types and the actions they may take during hot weather (i.e., leaving the doors and windows open overnight) can support decision-making towards socially sustainable options for retrofits.

5. Communication activities and their results

The study and provisional results were discussed in a livestreamed broadcast via the KiraHub on November 17th, 2023. This report will act as a basis for the peer reviewed journal article (expected to be submitted before summer 2024), and the results here will be shared with collaborators and discussed in a workshop at a later date.

The project realised the planned research objectives of the study. An output to the study was a publicly available journal paper/report on the findings, which is still under preparation and due to be submitted to a journal by early summer 2024. As a result, final results have not yet been communicated widely. While it was expected that the final publications would be finalised in mid-2024 due to the slow process of academic publishing, delays of three months while we recruited a researcher to conduct the building simulation modelling mean that the final publication is still under preparation.

6. Sustainability and utilisation of the results

This study's results indicated a significant modelled and self-reported overheating risk in the apartment buildings, making apparent the need for various cooling measures to be applied. However, model results were from a single case-study building while results from the survey were from residents of VTS housing biased towards specific population groups and a non-representative sample of all individuals. This means that appropriate measures for each building need to be assessed individually, and more research is required to identify the effectiveness of adaptations in different building types and latitudes.

The evidence from this and other papers indicates that overheating is an issue in existing apartments of this era, and issues will continue to increase in the future if measures are not taken to mitigate heat. Finnish guidelines to assess overheating risk exist at the design-stage, and there is evidence that modern buildings built within these guidelines overheat less than older buildings [18].

Results demonstrated the performance of different window adaptations in terms of overheating, energy, daylight, and occupant preference, which can support the decision-making on the window retrofits in VTS-kodit properties in the future, as well as for similar buildings. Therefore, there is a clear pathway for the results to be utilised in the future.

Regardless of whether the policies implemented for reducing overheating in new buildings call for active cooling or not, it is important that passive cooling measures are included in order to reduce active cooling demand and improve passive survivability. For example, guidelines for construction design and engineering in other parts of Europe, such as London, allow for active cooling only when all other passive options have been exhausted [19]. Results of this study are valuable to help evaluate the effectiveness of sustainable alternative to active cooling systems which may reduce the need for energy-consuming active systems as much as possible.

Finally, it is important to highlight that although many residents were interested in using mechanical cooling in the future, windows with solar protection, a ventilation side window, and with integrated blinds were the most popular window option, and so future windows retrofits should be designed to promote occupants' behaviour change.

7. Conclusions

This study aimed to evaluate the occupant experiences and responses to overheating, and evaluate the suitability and effectiveness of different window adaptations for indoor temperatures, energy performance, daylighting, and occupant preference. Results indicated a high level of dissatisfaction with indoor temperatures during periods of hot weather, with residents exhibiting a range of personal and building adaptations to help reduce the effects of

[18] Farahani, A.V., et al., 2023. Overheating assessment for apartments during average and hot summers in the Nordic climate. *Building Research & Information*, pp.1-19.
[19] https://www.london.gov.uk/programmes-strategies/planning/london-plan

the heat. Furthermore, a significant increase in self-reported indoor temperatures by floor level (top floors with the greatest rates of overheating) and orientation (North-facing having the least amount of overheating) highlights those apartments with higher risk of overheating and where further actions could be implemented if passive solutions are not enough. Simulation results indicate that increasing ventilation and reducing the solar gains through the windows can significantly reduce overheating in the future. Overheating risk varied depending on the metric used, with adaptive thermal comfort indices showing that a combination of occupant physiological adaptation and window shading and ventilation can reduce indoor overheating levels. These findings show the potential of implementing a human-centred design approach, with retrofit solutions designed in collaboration with occupants, to facilitate adaptation and interaction with the implemented passive solutions, to reduce overheating risk and, consequently, energy consumption and social injustice.

8. Acknowledgements

We acknowledge the support of our collaborators at Pihla Oy, who have provided window information and funding, as well as Miska Pöyry from VTS-Kodit who supported the development and delivery of the survey and provided information on the buildings. Our thanks to the many residents of VTS-kodit homes who completed the survey and provided their valuable information.

Appendix 1

Survey Results

There were 136 responses to the survey, with respondents from 49 different VTS apartment buildings. The majority of respondent lived in the top or second top (36.2) or middle (35.4) floors of their buildings. Most apartments were oriented towards south (21.7%) or west (21.3%). The apartments represented residences for 680 people, the age distribution of which can be seen in Figure S1. The apartments were consistently occupied throughout the day, particularly on weekends (Figure S2)

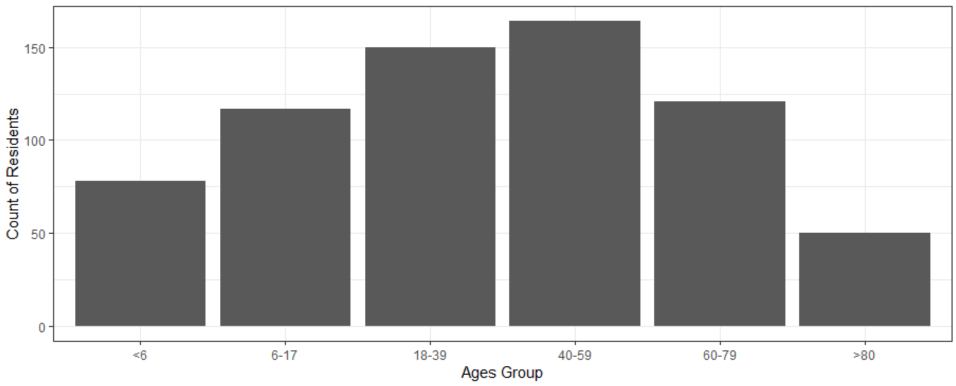


Figure S1. Age distribution of responding households.

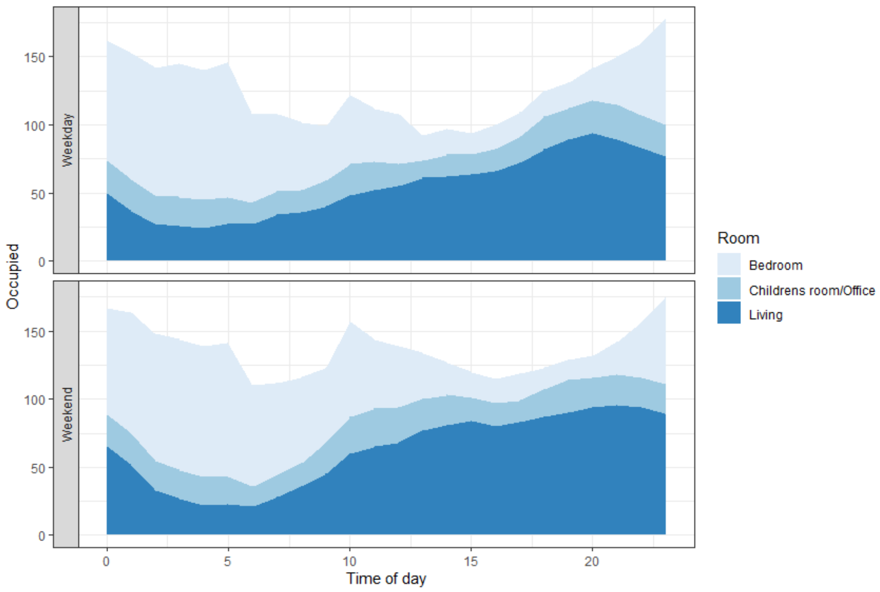


Figure S2. Apartment occupancy during typical days.

Experience with Overheating

Respondents indicate that apartments had a significant overheating risk (Figure S3), with 62% responding that their living rooms were hot during the day, or 92% responding that they were too warm or hot. Rates of uncomfortable nighttime bedroom temperatures were also found to be very high, with 49% responding that temperatures were hot and 39% responding that they were too warm. The ordinal logistic regression indicates a significantly increased risk of overheating in South, Southwest, and West-orientated apartments (Figure S4A) and in top and middle floor apartments (Figure S4B).

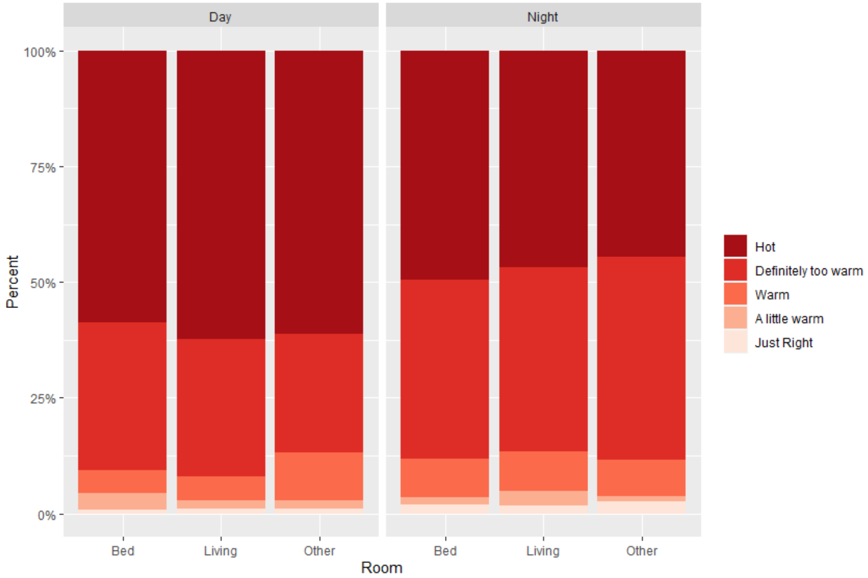


Figure S3. Subjective overheating in respondent apartment buildings when outdoor daytime temperatures exceed 25C:

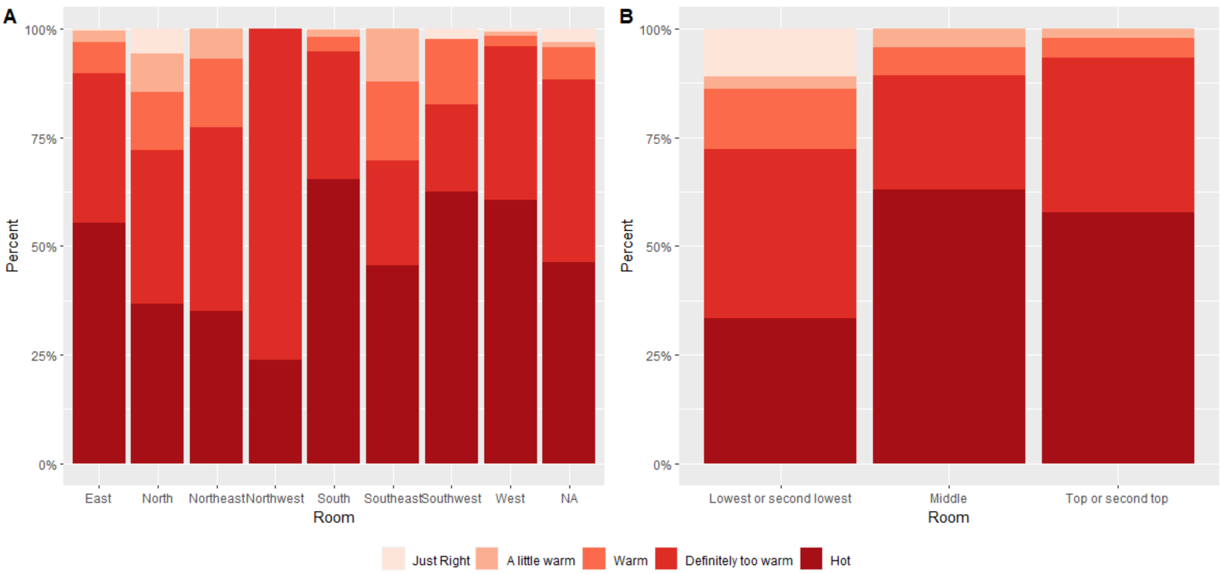


Figure S4. Reported overheating by A) orientation and B) floor level.

Occupant Response to Heat

In response to hot weather, respondents often opened windows and balcony doors to ventilate their properties (Figure S5). The rates of opening decreased during the middle of the day, reflecting the times when occupants were less likely to be home. Ventilation through openings decreased at higher outdoor temperatures, possibly due to actions to limit hot air coming indoors. The different reasons for ventilation can be seen in Figure S6. The predominant driver was for fresh air and to cool down the apartment, while less commonly for pollutant removal and connection with nature. Balcony doors were used more often than windows both during the day and at night.

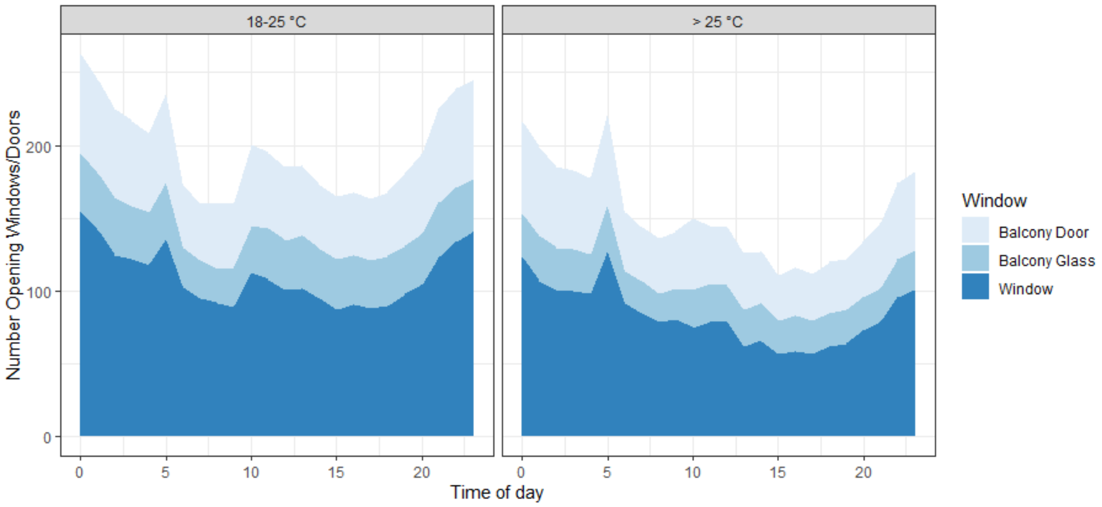


Figure S5. Occupant ventilation patterns during the day.

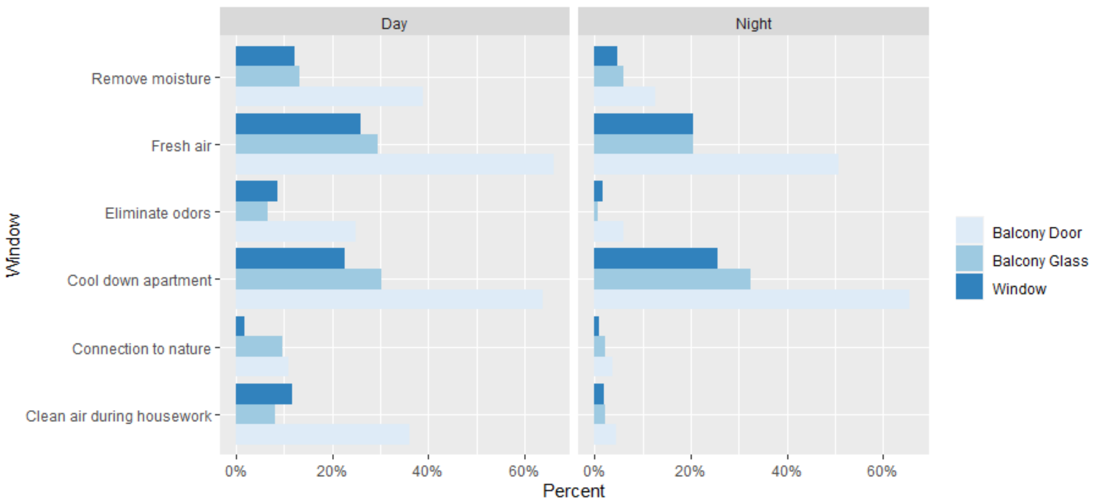


Figure S6. Reasons for ventilation, by opening type and time of day

The predominant reason that respondents did not use windows was due to outdoor noise levels and insects, while energy saving was less of a concern (Figure S7). A selection of free text answers indicated that domestic pets were another reason for not opening windows.

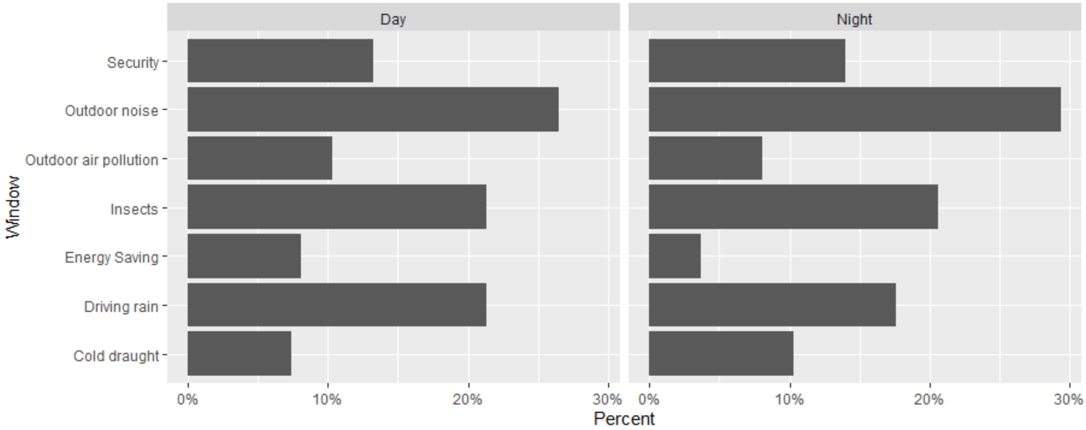


Figure S7. Reasons why respondents did not open windows or balcony doors.

Apartment and Individual adaptations

Respondents often made multiple adaptations to their buildings to reduce temperatures (Figure S8). The majority used electrical fans and integrated window blinds to help reduce indoor temperatures. Around half were interested in having active cooling systems in the future, while around 40% were interested in having external shading installed. Individual actions taken to keep cool can be seen in Figure S9. The most common actions are to drink cool water and use fans, while a minority do not change their behaviours to adapt to the hot weather. There were no significant differences in individual adaptation behaviour between age groups.

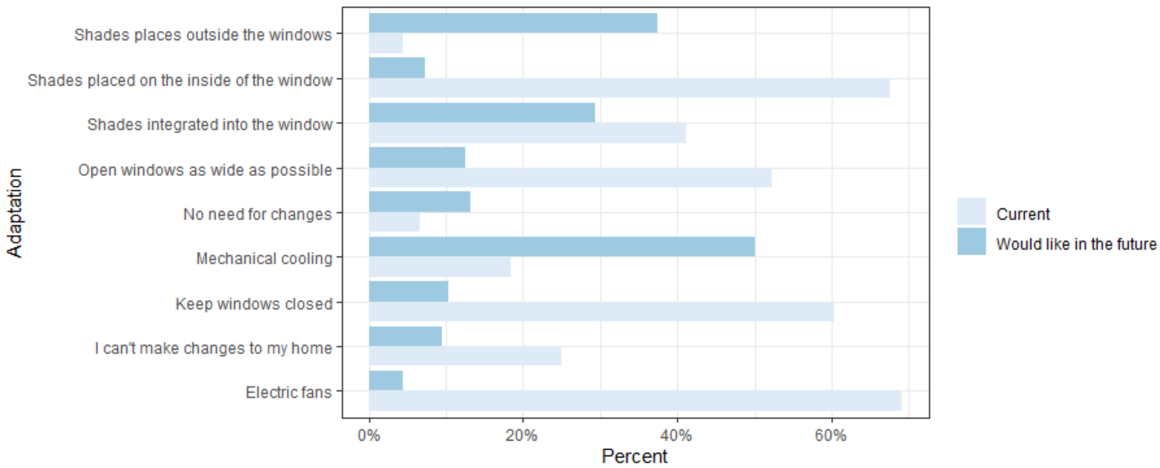


Figure S8. Respondent actions to cool their apartments

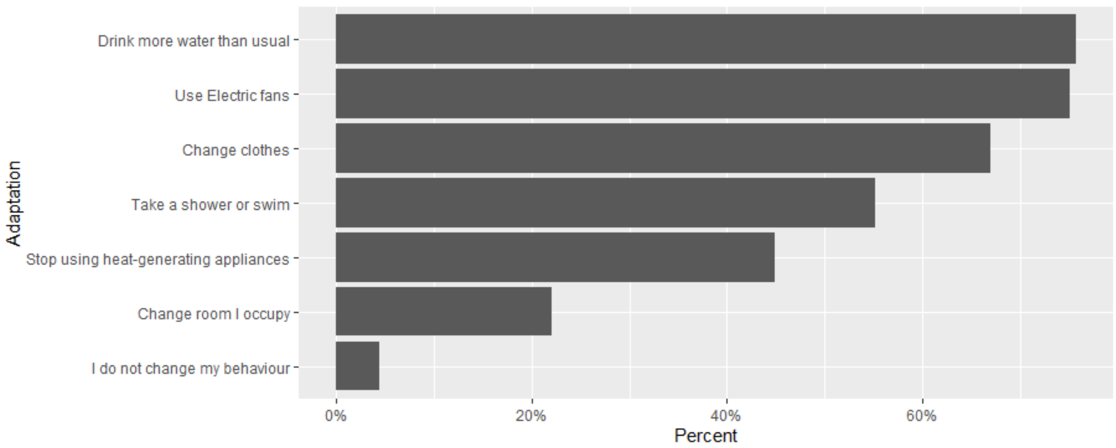


Figure S9. Individual adaptations to keep cool.

Occupant Window and Shading Preferences

Respondent preferences can be seen in Figure S10. Fixed or tilting windows were less popular than windows that limited solar raditation and fixed windows with ventilation openings. Blackout curtains or blinds, integrated blinds, and smart blinds were popular shading solutions, with external shadings such as awnings and external shutters less popular. For residents, ventilation and isolation are important characteristics for windows, while view and connection to nature were relatively less important (Figure S11)

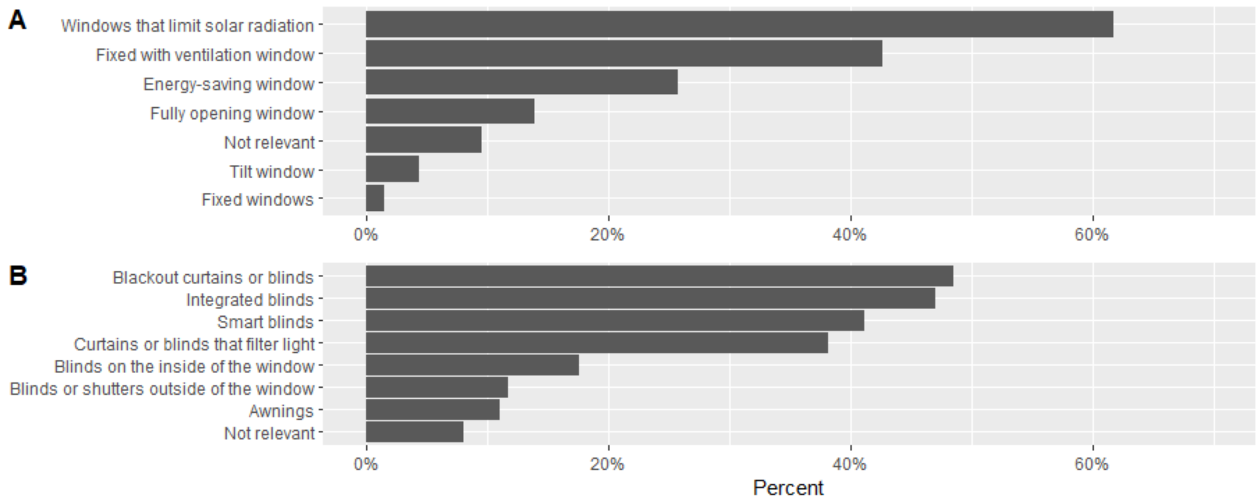


Figure S10. Windows and shading solutions by resident preference.

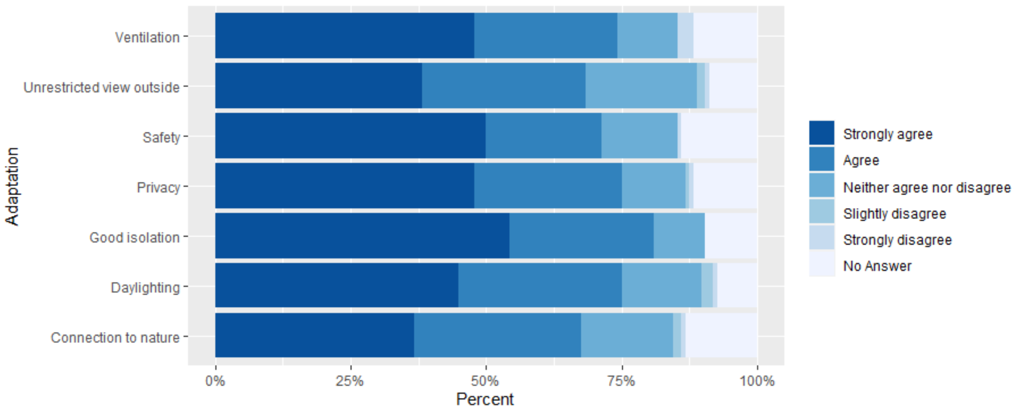


Figure S11. The importance of different window features to residents.