D3.1 Knowledgebase for occupant-centric space cooling

Cool LIFE

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List of Acronyms

AC	Air conditioning
AMV	Actual Mean Vote
Clo	Clothing factor
DR	Draught rate [%]
Met	Metabolic rate
PD	Percentage Dissatisfied [%]
PMV	Predicted Mean Vote [%]
PPD	Predicted Percentage of Dissatisfaction [%]
SC	Space cooling

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Keywords list

- Occupant behaviour
- Thermal comfort theory and standards
- Socially constructed theory of thermal comfort
- Sustainable space cooling
- Survey on occupant behaviour in residential buildings in summer

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Executive summary

This research conducts a comprehensive literature review of the socially constructed concept of thermal comfort, with a focus on summer comfort, the origins and development of the term and the influence of external and internal factors for its determination, in order to highlight the importance of lifestyle and user behaviour in space cooling demand. At the same time, the report includes a case study for Hungary, where exploratory surveys were carried out on the topic, providing relevant insights such as patterns of energy demand, schedules of occupancy, and space cooling related comfort requirements, among others.

Chapter 2 provides a theoretical framework, with the rationale behind this research and different definitions of thermal comfort, as well as definitions of the indicators used.

Chapter 3 describes the methodology used for the general literature review of this report, as well as the collection and analysis strategy of academic literature. At the same time, it provides the methodology used for the surveys, including the data collection techniques, the design and structure of the research and a description of how the survey was conducted.

Chapter 4 provides a comprehensive analysis of the meaning of thermal comfort with regards to space cooling. In this chapter, we analyze the origins of this notion, the evolution of the concept (from merely a state of mind to complex quantitative parameters enshrined in building codes and international standards nowadays) and the impacts it has in modern life. We also provide insights on the drivers behind the different perceptions of comfort, and argue that there are four dimensions that must be considered for its conceptualization, namely mind, body, space, and culture. Moreover, we offer examples of the region-specific traditional practices in coping with summer weather. In this chapter results for the literature review of standard indoor temperature requirements, and preferred indoor temperatures of residential building occupants in different regions of Europe is presented. It is concluded that while the comfort requirements are well aligned throughout Europe and implemented in commercial buildings, academic information on space cooling preferred setpoints for residential buildings is very limited as opposed to literature regarding heating setpoints. The review reveals that occupant's behaviour in using active space cooling is different than what is seen for heating, as the preferred summer temperatures cannot be taken as realistic setpoints. Preferred temperature values are heterogenous and limited information is available on to what extend and how active SC devices are used to reach this targeted value. The relationship of preferred, actual temperatures and SC setpoints are also presented in this survey as a finding. Finally, in this section an overview of the development of comfort theory is provided in order to analyze the origins of the standard approach, including a critical review of the standardization of these parameters in the built environment. We find that a number of simplifications in the standard methodologies cannot address the complexity of the thermal sensation of each individual, and also can have limitations regarding space types in their application.

Chapter 5 contains all the analysis of the exploratory surveys: the results are presented and discussed, including temperature preferences, shading patterns, space cooling techniques, and patterns of air-conditioning use. In addition, the characteristics of the respondents and the dwellings are described, in order to display a more accurate characterization of the building occupants. As part of the findings, we observe that, when asked about their preference

regarding the temperature in their dwelling during summer, respondents' mode and median values reflect preferences for a lower temperature, with the median value being 22°C. There is a correlation between the actual temperature in the dwelling and the preferred temperature in summer at daytime when household members are at home. Those who have a relatively low temperature in their dwelling (18°C - 17°C or less) mostly desire the same temperature. A smaller proportion of them would feel more comfortable with a higher temperature. The ratio of those preferring a warmer temperature in their dwelling is shrinking as the temperature measured in the dwelling rises. The turning point can be detected at a temperature of 25°C in the dwelling as the greater part of the respondents who have 25°C or more in their dwellings (65.0%-88.7%) wish for a colder temperature. However, many respondents are comfortable with temperatures out of the comfort range suggested by the comfort theory. 20% of people are satisfied with 28°C at daytime, and this is close to 30% at night time.

As for personal space cooling techniques in a hot summer day described in the investigation almost everyone (97.1%) applies wearing lighter clothing, but opening or closing of the windows (86.0%) and shading (82.7%) also prove to be wide-spread techniques, and also a relatively higher share of the respondents mentioned moving less, resting (76.1%) and taking a cold shower or bath (69.6%).

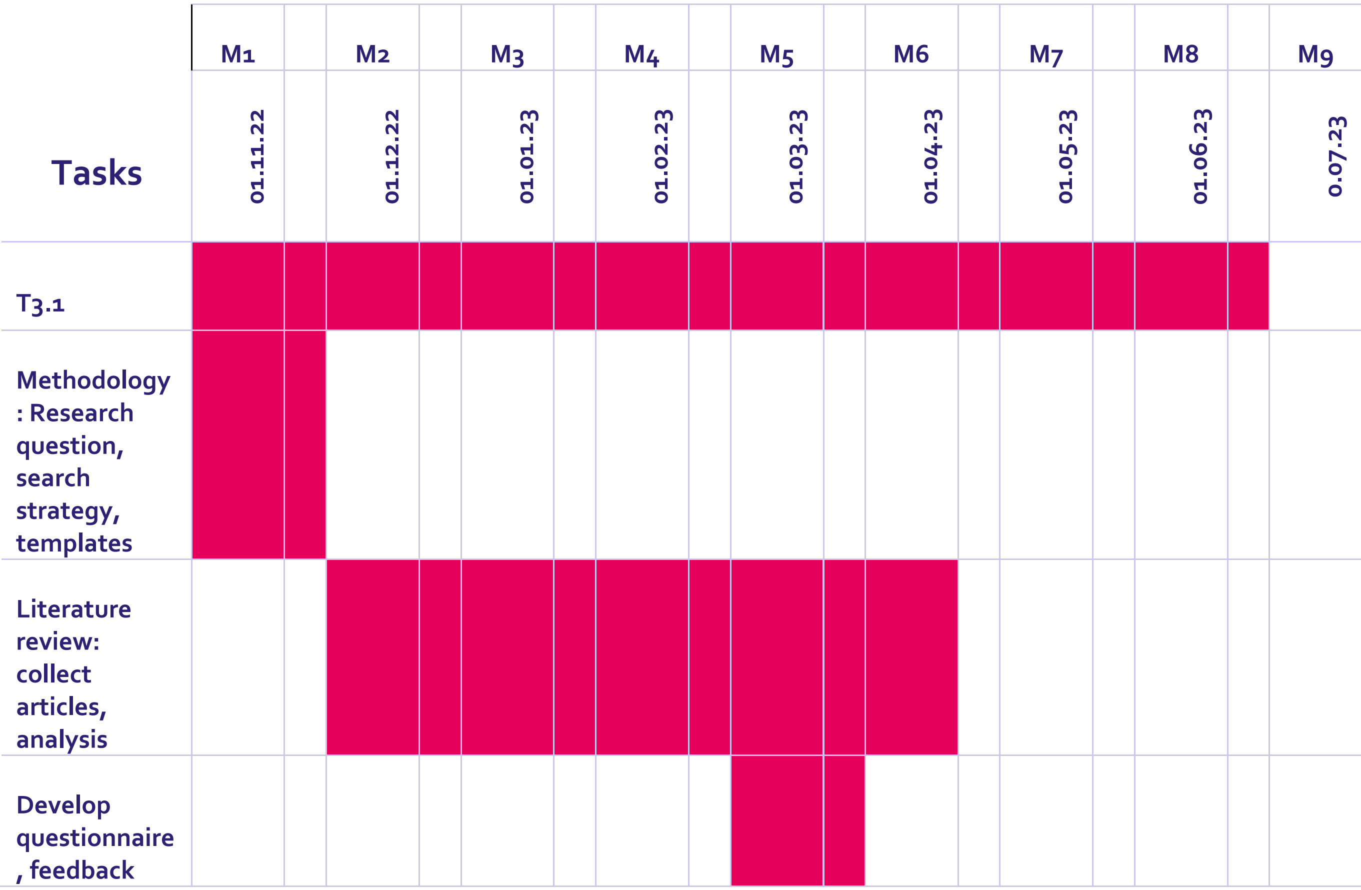
In regards to air-conditioning use it is seen that 39.5% of the respondents installed SC devices, however 5.6% of them never use it. From those who choose to use the air conditioning dominantly set a temperature of 25°C (13.5%), and a similar 13.3% make the device on 24°C. A further 12.4% and 12.7% aims a temperature of 22°C and 23°C respectively, and still one-tenth of the respondents answered to set a temperature of 26°C. As an overall pattern the air conditioning is used at an average temperature of 22.67°C and the median is 23°C. The majority of the respondents adjusts the air conditioning to a fixed temperature (53.7%), and the rest of the sample (46.3%) choose to decide about it depending on the outside temperature. The mean value for adjusting the air conditioning is 22.4°C, the median is 23°C, and the most frequent value is also a similar temperature: 24°C. While these values are in the comfort range, it is seen that the majority of the households do not use ACs to maintain indoor temperatures.

Finally, specific conclusions and closing remarks are provided in Chapter 6. Here, we argue that the current meaning of summer thermal comfort is strongly associated with the use of air conditioning (AC) from building occupants' perspective. This report tries to give visibility to the fact that this concept is not fixed and set in stone, but that it has evolved throughout time and that it could keep evolving, in order to support the adaptation capacities of individuals. Therefore, a key takeaway is that the design of solutions to reduce space cooling demand should be greatly informed by the social, physiological, spatial, and cultural dimensions of this concept.

1. Introduction

1.1. Background

This report is part of the CoolLIFE project, funded by the European Commission under the LIFE 2021 Clean Energy Transition program. The CoolLIFE project aims to develop an open-access online tool and knowledge hub to support sustainable ways to meet the rising demand for space cooling energy in European buildings, through the implementation of innovative technologies and measures. This includes taking into consideration the pivotal role of thermal comfort, lifestyle, and user behaviour in the energy requirements of residential and commercial buildings. This report is focused on conducting a background literature review of the concept of thermal comfort, under the premise that it is socially influenced and varies according to different sociocultural factors. We aim to highlight the differences in thermal comfort perceptions, drivers, expectations, and requirements across European regions and societies by going back to the origins of this concept. At the same time, this task also turns to exploratory surveys in Hungary as a case study, to feed and provide insights to the literature review. Figure 1 shows the timeline for this task.



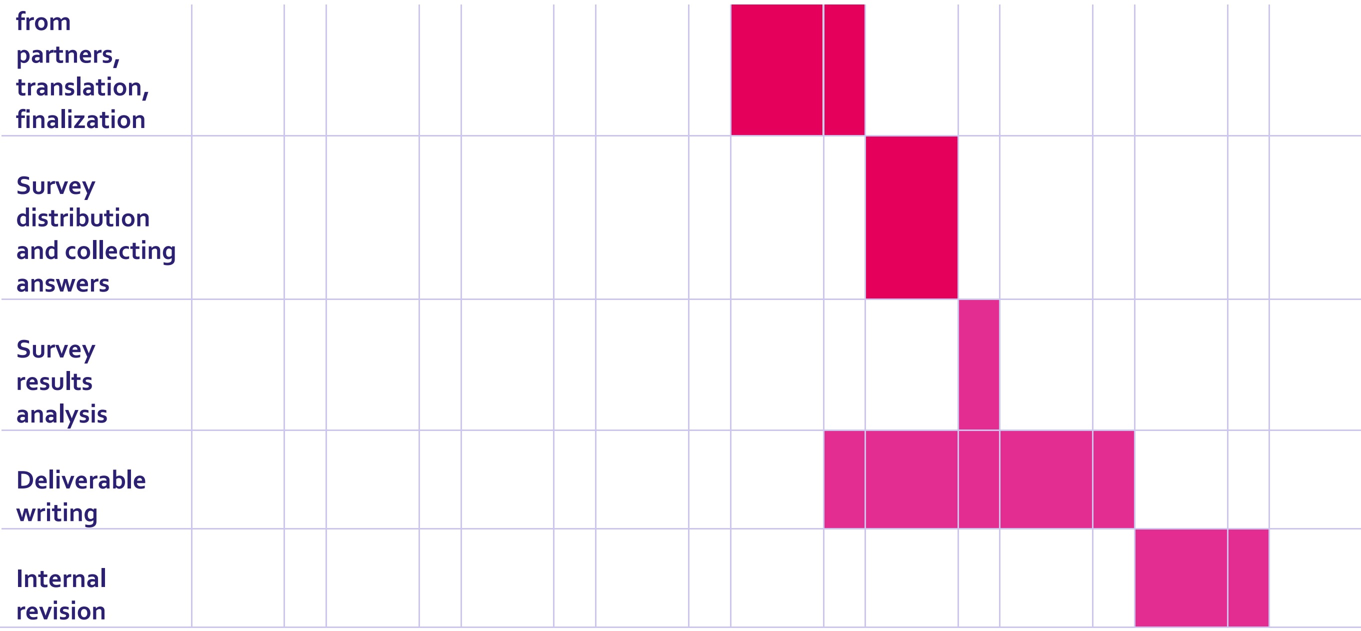


Figure 1. Timeline

1.2. Aims and objectives

This report pursues objectives from an academic and project implementation perspective:

From an academic perspective:	From a project implementation perspective:
• *Increase the knowledgebase of regional and traditional space cooling behavior and practices* • *Highlight the differences in thermal comfort perceptions and preferences across European regions.* • *Provide theoretical background on the concept of thermal comfort* • *Contribute to existing literature on occupant behavior surveys*	• *Provide input for the geospatial informational layer in the CoolLIFE tool.* • *Provide input for the design of user behavioral profiles*

1.3. Target audience

- Scientific research organizations and researchers who can use these findings as a base for further investigations.
- Users of the CoolLIFE tool who need to consult the theoretical bases and rationale behind the online tool.
- Professionals in social and behavioral sciences and in the energy field who are engaged in research in these fields and can use this report for consultation.

1.4. Interlinkages with other project activities

Particular insights from D3.1 will be shared among the consortium partners and the wider CoolLIFE community, mainly through the communication and dissemination campaigns of the project (T8.4 Awareness campaign and promotion of best practices) focused on lifestyle, comfort and occupant behavior activities. They will also be further disseminated through the use of the CoolLIFE online tool, which will display a number of these findings. This research was carried out in parallel with activities from T3.2 (Lifestyle and user behavior interventions) and T2.2 (Measures scouting), reinforcing their synergies and interrelated approaches.

2. Theoretical Framework

2.1. Rationale of the research

Defining thermal comfort has been mostly a matter of narrow parameters stipulated in international building codes and standards, related to the development of HVAC (Heating Ventilation and Air-Conditioning) systems that can control these indoor parameters from the early 20th century. Technical working groups from organizations such as ASHRAE and ISO have been mainly in charge of determining the specific conceptualization and definition of the term. While there has been widespread agreement on the technical specificities, there has been scant attention to the underlying sociocultural dimensions that contribute to our perception of thermal comfort. In this report we shall place these sociocultural dimensions in the centre of analysis and highlight their importance for a more holistic understanding of thermal comfort.

The perception of what would be feeling cold or warm has indeed evolved strongly over the centuries, and especially since HVAC systems have become widely used. While air-conditioning developed in the early 1900's in the United States first for the needs of professional environments, it then rapidly expanded to the whole built environment, enabling demographic growth in regions with hotter climates [1]. More recently, thermal comfort has also been closely related to the definition of energy poverty, commonly defined as the impossibility of meeting basic needs, including maintaining home adequately warm or cool[1].

This research departs from Shove's arguments on the standardization of comfort [2], the variations of its meaning, and the origins of air-conditioning expansion [2]. Our investigation then builds on the social implications of mechanical conditioning systems and what it means for occupants' preferences in indoor environments. In order to provide real-case insights, we analyse the results of surveys carried out in Hungary.

The literature review supports one of the main arguments behind this investigation is that there is no "one-size-fits-all" definition of thermal comfort, but this concept is rather constantly evolving and debated. Throughout this report we outline the reasons for these changes, the dimensions behind this concept, the modern understanding of thermal comfort and its implications for energy demand.

[1] See for example the definition of 'energy poverty' included in the proposal of recast for the Energy Efficiency Directive (Article 2(49) of COM(2021) 558 final): "*'energy poverty' means a household's lack of access to essential energy services that underpin a decent standard of living and health, including adequate warmth, cooling, lighting (…).*"
The Eurostat indicator "Inability to keep home adequately warm" (indicator ILC_MDES01 of the EU-SILC survey) is also frequently used among the key indicators to assess the number of energy poor households. About space cooling, the complementary indicator would be the "share of population living in a dwelling not comfortably cool during summer time" (indicator ILC_HCMP03). However, this indicator has been surveyed only once (2012).

2.2. Definitions and indicators

As stated in the previous section, there is not a fixed definition of thermal comfort. Several authors have tried to explain this term throughout time:

- *"Thermal comfort refers to the condition of mind that expresses satisfaction with the thermal environment. It is achieved when the human body is able to maintain thermal equilibrium with its surroundings, and when there are no sensations of either heat or cold. Thermal comfort is influenced by various factors, such as air temperature, radiant temperature, air velocity, humidity, and personal factors like clothing insulation, metabolic rate, and activity level".* [3]

  Probably the best known and most widely adopted definition of thermal comfort, as this definition is included in international standards such as ASHRAE 55-2022. However, there are many other examples:

- *"The thermal state of an individual that satisfies physiological and psychological needs for thermal equilibrium with the environment."* [4]
- *"The subjective perception of a person's thermal environment that is influenced by the thermal environment and the person's own thermal sensation, expectations, and preferences."* [5]
- *"The degree of satisfaction with the thermal environment as perceived by an individual, which reflects the body's state of thermal balance with its surroundings."* [6]
- *"The perception of thermal conditions that enable individuals to maintain thermal balance and satisfaction."* [7]

As noted, defining thermal comfort as such is a complex task, which requires a deep analysis of the historical meaning of the concept, as well as understanding the dimensions interplaying behind its evolution. A number of indicators have been introduced to try to quantitatively assess thermal comfort:

- PPD (Predicted Percentage of Dissatisfaction [%]): It is a measure that predicts the percentage of occupants likely to feel dissatisfied with thermal conditions. PPD takes into account the predicted mean vote (PMV) and provides a quantification of the potential dissatisfaction among building occupants. [3]
- PMV (Predicted Mean Vote [%]): It is a measure that predicts the mean value of the thermal sensation votes of a large group of people exposed to a particular thermal environment. PMV is a scale that ranges from -3 (cold) to +3 (hot), with 0 representing a neutral thermal sensation. [8]
- DR (Draught rate [%]): It is a measure that indicates the percentage of people likely to perceive a draught or discomfort due to air movement. It is typically expressed as a percentage of the total occupied space. [9]
- Met (Metabolic rate): It is a measure that represents the rate of heat production by the human body during various activities. Metabolic rate is expressed in metabolic equivalents (METs), where 1 MET is equivalent to the resting metabolic rate of an individual. [9]

- Clo (Clothing factor): It is a measure that quantifies the insulation provided by the clothing worn by individuals. Clo values indicate the thermal resistance of clothing and are used in thermal comfort calculations. [9]
- PD (Percentage Dissatisfied [%]): indicates the percentage of people that experience local thermal discomfort caused by an abnormally high vertical temperature difference between the head and ankles, by too warm or too cool a floor, or by too high a radiant temperature asymmetry. [9]

3. Methodology

3.1. Methodological approach for literature review

For this task, we adopted a traditional methodology for the literature review, in which we identified key academic research articles and standards from the field, based on databases and our own knowledge. We derived to more literature as we define the research questions, and further refined our search based on the findings. The research questions we established emerged from the objectives of the project and the theoretical framework of the investigation:

1. *Where does the concept of "thermal comfort" come from?*
2. *What makes the difference in thermal comfort perceptions? What are the drivers behind these perceptions?*
3. *What regional or traditional practices have occupants used to adapt their thermal comfort levels?*

As part of our review, we also included a research question focusing specifically on methodologies to carry out accurate surveys for space cooling behaviors, since the results of these surveys will be a key insight of this report:

4. *Methodologies for occupant behavior surveying*

With these questions in mind, we started the search for academic articles in different databases, such as Web of Science, Scopus, Google Scholar, and Science Direct. As we conducted a manual search, we relied on our expertise and previous knowledge of the topic. We defined selection criteria that will help us decide which articles to consider and include in our work. The criteria were:

- Language: English (consider other languages if at least two people in the team speak it)
- Geographical area: Europe and/or global (for relevant examples)
- Type of literature: academic publications, grey literature, industry standards
- Time period: literature not older than 15 years (with exceptions in cases of key publications)
- Academic relevance

For this project, we have selected and reviewed several key articles. The literature was retrieved in Zotero, a library management software that allows for joint consultation and collaboration within the team. We classified and tabulated the literature according to their relevance for our research questions (RQ).

Analysis Strategy

As previously mentioned, this review is not intended to exhaustively revise all the literature written about this specific topic (as it is not a systematic review), but rather to search for different "theories" and points of view that complement each other and help us to disentangle the complexity of the topic. Thus, our analysis was centred on breaking down the different dimensions of thermal comfort, their origins and evolution throughout time. The relevant literature was summarized in a structured and comprehensive way that allows for consultation or also as a base for possible further elaboration of the concepts herein described.

3.2. Methodological approach for surveys

3.2.1. Data collection techniques based on the literature review

As occupant behaviour has recently become a wider topic of study in the field of energy in buildings, the number of studies has grown largely in recent years. Most of the studies reviewed are based on the analysis of Chinese residential buildings, followed by Denmark, Italy, Australia, Cyprus, Finland, Portugal, Spain, and Switzerland. The sample size as well as the period of data collection varies considerably from one residential building to 8,293. Similarly, the period of data collection varies from 6 days to 7 years. [10]

CoolLIFE's literature review indicates that due to the subjectivity of thermal comfort, practitioners have typically used methods to assess thermal comfort perceptions (e.g., through user interfaces [11]) where continuous feedback is required from the occupants. Despite accurately capturing the thermal comfort of an individual via the survey method, this approach may induce survey fatigue among participants, leading to increasing uncertainty of subjective votes, and making it arguably inefficient and time-consuming. [12]

Logging activities is the best way to get a detailed, accurate assessment of users' daily activities. In the study of reference [13], 57 households in three areas participated in a diary study on everyday behaviour. The diaries recorded the time used for everyday activities in the households. In total, the households comprised 171 family members, whereof 134 were 12 years old or above, and were asked to write individual diaries. In the end, 141 persons wrote diaries for four successive days which means 564 diary sheets were completed (four days and nights). In parallel with diary keeping, energy use in the dwellings was measured.

Nakano and Tanabe [14] used three methods for data collection: (1) investigation of occupancy conditions, (2) questionnaire survey, and (3) measurement of the thermal environment. The survey focused on "short-term visitors", i.e., visitors who actually settled in the survey area; passers-by or standing persons were not considered.

The current building survey in Australia combines methods and examines the space cooling practices of households living in predominantly naturally ventilated dwellings in Darwin, Northern Territory, through a survey of dwelling behaviours, preferences and construction methods and a 12-month longitudinal study of thermal comfort in 20 homes. [15]

With the spread of online tools (since 2002), there is the possibility of directly recording the individual perception of thermal comfort. This trend was later complemented by contextual participatory measurements using smartphones. [16]

The disadvantage of online self-reporting is that the number of respondents is very low. This is reflected in Zhang's research [17], where the response rate was 5.5%. The investigation included a questionnaire that was designed for occupants of residential buildings and a field survey (pilot survey) conducted in July 2017 in Beijing, China, followed by online deployment of a questionnaire survey from January 2018 to August 2018 on the platform supported by a professional data services company in China – SoJump. A total of 566,219 potential respondents were invited to take part in the online survey, and 31,293 participants submitted answers that passed the platform's preliminary screening, giving an initial response rate of 5.53%. After a time-intensive manual screening of the responses concerning a set of essential questions, a total of 1,003 valid responses, a valid response rate of 0.18%, were ultimately obtained and used for further analysis. Responses were considered valid if essential questions regarding personal and household information, energy-related behaviours and household energy use information were answered.

Social researchers cite low response rates and a non-representative sample as disadvantages of the online survey. In order to avoid this, researchers often use online panels of market research companies to obtain a representative sample. The survey by Sovacool et al. [18] was conducted online with the help of a market research company (Dynata), using a panel of respondents from five European countries (Germany, Italy, Spain, Sweden, and the United Kingdom) in 2020. A sample size of roughly 2,000 per country was deemed sufficient to fill all quotas based on a combination of age, gender, location, and income. Respondents were selected randomly, and 91% of selected respondents completed the survey. A total of 514 respondents were screened out based on quality checks.

3.2.2. Research design of CoolLIFE household survey

Lately several researchers conducted literature review on user behaviour in relation to energy efficiency. They point out that energy transition is both a technological and a social challenge and so far the focus has been mainly on the technical part. Residents' willingness to change their behaviour in terms of energy consumption is still a question [10]. Therefore, there is a need for surveys that take a multidisciplinary approach [19]. Such empirical studies that offer insights into residents' behaviour could fill the gap left by studies that only consider environmental and technical factors, without analysing social factors.

The CoolLIFE literature search revealed a number of studies dealing with heating and space cooling (H&SC). However, there are only a few studies that pursue a similar goal as the present research. Investigating the energy saving potential of user behaviour in residential buildings is less common in the reviewed articles than in commercial buildings.

The empirical analysis of user behaviour is a relatively new concept in the field of energy-related research in residential buildings. There is a growing body of research that attempts to establish links between people's behaviour and local comfort parameters [20]. The overall aim is to obtain information about comfort requirements, occupant behaviour patterns, drivers, causes and perceived effects of behaviour. ([17], [21], [22])

The spatial focus of empirical research using quantitative techniques is also limited. According to [19] and [20], most of the data is coming from the USA and China. Among European countries, the study of Mediterranean cities is more frequent (Italy, Portugal, Spain).

The general objective is to study user perceptions about thermal comfort and its role in the energy performance of buildings using qualitative or quantitative methods or a combination of both. There are few studies that deal exclusively with space cooling behaviour and do not relate it to space heating behaviour and the energy efficiency of the building.

As the CoolLIFE's and other literature reviews ([17], [19], [20]) showed, survey technique was most often used to investigate the followings:

- Relationship between the actions of the occupants and the characteristics of the building.

- Relationship between the performance of air conditioning systems, occupant behaviour and the characteristics of the building.
- Relationship between the type of ventilation chosen by occupants, indoor thermal comfort and air quality requirements.
- Relationship between actions of the occupants and the characteristics of the building.
- Identifying occupants' behavioural patterns related to energy consumption for space heating and space cooling.

Specific context has been explored only in relation to space heating. The CoolLIFE research extends the scope to space cooling behaviour, applying the survey method to the followings:

- Determine the impact of social characteristics and building features on space cooling behaviour.
- Analysing the potential for energy savings based on occupants' space cooling behaviour.

A number of research points to the importance of obtaining information on contextual factors (e.g., available control options, social factors), to enable accurate prediction of occupant thermal response. [23], [24]

A number of aspects of energy use - such as valid information on energy use in a detailed timely breakdown - cannot be investigated with survey methods (for such purposes, monitoring of energy use through e.g. loggers may be used). The CoolLIFE survey could therefore not provide a detailed schedule of hourly occupancy, lighting, space cooling practices, electrical appliances, metabolic rate and clothing, differentiated by weekdays, weekends and holidays (such issues were addressed in the questionnaire, for specific dates). However, the survey method can be used to obtain an idea on space cooling behaviour patterns, temperature preferences and other important social factors of energy use.

3.2.3. Background and structure of the research

A nationally representative survey was conducted in one CoolLIFE partner country (Hungary) as a pilot study to better understand the space cooling preferences and behaviour patterns of residents. It covers a wide range of factors that determine preferences and choices at both the individual and household level in order to understand the socio-cultural, economic and technological factors that influence the everyday practices of citizens.

The survey covered external (e.g. infrastructure) and internal factors (e.g. attitudes and habits) that affect both individual and collective space cooling behaviour, thus providing an insight into the factors that influence individual and collective decision-making. For specific topics (energy consumption patterns and everyday space cooling practices), the possible gender-specific perceptions were given special consideration;

Six interrelated issues were addressed:

1. Patterns of energy demand, energy efficiency, and energy use in everyday situations (e.g. home office, use of smart meters, etc.), with a focus on space cooling;

2. Schedules of occupancy, differentiated by weekdays and weekends; The temporal resolution of occupations and practices;

3. Space cooling related comfort requirements; Thermal comfort and practices, including coping strategies with hot weather;

4. Location and characteristics of dwelling: housing type and size, tenure; insulation of dwelling, space heating and space cooling systems, and availability of smart meters;

5. Characteristics of households: socio-economic characteristics as gender, age, education level and financial situation.

The main research questions of the survey were elaborated in accordance with the corresponding objectives of the project and the addressed interrelated issues:

1. What are the main daily household activities related to space cooling and how do they differ in different dwellings?

2. What is the combination of factors that influence the space cooling behaviour on individual and household levels and how they differ across dwellings?

3. What are the characteristics of groups that are less committed to energy-conscious space cooling practices?

3.2.4. Conducting the survey

The questionnaire comprised 5 sections and was to be completed in 20 minutes. The first section contained questions about location and building characteristics and household composition. The second section investigated schedules of occupancy. The third section examined space cooling related comfort requirements. The fourth section analyzed the thermal comfort and practices and set-points. The fifth section looked for temporal resolution of occupancy and practices. Several Likert scale questions (1 = strongly disagree, 5 = strongly agree) were used for the questions designed to capture respondents' opinions.

To comply with the working language of the consortium and future adaptability, the questionnaire was prepared in English. The pilot study was made in Hungary. The questionnaire was fully translated into the national language by the members of the consortium.

The pilot phase of the survey took place in early April 2023. The final data collection lasted one month between mid-April and mid-May 2023.

The survey was conducted online using a pool of 165,000 possible respondents from a survey panel of a market research company. The panel was created using incentives to reward participation in the survey. Unique personal links were sent to the respondents of the panel.

The sample consisted of residents 18 years and older. A quota sample was used with a combination of age, gender, education, region (NUTS1) and settlement type. Respondents were selected randomly. The response rate was high: 99,9% of the respondents completed the entire questionnaire. On average, it took 10-20 minutes to answer the questions.

4. Analysis of space cooling related comfort

In this chapter, we analyze thermal comfort from two different perspectives: first, we describe the standardized approach that currently dominates the discourse about occupants' comfort perceptions, and secondly, we focus on the sociocultural dimension and how it has influenced the concept of thermal comfort. We will then provide information on regional aspects of thermal comfort and space cooling requirements.

4.1. Standardized thermal comfort requirements

The standardized approach is important for the construction renovation and building operation industry, and according to Berger et al *"the scope of standards is seen as sharing of and capitalizing on scientific and technological progress, which evolves via research, development, and application"* [25]. Standards include a set of requirements that guide designers and building operators to maintain a thermal environment that is generally accepted, in lack of the knowledge of the preference of the individual occupants. Standardized indoor thermal environments are also important in modelling building, e.g., the models used for energy performance prediction, where the standards set a basis for basis for comparison between different buildings. It is indisputable that standards are needed and methodologies outlined in them together with the parameters are useful. In this section we provide an overview of the considered factors within the standards addressing indoor thermal comfort, that will be reviewed critically reviewed based on their applicability to certain building functions, population group, or inhabitants with different background or living in different regions.

4.1.1. Short history of thermal comfort theory

In this section we give a short overview of how the standardized criteria for designing indoor thermal environments have evolved throughout the history, identifying variables that are taken into account during comfort assessment, and the scales used in expressing the thermal sensation.

Based on the work of Teitelbaum et al. [26] and Blackburn [27] the development of comfort theory is summarized, see also Figure 2.

- In 1876 Osborne defined a list of descriptive terms for the assessment of sensible temperature using a 20-scale comfort vote approach [28], but this had not yet been done under controlled conditions and the required conclusions could not be finalized.

- In 1911, Willis H. Carrier [29], known as the Father of Air Conditioning, established the scientific foundation of air conditioning with his paper titled "Rational Psychrometric Formulae." While the psychrometric chart started as a method for characterizing the air as it moves through a comfort conditioning system, the chart has – misleadingly – been used as a means of assessing comfort in the occupied space, and was developed by several authors. [26]. Their work was built on by Houghten and Yagloglou, who they defined the effective temperature as 17.8°C and the comfort range between 16.7°C – 35.6°C, which is a far wider range than what is considered acceptable today. In 1925 Yaglou and Miller added a new dimension of moving air to the Phycrometric chart and extended the chart as a nomogram, illustrating the nature of the "neutral point" where the effects of moving air have no effect on body heat storage [30]. This was later refined by the same authors including seasonal variations in the comfort zone, however, these experiments lacked the analysis of the clothing levels. In 1932, Vernon [31] replaced the dry bulb thermometer with the black globe thermometer explicitly with the intent of measuring the effect of radiation on thermal comfort. This was extended by Bedford, who developed an equivalent temperature framework for air velocity, globe thermometer temperature, and air temperature, still using a fixed parameter for radiation.

In these works, two-dimensional (temperature – humidity) comfort landscape was believed to be sufficient for describing the modulations available to maintain thermal comfort in buildings, sometimes adding a third dimension in air velocity if required. None of these studies viewed radiation as an independent variable for comfort regulation. Although the modern comfort theory has proven that thermal sensation is dependent on the radiative temperature as well, the built environment in the early 20th century could explain why these models gave acceptable results. Highly glazed façades came to be only part of the architectural toolbox in the 1950's, which can explain the reason why the lack of the radiation component in the calculations was not apparent. Also, the development of the comfort theory was driven by the air-conditioning industry, which does not control this parameter.

- The work from Victor Olgyay took another path in the approach towards thermal comfort, away from the conditions based on the findings of the air-conditioning industry. In 1963 he published "Design with Climate" [32], where he introduced charts showing the comfortable range in relationship to humidity, temperature, also incorporating strategies to maintain thermal comfort outside this range. Different levels of radiation were indicated, necessary to offset the decrease in temperature below the lower boundary of the comfort zone by up to 10°C with appropriate shading. Likewise, to retain comfort up to around 10°C above the zone, wind speed was indicated as a mean to offset the increase in temperature, and evaporative space cooling was also mentioned to retain comfort at high temperature values but low humidity. In his work also a contour relating to metabolic rate was also included, indicating when light work was acceptable, for instance.

The above model still included a number of parameters that could describe the thermal environment more or less successfully, but these were not fully applicable to be applied to any condition. A groundbreaking change in the thermal comfort models that are adopted in the standards to date was done by Fanger in 1972 [3], who introduced a calculation model for the Predicted Mean Vote (PMV), which takes into account the following factors:

- air temperature,
- humidity,
- air velocity,
- clothing insulation
- and metabolic rate to predict thermal comfort.

Based on the PMV value, the calculation of the PPD (Predicted Percentage Dissatisfied) had also been introduced. His work made a great impact on the thermal comfort prediction methods used for the built environment, consequently, the currently used thermal comfort standards are based on his models. However, it is important to be aware that his model was intended for application by the HVAC industry in the creation of artificial climates in controlled spaces.

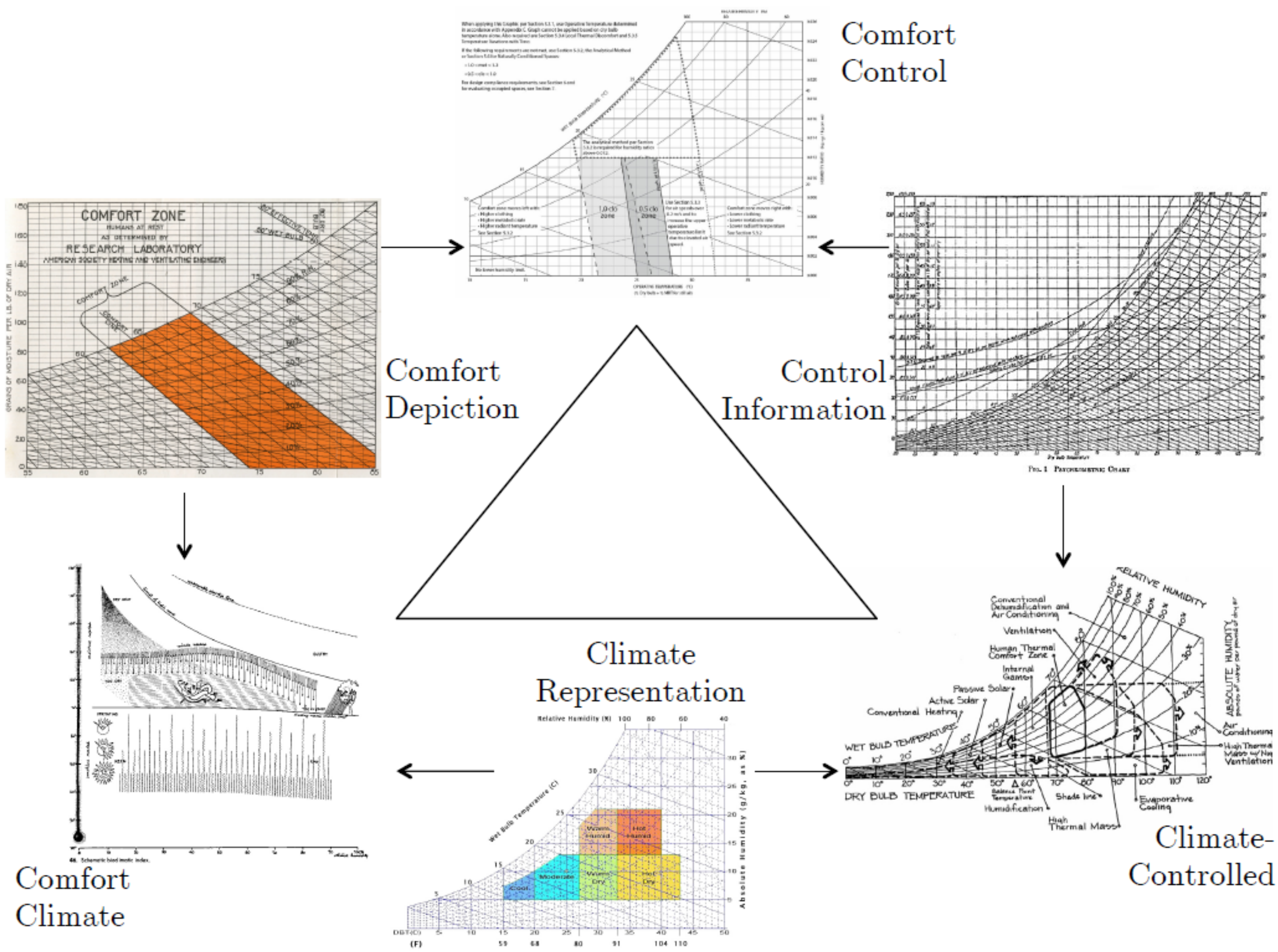


Figure 2. Use of psychrometrics throughout comfort, controls, and climate frameworks, combining pure psychrometric representations along the lines of the triangle into applied frameworks at the vertices. Source: [26]

Further on, the extrapolation of the model's scope to all spaces intended for human occupancy, including those with natural ventilation, was a later development, and had been proven to be wrong through the research done by Richard de Dear and Gail Schiller Brager [33]. They developed the Adaptive Comfort Model in 1998, which acknowledges that people can adapt to a range of thermal conditions depending on factors such as outdoor climate, cultural expectations, and individual preferences. They described one of the predictions of the adaptive hypothesis as people in warm climate zones prefer warmer indoor temperatures than people living in cold climate zones, which is contrary to the static assumptions adapted previously. Occupants in naturally ventilated buildings were tolerant of a significantly wider range of temperatures, explained by a combination of both behavioral adjustment and psychological adaptation. These results formed the basis of a proposal for a variable indoor temperature standard.

4.1.2. Common approaches to assess thermal comfort

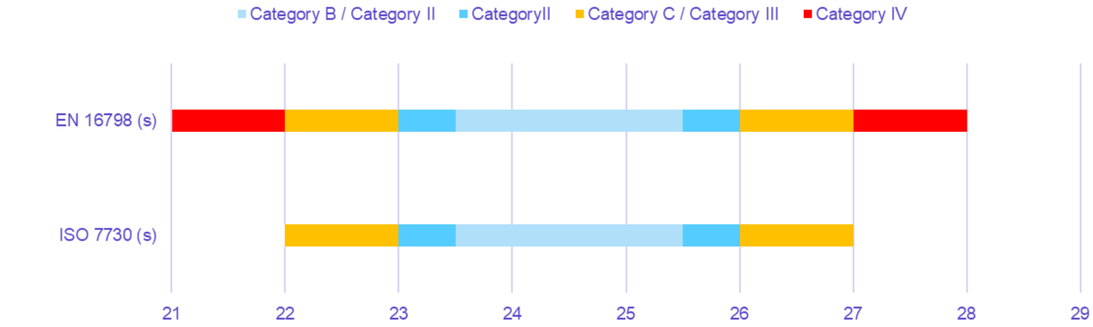
Comfort standards

The first thermal comfort standard to implement the above methodologies was the USA ASHRAE-55 that was first published in 1966. The current standards implemented in Europe and internationally are the ISO 7730:2005, which describes the calculation methods for the comfort indices and indicative target levels in three categories (A, B and C) in Annex A, while localized standards EN 16798-1:2019 in Europe and the ASHRAE 55:2020 in the USA provide further suggestions for the target values. The EN standard suggests four levels of Indoor Environmental Quality (IEQ_{I-IV}) that can be considered during planning, the ASHRAE method suggests only one.

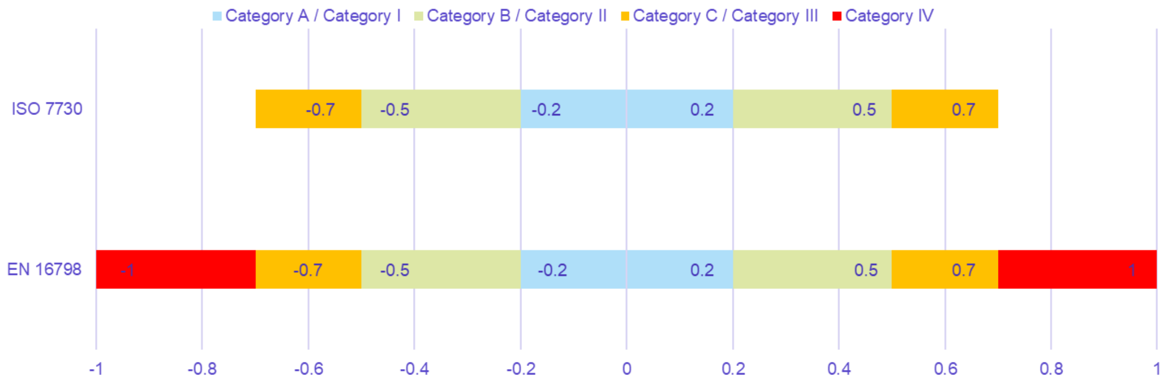
In current comfort standards in addition to the PMV and PPD calculations the consideration of local discomfort has been implemented based on concepts developed in the 1980s, e.g. based on the work of Fanger et al. [34]. The PMV and PPD indices express warm and cold discomfort for the body as a whole, but it has been realized that thermal dissatisfaction may also be caused by unwanted space cooling (or space heating) of one particular part of the body, which is called local discomfort. This might be caused by draught, high vertical temperature difference between head and ankles, too warm or too cool floors, or by too high radiant temperature asymmetry. People engaged in light sedentary activity are the most sensitive to local discomfort. Additionally, the standards include indoor operative temperature corrections for buildings equipped with fans or personal systems providing building occupants with personal control over air speed at occupant level.

The ISO 7730 standard describing Fanger's model addresses the thermal sensation in mechanically cooled buildings in summer and winter conditions similarly. The standards EN 16798 and ASHRAE 55 however indicate different limits for the summer and winter conditions, which difference is based on the assumption of the different clothing levels. Thus, the suggested operative temperatures in summer are calculated with 0.5 clo level, while for winter 1.0 clo level is considered. No further seasonal adaptation is considered for the mechanically cooled buildings.

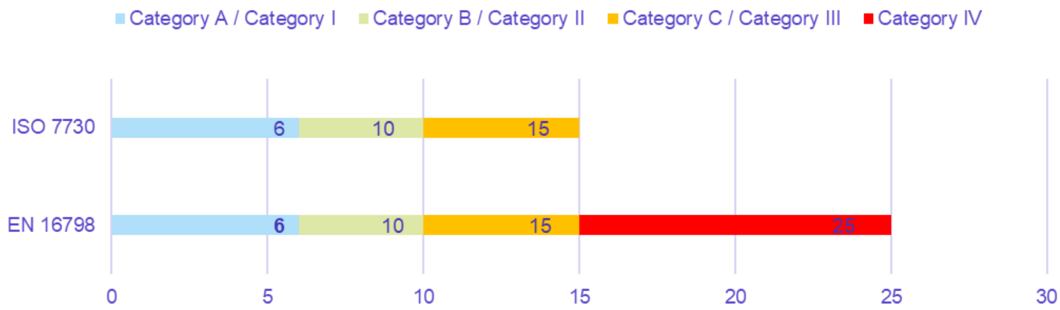
The suggested operative temperatures for summer are shown on Figure 3.



a) Operative temperature



b) PMV



c) PPD

Figure 3. Acceptable operative temperature ranges based on Table B.4 of the EN 16789 standard (residential buildings, living spaces, sedentary activity for summer (1.2 met, 0.5 clo), and the A.5 Table of the ISO 7730 standard. b) PMV categories c) PPD categories based on the Table A.1 in the Annex A of the ISO 7730 standard and the Table B.1 of the EN16798-1 standard

The adaptive comfort method is also implemented within both the EN 16798-1:2019 and the ASHRAE 55:2020, however, with different methodologies. In building without mechanical space cooling, the criteria for the thermal environment can be specified through the adaptive comfort method that takes into account adaptation effects. As detailed in the EN 16798 the method only applies to occupants with sedentary activities without strict clothing policies and where thermal conditions are regulated primarily by the occupants through opening and closing the elements in the building envelope (e.g. windows, ventilation flaps, roof lights, etc). This method applies to office buildings and other buildings of similar type used mainly for human occupancy with mainly sedentary activities where there is easy access to operable windows and occupants can freely adapt their clothing to the indoor and/or outdoor thermal conditions. The field studies were conducted in office buildings, but the method may also apply in other building spaces with similar individual possibilities for adaptation, e.g. in residential buildings.

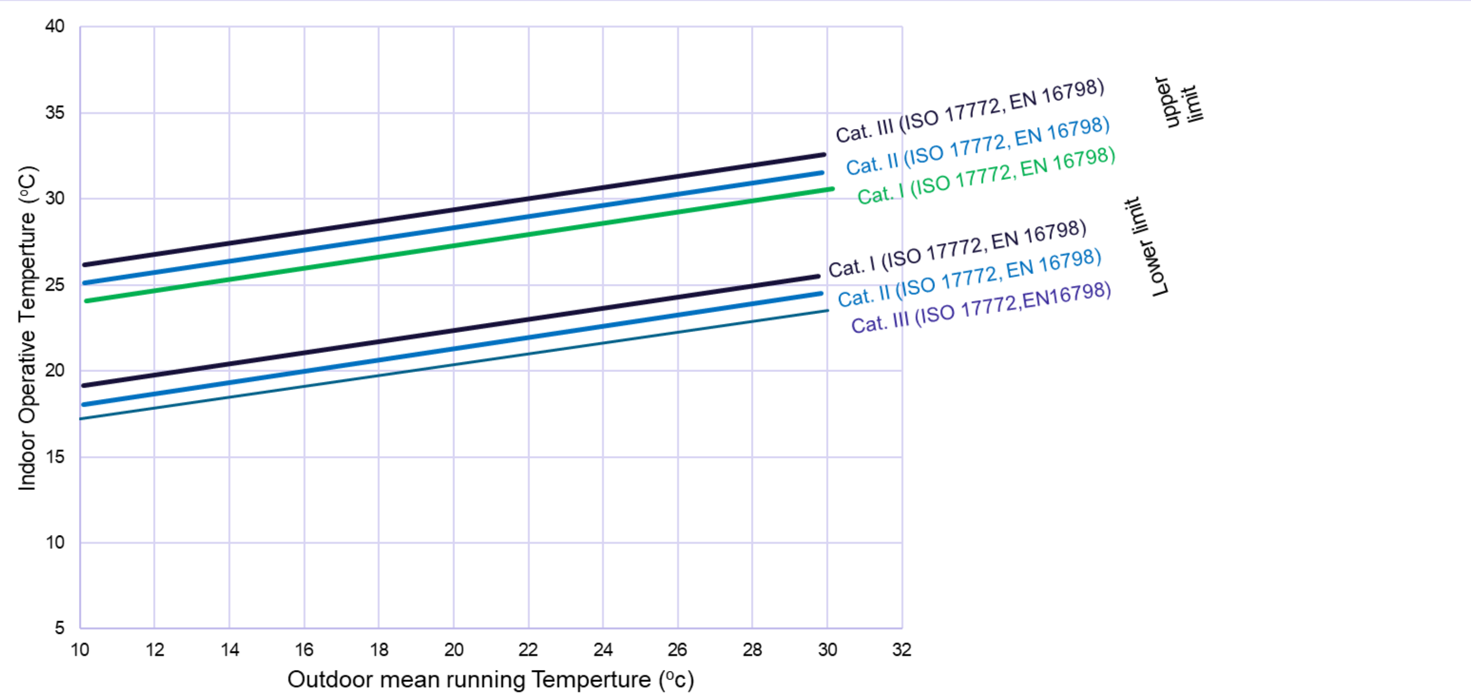


Figure 4. Adaptive comfort ranges in the EN 16789 and ISO 17772 standards

Scales for expressing thermal sensation

People's subjective response to any thermal environment is commonly investigated by using rating scales describing the degree of thermal sensation, comfort, and acceptability. The first scale was the 20-scale questionnaire mentioned above from Osborne. Among several sensation scales found in the literature, ASHRAE scales and the Bedford scales are the most widely used, and there is a widely accepted assumption of the exchangeable use of these two. The Bedford scale was developed by T. Bedford in 1936, [35] in his work describing the effects of various systems of heating and ventilation on the feelings of warmth comfort experienced by people engaged in light sedentary occupations, enquiring around 2,000 people, mostly women, during the winter.

	-3	-2	-1	0	+1	+2	+3
Bedford [35]	much too cold	too cold	comfortable cool	neither warm nor cool	slightly warm	too hot	much too hot
ASHRAE (Fanger)	cold	cool	slightly cool	neutral	slightly warm	warm	hot

Table 1. Comparison of the Bedford and ASHRAE (Fanger) comfort scales

The main difference in these 7-point scales is that ASHRAE assumes that thermal comfort is equivalent to any sensation from the central categories (i.e., slightly cool, neutral, slightly warm), whereas the Bedford scale integrates (comfort) in its categories.

Thermal sensation scales are continuously applied. However, challenges may be classified into those related to scales in their English or original form and those related to the translated versions. The reasons for these challenges include the difference between neutrality and comfort, the effect of the climatic and cultural background, and participants' difference in realizing thermal sensations and their distribution on the thermal continuum [36].

As Schwieker et al. summarized, [37] *"in the ASHRAE scale the classic assumption is that the middle three verbal anchors, i.e. "slightly cool", "neutral", and "slightly warm", represent thermally comfortable or acceptable conditions, i.e. satisfaction. This assumption is the basis for the relationship between predicted percentage dissatisfied (PPD) and the predicted mean vote (PMV) and was used to establish acceptance levels for the adaptive comfort model. This assumption appears to originate from a study by Gagge et al. that found that the subjective perception of "comfort" and "neutral" from one male subject occurred at the same temperature, and that discomfort began to occur at "slightly cool" or "slightly warm". Fanger cites these findings in his formulation of the PPD index, which is subsequently cited by de Dear and Brager in the development of the adaptive comfort model's upper and lower acceptability limits."*

4.1.3. Summary

As seen in the literature the standardized approach towards thermal comfort has been first developed based on the psychrometry chart, that was meant for determining the physical states of the air within the air conditioning systems. The current standard indices for determining satisfaction with the indoor thermal environments are similar all around the globe and have been developed based on Fanger's model for the PMV and PPD from the '70s. This calculation methodology takes into account the thermal sensation of the whole body, based on the following factors:

- air temperature,
- mean radiant temperature,
- humidity,
- air velocity,
- clothing insulation (expressed in Clo)
- and metabolic rate (met).

The PMV-PPD approach is meant for buildings with air conditioning, and the standards also incorporate methods to address local discomfort. Also, the standards incorporate methods for implementing the effect of increased air velocity, which represent the use of fans that is an important measure do deal with too warm environments.

For space without air conditioning adaptive thermal comfort calculation methods based on the outdoor running mean temperatures have been included in the standards.

4.2. The socially constructed concept of thermal comfort

Being "thermally comfortable" in indoor environments has not always meant the same. Throughout time and geographies, this concept has constantly changed and evolved shaped by different factors. This section tries to illustrate how the meaning of "comfort" and – more specifically – "space cooling needs" (the need to feel cool enough during warm seasons) have been collectively redefined based on cultural influences and technological developments experienced by societies.

The word "comfort" is extremely complex and difficult to define and measure. Scientists and engineers have continuously tried to introduce indicators and parameters that would provide specific quantitative insight to this "state of mind" in order to design indoor environments that would prove to be tolerable, satisfactory, and "comfortable" for everybody, at any time. The ambition to attain a neutral environment in which people do not report to be "uncomfortable" led to the artificial manipulation of indoor conditions, mainly driven by engineers and the construction industry, which triggered the increased adoption of air conditioning systems for the standardization of space cooling. This provision originated a self-reinforcing loop in which the expansion in the use of mechanical systems reinforced occupants' idea of how an ideal indoor environment should be like, therefore influencing their understanding of neutral indoor conditions.

The influence of air conditioning for thermal comfort in our current society is undeniable, but it is important to note its role in impacting thermal comfort in the present time, and understand how this came about There are many factors to take into account to answer this question. As appointed by Brager and de Dear [7], media marketing played an important role in the early adoption of mechanical systems, especially in the United States. Advertised as a "necessity for the ideal home", air-conditioning tried to sell the idea of luxury, convenience, comfort, and modernity for households, particularly aimed at women. By 1950, air-conditioning was the second fastest growing industry in the US, showing the large success of advertisements promoting this "climate control" as a means to attain higher social status and reduce the burden of household work. This is also highlighted by Mazzone and Khosla [38], who argue that the media spread ideas of modernity and desirability behind the adoption of ACs, especially considering that AC ownership was a symbol of social power. But media was not the only way. Building industries, technology producers and engineers from influence groups and capital markets promoted the creation of space cooling needs and a cultural ideology of comfort by pushing for these ideas in the political agenda, arguing that, for example, office workers increased their productivity in optimal thermal conditions, especially during summer [39]. Soon enough, these influencing networks controlled the development of indoor conditioned spaces in most regions (especially in the US) and, at the same time, embedded these narrow temperature requirements in the building codes and regulations that are now global standards for the design of any building, limiting this definition to numerical parameters, leaving aside the social and cultural implications around the term.

Nevertheless, industry alone was not the only one on this push for indoor-climate conditioning. The massive deployment of AC was also possible at the beginning thanks to the wide acceptance of the population, peer-emulation, and an increasing appeal for this device prompted by word-of-mouth. In addition to the feeling of wellbeing provided (temperature-wise), the accomplishment of aspirations of human victory over nature and technological abundance further intensified the relationship between people and AC, becoming so strong to the point of being considered a sort of "addiction" [7].

Globally, the continued use of and exposure to air conditioning spaces triggered substantial changes in behaviour and attitudes, including the societal rejection of body fluids, smells and odours enhanced by sweating in hot temperatures, new ideas of hygiene and cleanliness, changes in social etiquettes and conventions, the widespread of Western influences, and, more critically, the changes in expectations. Several analyses of these trends are provided by Mazzone and Khosla [38], where they underline different social phenomena associated with these effects. For example, the rejection of body fluids and smells from sweating can be linked to gender and status connotations, as malodour and sweat has been historically related to working classes, and therefore the aim of neutral indoor conditions is also a desire of higher social status. Women were especially affected by this phenomenon, as it reinforced the idea that sweat stains in clothes were not "feminine" and therefore increased pressure on looking immaculate. New ideas of hygiene also emerged from AC use, as societies started to give more value to the complete absence of body odour and perspiration, especially in work environments. Consequently, new forms of clothing (suited for cooled-down spaces) were introduced globally, as people no longer needed to dress according to local conditions – giving room for the adoption of, for example, Western business suits.

However, the biggest implications of this air conditioning take over have been in households and buildings design and use. With the adoption of air conditioning systems, suddenly there was no need for naturally ventilated houses or the passive space cooling designs and materials developed by traditional architecture. More and more, new buildings have started to be built *for* air conditioning, particularly in regions like the US, with designers assuming that this technology will be available at scale and be the main source of space cooling. Traditional architecture in warm areas, which typically used verandas and vernacular styles, slowly started to be replaced by large glass boxes that rely entirely on air conditioning systems, losing also the distinctiveness and sense of belonging in a place [1]. The social and cultural impacts of these homogeneous constructions in population are notorious as well. Since people do not have a veranda anymore, there are no possibilities of sitting outside and socializing with neighbours. Casual meetings shifted from outdoor spaces and squares to indoor conditioned environments. The availability of uniform climatic conditions that do not change over the year also changed the pace of life, as it eliminated the need for a pause during the hottest part of the day, therefore removing traditional practices like the siesta. Individual behaviour strategies to cope with hot weather started declining, as people no longer felt the urgency to *make themselves comfortable* [2].

For the purpose of this research, we are particularly interested in the changes in people's expectations regarding space cooling. As observed lines above, air conditioning adoption and wide deployment allowed for the creation of a self-reinforcing feedback loop in which building occupants are used to conditioned environments and have come to think of them as the definition of "comfort" (and therefore set their expectations accordingly) which in turn involves the use of even more air conditioning to satisfy these expectations. It is therefore important to consider these dynamics when investigating solutions for space cooling, as they have created a co-dependent relationship that significantly influences occupants' behavioural choices.

4.3. Differences and drivers in comfort perceptions and expectations

"While the addiction to air conditioning may have initially been driven by cultural and social issues, it can eventually evolve into a physiological addiction where 'air conditioning rapidly teaches the body to hate the heat' [40]*, and changes our perception and expectations of unconditioned spaces and the outdoors. We create artificial islands of cold within surroundings that are then characterised as 'hot' in contrast to those air conditioned spaces."* [7]

As discussed in the previous section, the concept of "thermal comfort" and its related expectations is deeply influenced by external sociocultural factors and differs greatly within times and regions. However, it is important to point out that this perception is physiologically informed too – there are many internal factors that contribute to a significant variation in human perceptions and expectations. But what can we attribute these differences to? What are the drivers behind people's perception of comfort?
We can lean on the analysis of several authors to try to explain these variations and their implications for the design of space cooling solutions.
For example, Stoops [41] argues that there are five variables to determine human comfort:

1. Physical environmental variables: it is important to understand our environment as more than just physical attributes that surround us, but also our connection to those attributes, and the influences that these relationships have in our perceptions of comfort. The author proposes to consider the environment from the human perspective of safety and security, as protection from elements (precipitation, wind, snow), as

providing thermal attributes, and also the influence that air quality, acoustic conditions, light, aesthetics, controllability opportunities and physical size can have in our senses.

2. Physiological variables: every person and their physiological characteristics are unique, and therefore should be considered as such. These variables can highly influence different perceptions of comfort, for example metabolism, age, sex, time, health conditions, medication, and acclimatisation. They all represent inherent characteristics of every building occupant that should not be underestimated when designing space cooling solutions.
3. Behavioural variables: just as physiological variables are inherent to every person, the decisions they make and their behavioural attitudes are also unique, and must be taken into account for their thermal well-being. Behavioural choices can include clothing, location, activity levels, posture, and use of controls. (The occupants' drivers and actions regarding the interaction with building elements and space cooling devices in order to maintain their thermal comfort and adapt to environments are investigated in detail in D3.2. *Analysis of Behavioural Interventions Across Europe.)*
4. Psychological variables: as defined by ASHRAE *[9]*, thermal comfort is a "condition of mind". While it is certain that our physical perceptions have an impact on our thermal feeling, ultimately it is a matter of state of mind that defines whether we are comfortable in a place or not. Psychological variables could be impacted by family or personal relations, relations at work or school, stress, work satisfaction, perception of control, and psychosis.
5. Preferred conditions: even though we can try to explain and formalize human perceptions of comfort through different variables, the reality is that individuals are unpredictable, and often their comfort levels can be guided solely by personal preferences, so it is important to consider this parameter in space cooling solutions as well.

On the other hand, Mazzone and Khosla [38] propose that space cooling needs are informed from both cultural and physical perceptions, which could locate them as part of a body-mind-space-society model. They point out that these dimensions are interrelated and interact with each other to form our thermal comfort needs and perceptions. A thorough analysis of these dimensions is necessary to understand their influence in the conceptualization of thermal comfort:

1. The body dimension: just as previously described, the body (physiological features) of every person impacts their ability to perceive temperatures. For example, women tend to feel more comfortable in warmer environments, the same as people with lower Body Mass Index (BMI) and the elderly, given that lower metabolism likely contributes to different ambient temperature perceptions. However, it is worth tnoting that metabolism can be influenced by social practices, activity levels and even the food we eat. Bodies are not necessarily a passive recipient of stimuli, but they also evolve and adapt according to our routines. Specific studies have shown that people who are constantly exposed to extreme temperatures (such as miners or builders) develop a thermal adaptation to these conditions *[42]*. This is also related to people that are exposed for long periods of time to air-conditioned environments (such as office buildings) and develop a lower tolerance to warmer temperatures, which is reinforced by habits and routine. Nevertheless, the body dimension is only one angle in the approach of thermal comfort.
2. The mind and mind-body dimension: the authors consider the interactions between the body and mind as contributing factors to the experience of thermal comfort. They base their argument in several studies that tried to expose how room temperature and physical sensations of warmth and coldness are intertwined with emotions, feelings, and sense of belonging. People tend to associate physical coldness with feelings of

loneliness and vice versa, as the body can register emotions from experiencing certain temperatures. Moreover, Damasio et al. *[43]* show how “some temperatures may induce certain emotions and, conversely, emotions or psychological states can regulate body temperatures”.

3. The embodied experience of space dimension: this dimension refers to the influence of our senses (vision, touch, taste, thermoception, among others) when processing external stimuli and triggering bodily and emotional reactions. Our thermal perceptions are much more complex than temperature or heat-exchange models and, as the authors argue, they are impacted by the shape, texture, colour, smell or even the sound of a place. For example, Brambilla et al *[44]* found that warmer reddish lighting improves occupants’ thermal comfort in cold environments without the need to increase energy consumption.
4. The sociocultural dimension: as described more extensively in section 4.1, this dimension is linked to the social meanings and practices we give to different objects, such as air conditioning devices. It is important to note that these “mental hooks” (created by peer emulation, routines and social influence) can give room to the construction of space cooling needs. The authors also mention traditional practices to cope with hot temperatures as part of these cultural heritage, for example the acceptability of different daily schedules such as pauses in the middle of the day to take a siesta, or changes in dress codes.

As evidenced by the authors, there is a number of inherent factors and drivers behind the differences in thermal comfort in building occupants. These differences interact with each other and intertwine to make up the complexities behind human comfort. Moreover, they also evolve based on the thermal experience and stimuli that people receive throughout their lives. In this regard, several studies strongly suggest that people who are constantly exposed to air conditioned environments develop a deep preference (to the point of being considered an “addiction”) to AC systems, whereas occupants of non-conditioned buildings tend to prefer natural ventilation and not to have AC. Candido et al [45] carried out studies to explore the implications of long AC exposure by building occupants in their workplaces, finding that thermal preferences vary depending on previous exposure. They found that “the percentages of occupants preferring ‘no change’ were significantly higher for those without AC systems at their workplace. Thermal preferences for ‘cooler’ were significantly higher for occupants who had been exposed to AC systems at their workplace compared with occupants without AC exposure.”

As observed in Figure 5 the constant exposure to air conditioning systems also reinforces preferences for space cooling solutions: those who are more exposed in their workplace tend to prefer these systems over natural ventilation, whereas the opposite happens for those without exposure to AC. This brings forward further issues when designing space cooling solutions: as people become less tolerant of the temperature variations of naturally ventilated environments, they start to lose their adaptation capacity. People who have lost their adaptation capacity tend to reject other forms of achieving comfort, such as opening windows during the night or changing their clothes or schedules. As we try to reduce our dependence on artificially conditioned environments, adaptation capacity is a key aspect of this endeavour.

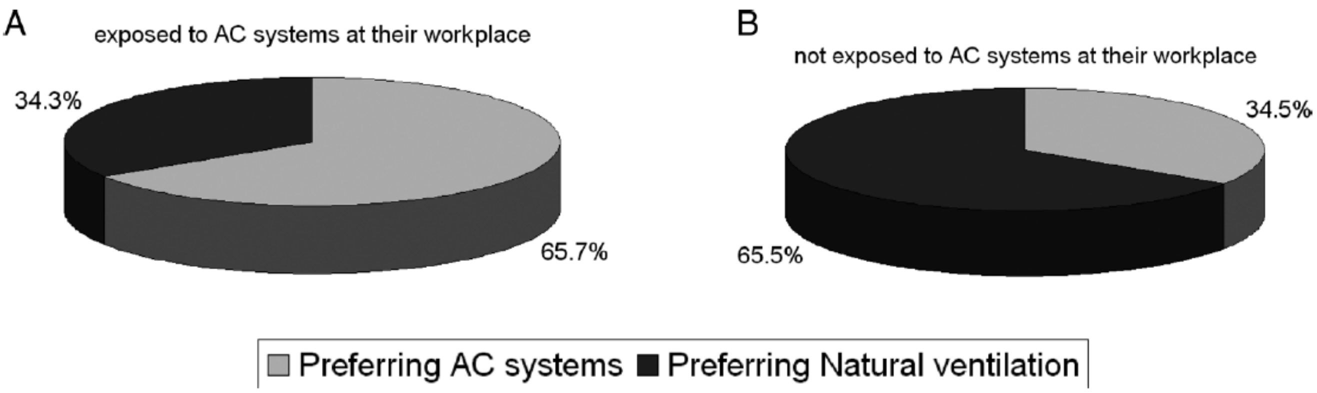


Figure 5. Overall space cooling preference votes: (a) occupants exposed to AC systems at their workplace and (b) occupants without exposure to AC systems at their workplace (source: Candido et al [45])

4.4. Traditional practices and regional differences in meeting SC related comfort requirements

As part of human adaptation to hot temperatures (mainly in regions in a warmer climatic zone), traditional practices passed down through generations have been mainly focused on features of the building design that helped people to live comfortably in the hot periods of the year. These passive solutions ranged from the inclusion of courtyards, water fountains, verandas, patios, and small ponds in buildings, to the selection of materials and colours for their construction (such as mud bricks and white-painted walls). However, behavioural actions have also played a part in people's adaptation to heat. Practices have traditionally varied from wearing light-coloured and loose-fitting clothes, eating light cold meals and drinking plenty of fluids to carrying out activities outdoors (informal meetings or sports). The way societal practices and "rules" functioned was in line with the necessary measures to cope with the corresponding season: in the summer, people used to arrange work-related meetings in outdoor spaces, stopped their day for a siesta, or carried out their daily activities (such as eating, or sharing family time) in their patios, which in turn led to more communication with neighbours and more use of outdoor living spaces. As described in the previous sections, the spread of air conditioning systems changed these traditional practices and standardized our expectation of comfort, transferring more activities to indoor spaces. The passive and lifestyle measures for coping with summer weather and high temperatures have been compiled within *Task 2.2 Measures scouting*, and the method on how they work will be presented in *D2.1 Taxonomy of space cooling technologies and measures*. The current section gives an overview of the geographical distribution of traditional behavioural practices and passive solutions are still present in different European regions, which could be of great use as an alternative to active space cooling systems. In this regard, we can mention different examples, as displayed in Table 2. The way occupants implement these are detailed in *D3.2 Analysis of behavioural interventions across Europe.*

Climatic Zone	Countries	Space cooling Practices	Reference
Medi-terranean	Spain, Italy, Greece, Portugal, Cyprus, Malta, Croatia	Natural ventilation design: This can include features such as high ceilings, cross-ventilation, and operable windows.	Sabatino, M. [46]
		Use of shutters, awnings, and thick walls for shading	Serguides, D. [47]
		Use of traditional courtyards and fountains for natural space cooling	Grube, E. J. et al. [48]
		Wearing light-colored and loose-fitting clothing with large body parts exposed to the environment: In many Mediterranean countries, traditional clothing is made from lightweight and breathable fabrics such as linen and cotton, and is designed to be loose-fitting to allow air to circulate and keep the body cool	Salata et al. [49]
		Taking siestas: people often take a siesta, or midday nap, during the hottest part of the day. This allows them to avoid the peak heat and rest during the time when their energy is likely to be lowest	Mazzone and Khosla [38]
Temperate Maritime	United Kingdom, Ireland, Norway, Denmark, Netherlands, Belgium	Use of natural ventilation and ceiling fans	Mushtaha et al. [50]
Continental	Germany, France, Poland, Czech Republic, Austria, Switzerland, Hungary, Romania	Window shading: People use window shading devices such as blinds, curtains, or shutters to block out the sun during the hottest parts of the day.	Grynning et al. [51]
		Use of natural ventilation and heat recovery systems	Hughes, Chaudhry and Calautit [52]
Boreal	Sweden, Finland, Norway, Iceland	Passive space cooling by nigh-time ventilation	Artmann, Manz and Heiselberg [53]

Climatic Zone	Countries	Space cooling Practices	Reference
Alpine	Switzerland, Austria, France, Italy	Evening activities: people can schedule outdoor activities for the evening when temperatures are cooler.	Fan et al. [54]
Subarctic	Norway, Sweden, Finland	Evening activities: people can schedule outdoor activities for the evening when temperatures are cooler.	Fan et al. [54]

Table 2. Space cooling practices per European region

4.5. Differences in space cooling-related comfort requirements

In this section we focus on the findings in the literature for the differences in SC-related comfort requirements amongst EU countries, particularly focusing on summer temperatures required by standards or legislation in residential buildings. We also explore the literature and case studies on whether regional differences can be evidenced in empirical data, i.e. the setpoints set for SC devices, or the summer temperatures expected by the building occupants. We concentrate on the dwellings, as these building types offer the maximum level of freedom to building occupants in adjusting their thermal environment.

4.5.1. Requirements

As detailed in Section 4.1 above, the informative Annex B of the EN16798-1 standard suggest default categories for design of mechanically heated and cooled buildings. For residential buildings, living spaces, (bedrooms, living rooms, kitchens, etc) with sedentary activity (1.2met, 0.5clo) the maximum space cooling setpoint in are shown in Table 3. For other spaces in residential buildings no requirements are recommended. For unoccupied hours the informative Annex C recommends 32°C. Schedules for operating space cooling devices are not implemented in the standard, as the target temperatures are anticipated to be reached throughout the whole occupied period. For buildings without mechanical space cooling the standard allows the use of the adaptive method, detailed in section 4.1.2..

IEQ category	Operative temperature – Maximum for space cooling (summer season) approximately 0.5 clo
IEQ_{I}	25.5 °C
IEQ_{II}	26 °C
IEQ_{III}	27°C
IEQ_{IV}	28°C

Table 3. Maximum default design values of the indoor operative temperatures in summer for buildings with mechanical space cooling systems, EN16798-1

This standard is adopted around Europe for determining thermal comfort; however, a few countries have additional requirements that are different from the above, which are more related to energy consumption. A more detailed analysis of the legislation will be presented in WP4 - *D4.1 – Review and mapping of legislations and regulations on sustainable space cooling at EU and national levels*, while here the different approaches towards SC-related comfort requirements is provided, building on existing literature.

A summary from the REHVA in 2012 concluded that European regulatory values temperature limits for summer vary from 28°C to 25°C. [55] The comparative study done by BPIE in 2015 [56] on the analysis of residential building regulations regarding indoor air quality and thermal comfort in eight EU member states (BE, DE, DK, FR, IT, PL, SE, UK) found that *indoor air temperature* is an indicator of thermal comfort in all surveyed countries and there are requirements and recommendations in place for lower and upper limits during winter and summer respectively. In a few countries such as France and the UK, *operative temperature* is also used to assess thermal comfort. Five out of eight countries require minimal temperatures in dwellings in winter (i.e. France, Germany, Poland, Sweden and the UK). Only Italy demands a lower limit in summer (max. cooling) and upper limit in winter (max. heating). Five countries within that survey (Brussels-Capital Region-Belgium, Denmark, France, Germany and the UK) had *overheating* limitations (either mandatory or recommended), where overheating indicators differ by temperature and time limit. The extremes are found in Brussels-Capital Region (> 25°C for 5%/yr) and the UK (> 28°C for 1%/yr), but only as a recommendation in the latter case.

In Italy, Presidential Decree 74/2013 on space heating/cooling systems lays down a set of obligations and criteria applicable to public and private buildings. [57] They apply to most building uses and include ambient temperature limits for space heating and for space cooling. For the latter, the weighted average air temperature measured in each cooled space must not be below 26°C - 2°C tolerance in all buildings.

Spain's Regulation Royal Decree 1027/2007 of 20 July 2007 establishes recommended indoor workplace temperatures as being between 23ºC and 25ºC for summer. [58] Additionally, in August 2022 a decree was adopted to temporarily (until November 2023) set the minimum temperature setpoint for space cooling systems in public buildings to 27°C [59]. However, this is not relevant to dwellings.

In Hungary, the 7/2006 (V.24.) TNM Decree defines the national calculation methodology for the building energy performance. For internal temperature, the Decree allows to follow the MSZ EN 15251 standard, or also the settings defined in the decree are allowed. For residential buildings, occupied spaces (rooms, dining, bedrooms, etc.) Table 1 within the Section V. of Appendix 1 allows 26 °C as the maximum operative temperature and defines 23-26°C as the acceptable range with space cooling. For spaces without space cooling as outlined in IV. Section of Appendix 1. the risk of overheating needs to be assessed based on the average internal heat loads (q_b) of the building and the heat capacity of the building/space. If qb < 10 W/m^2, then the maximum allowed temperature difference between the outdoor and indoor temperature ($\Delta t_{bnyár}$) is $\Delta tb_{nyár} < 3$ K for buildings with heavy structures, $\Delta tb_{nyár} < 2$ K for buildings with lightweight structures. (heavy: m ≥ 400 kg/m2, lightweight m < 400 kg/m2).

In France, a provision entered into force in July 2007 about the minimum indoor temperature not to exceed in case of using a space cooling system, as an addition to the Construction and Housing Code, and then also in the Energy Code (Article R241-30) in January 2016 [60]. Temperature setpoint of space cooling systems should not be set to a temperature lower than 26°C. Exceptions may apply to buildings used for medical care (except for hospitals), for the elderly or young children. 26°C is also the indoor temperature used to define the limit between comfort and discomfort at night, with a limit set as the range 26 to 28°C during the day (considering adaptative comfort).

In Austria, there is no minimum setpoint temperature for cooling technologies in the building regulation, as the objective of the building regulation is to avoid the need for cooling technologies (especially in new buildings). Considering the limit between comfort and discomfort, the maximum indoor temperature is set at 26°C during the day and 28°C at night.

In Sweden there is no limit on the summer temperatures. The National Board of Health and Welfare's general advice is not to exceed 26°C in summer.

It is seen that the thermal standards adopted throughout Europe do not include regional variations, in contrast, the national codes are not unified. Where active space cooling is applied, 26 ºC is the most common upper limit as a setpoint for SC devices. However, where the avoidance of space cooling is the intention of the policy makers, when single temperatures are given, the requirements are relaxed, up to 28°C; or instead of using a single temperature, overheating limits are defined as a function of the building structure, or together with the maximum number of hours when this is allowed.

4.5.2. Preferred temperatures amongst EU countries

As detailed in *D3.2 Analysis of behavioural interventions across Europe*, a high portion of the performance gap between the calculated and real energy consumption can be assigned to occupant behaviour, of which one element is the interaction with SC devices. Hence, as part of this research, we explored the literature for realistic information on country-specific preferred space cooling temperature set-points adapted by building occupants. We have seen in the previous sections that the occupant's thermal sensation and their actions in maintaining them are strongly influenced by a number of factors, including the thermal environment they had been exposed to, coming from the different climatic conditions during their thermal history. Therefore, it had been hypothesized that a standardized approach for temperature setpoints covering the whole continent do not address these nuances and variations, and so if not considering regional variations, valuable insights and opportunities for efficiency get lost. However, the literature review had not been able to find robust data from field surveys or monitoring evidencing this. While there is a lack of large scale monitoring data on the applied SC setpoints in the residential sector, some sources indicate preferred temperatures, which due to the lack of climatic and building related context might not be representative setpoints that are maintained by active space. Also, self-reported values from questionnaires on setpoints or preferred temperatures alone might be biased, as opposed to monitoring data. While literature widely exists for heating season and for commercial buildings, indoor temperature data maintained by space cooling, based on monitoring residential buildings in summer was found for case studies only.

Also, the literature seems to indicate that, as opposed to space heating, the information on “setpoints” might not be the most relevant indicator when SC demand in residential buildings is of concern, as AC devices are not operated in the same way as heating devices. On one hand, the penetration of AC devices in dwellings is still low in many countries. On the other hand, as detailed below, occupants tend to operate AC devices intermittently, with setpoint temperatures that are not actually achieved.

Examples for commercial buildings, indicate that the suggested operative temperatures are within the standards comfort range, however, these are lower than the maximum values allowed standards, which is acceptable for thermal comfort, however, means that energy used for SC is higher than expected. For example, data on the preferred temperatures based on field studies in office buildings in the UK have been summarized in a review paper. [61] Their findings for one case study showed that summer setpoint temperature were lower than 24 °C for more than 60% of buildings, while another found that increasing the setpoint temperature from 22–23 °C to 24 °C was acceptable, however, for an open-plan office area 24 °C was found to be near the maximum level of the actual percentage dissatisfied, implying that 24 °C might be the maximum cooling setpoint temperature for this office environment. Nevertheless, another study referenced indicated that with temperature setpoints between 24 °C and 26 °C the indoor environment was considered acceptable.

For Greece, the same paper stated that by temporarily increasing the classrooms cooling setpoint temperature from the typical 21–22 °C up to 25 °C, the occupant’s Actual Mean Vote (AMV) values did tend to increase but for most cases the class averages remained in an acceptable thermal comfort range.

Regarding a comparison of schools in various European locations, Aparicio-Ruiz et al, summarized that comfort temperatures between 20.5-24.5 °C had been found in free-running mode, where the study in the UK had the lowest, and the Spanish one the highest temperature. However, the preferred temperature was lower for the Spanish case, 22 °C was calculated. Regarding the classroom with a HVAC system and in the air-conditioned operating mode, the comfort temperature was 27.4 °C, and preferred temperature was 25 °C. [62] Authors however conclude that the temperatures were somewhat higher than expected from the adaptive comfort model, for which the cause may lay in the different thermal preferences of children.

In Italy four thermal comfort surveys conducted in naturally ventilated and air-conditioned commercial buildings (including offices, lecture rooms, and library reading rooms) located in Bari, in Southern Italy showed that while the thermal neutrality according to the ASHRAE seven point scale occurred at 24.4°C and 26.3°C in summer the “Preferred temperature,” based on McIntyre preference scale, was cooler: 24.2°C and 25.6°C respectively for naturally ventilated and air conditioned buildings respectively. [63]

Maximum temperatures in European office buildings to avoid heat discomfort has been studied by Nicol and Humphreys based on measure data from the project ‘Smart Controls and Thermal Comfort (SCATs)’, funded by the European Commission in 1997–2000. [64] Based on the measurements of conditions in 26 offices in 5 European Countries (France, Greece, Portugal, Sweden and the UK) comfort ranges were reconsidered based on a correlation to the running mean of the external temperature. Although monitoring data was used for several countries, they did not suggest to find any regional differences in the preferred internal temperatures.

These results on commercial buildings indicate that the actual preferred temperatures in mechanically cooled commercial buildings are within the temperature range of the comfort standards, but lower than the maximum threshold suggested. Findings indicate that the temperature setpoints could be increased to reduce SC demand. However, regional differences regarding these setpoints could not be revealed, as mechanically cooled buildings tend to provide the most comfortable environment within the internationally adapted comfort standards based on Fanger.

The literature of on preferred temperatures for SC in residential buildings and corresponding AC usage is however limited to a specific geographic area: several sources were found for USA, e.g. [65] [66] and Asia, e.g. [67] [68]. As opposed to studies on space heating set-point preferences, which are widely studied and available at national and subnational levels (e.g. [69], [70]), space cooling practice studies exploring realistic temperature set-points have not been developed as much in Europe. It seems that this data is not in the focus of the research field, for which the causes can be drawn from the literature.

Studies from outside Europe on behaviour regarding SC revealed that the occupants’ approach to setting a constant space cooling temperature is not adopted, on contrary to how heating setpoints are maintained by using a thermostat. For example, Kempton et al concluded that their initial hypothesis of people turning on an air-conditioners when they feel hot and set it to a temperature at which they will be comfortable was proven to be wrong through the field studies. [66] Instead, they revealed that when turning on devices, some residents set the thermostats to such a low setpoint that the thermostatic cutoff of the device – indicating that the setpoint had been reached – was not experienced before the residents manually turned the unit off. Similarly, Sekhar and Goh surveyed and measured AC usage at night in Singapore [67] and revealed that while the temperature of the air-conditioning unit was set to 20°C for 12 cases, the temperature only reached this value for one case according to the measurements. The measured mean temperatures fluctuated between 22.5°C and 26.5°C, which indicates similar to the findings of Kempton et al. that the SC devices in dwellings might not be sized right or controlled based on preferred temperatures, and operating these devices do not in fact mean that the intended temperatures are reached.

Implementation of this type of behaviour has been found in European literature as well. For example, Fokaides et al. compared measured and calculated energy consumption for ten dwellings in Cyprus and found 150% difference between the calculated and the measured cooling loads. [71] However, they had not included data in their research on set-points. Nevertheless, they pointed out that there is an important difference between the operation of the heating and cooling devices of the dwelling – as in the latter case only one or two occupied spaces are cooled – which results in uneven setpoints in the building. Their suggestion would be to develop a daily schedule for the cooling mode which defines the number of AC operation hours in the week and achieve a realistic temperature setpoint based on a schedule of operation of space cooling devices. The behaviour is similar to the findings in the paper of Xia et al, where AC operation was studied based on recordings from 102 bedrooms in several residential buildings of metropolitan Guangzhou, South China. Instead of implementing a setpoint, the internal temperature was controlled by a sequence of on/off operation of the AC systems. [72]

Another study has been focused on comfort temperatures during the summer in social housing in Spain. [73] As the users present very specific socio-economic profiles, these results cannot be extrapolated to the society as a whole. They found that the use of local cooling systems in the case studies is usually less than 10%, whereas the national average was found to be around 55%. Internal temperatures exceeded 34°C, and not unexpectedly a majority of the occupancy hours were found to be outside the comfort range.

In the literature, one specific example was found for Europe particularly indicating “temperature set-points” in summer. A study of Sovacool et al. [18] indicates specifically that thermostat setpoint are investigated, adapted by building occupants in winter and summer seasons in 5 countries, namely Germany, Italy, Spain, Sweden, and United Kingdom. In their article, Sovacool et al. carried out surveys to find occupants’ preferred home temperatures during winter and summer (i.e. the temperature at which they set their thermostat). Table 4 below shows occupants’ mean preferred home temperatures during summer as well as the mean seasonal temperature for the country. However, the results seem ambiguous when SC temperature preferences are considered, as for Germany, Sweden and the UK these are higher than the outdoor mean temperature, which indicates space heating rather than space cooling. There was no evidence in the paper whether these dwellings actually had SC equipment or not for providing the preferred temperatures.

Country	**Mean preferred summer temperature set-point [°C]**	**Mean seasonal temperature [°C]**
Germany	19.78	17.85
Italy	20.73	21.22
Spain	20.87	22.23
Sweden	19.17	13.18
United Kingdom	16.56	14.37

Table 4. Mean preferred summer temperature set-points [18]

Based on the above findings on the discrepancies of the setpoints and the actual temperatures, the results for Italy and Spain and cannot be considered as representative setpoints either, but rather a desire for temperatures that contrasts with the outdoor seasonal one, that is maintained for a limited period (meaning that, for example, if outdoor temperature is really warm in summer, people will ideally desire the coldest possible temperature in their homes).

Some examples also explored the actual temperatures based on questionnaires. Actual summer temperature in residential buildings was surveyed within the confines of the ENABLE.EU project in 2018 [74] based on a nationally representative survey on space heating and space cooling among the population of 5 of the project's partner countries – France, Germany, Hungary, Spain and Ukraine. The survey results outlined that the adapted temperature in the dwelling shows differences from country to country, but also cover a wide range within a single country. Some temperatures are much lower than the setpoints outlined in the standards and regulations, as shown on Figure 6. For example, in Germany, 79% of the respondents maintained an average temperature below 21°C in summer. Also, authors noted the controversial fact that households in Germany keep their homes much warmer during the winter (52% maintain an average temperature higher than 22°C) than during the summer (79% maintain an average temperature below 21 °C). Comparing these findings with the data from Sovacool et al. the mean actual temperatures are close for Germany (20-21°C vs 19.78°C), but are in contradiction with Spain (22-23°C as opposed to 19.17°C).

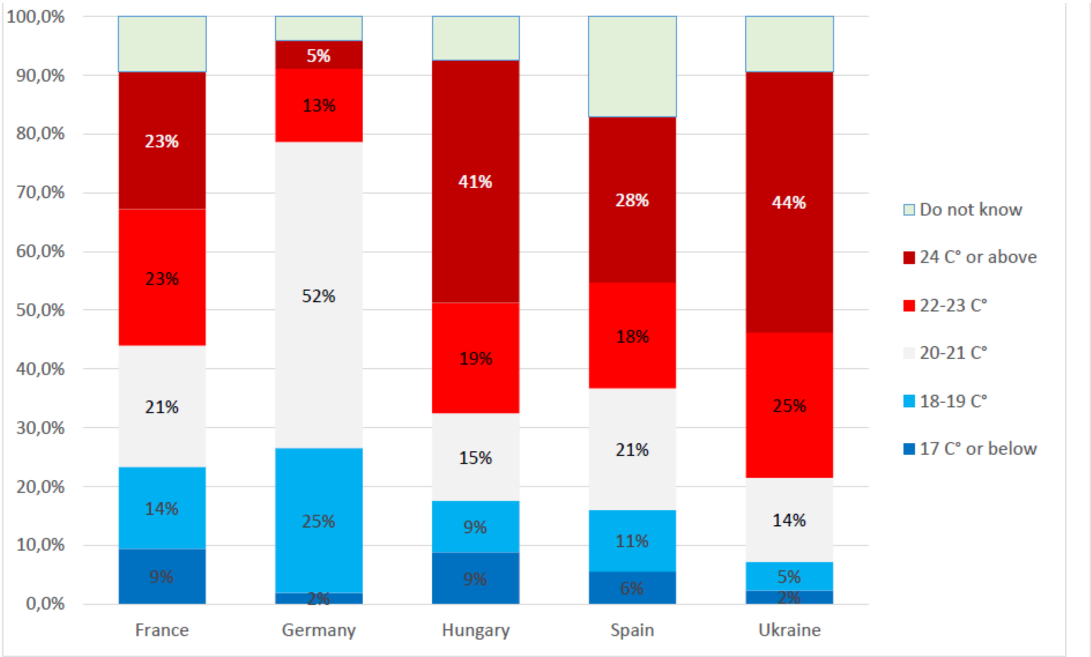


Figure 6. Usual temperature in the dwelling during the summer (% of the households) source: Enable.EU [74]

The causes for the heterogeneity of the data and differences between the different countries can come from various causes, as the climatic conditions, which had not been studied in the Enable.EU project. Within the research it had not been studied how these temperatures are maintained: by passive of active measures. Authors however conclude that only 3% of the respondents reported to have air-conditioning in Germany, 11% in Hungary, 18% in Ukraine, 21.4% in France and 49% for Spain. Hence, for Germany, it seems that these low temperatures are maintained by passive measures, which can be thanks to climatic conditions and the lower outdoor temperatures. Also, preference for a preference of using passive measures to cope with heat in Germany can be found in the literature [75]. However, in Spain nearly half of the respondents do have active space cooling, and around 55% of the respondents indicated temperatures 24°C or above, which seems to indicate that air conditioning is used to maintain temperatures that are lower than what is suggested as an upper limit in the standards.

In this research it had not been explored whether these temperatures are actually preferred temperatures as well, or the respondents are unsatisfied with the temperatures in the dwelling but are hindered in changing their environment due to economic or other reasons.

These results seem to indicate that the preferred temperatures for dwellings cannot be generally be defined, and self-reported preferred temperatures surely cannot be regarded as SC setpoints, but similarly to the suggested approach of Zhang et al, [76] several temperature thresholds might exist where residents start to take actions. For example, when using buildings in free-running mode the higher temperature values according to the adaptive comfort model might be accepted, which can be acceptable by implementing passive measures. However, when the thresholds of unacceptable temperatures are reached, residents activate SC devices that are then run on full power with unrealistically low setpoints to reach thermal comfort as soon as possible again.

Also, as adapted in the regulation of some countries, e.g. UK, high internal temperatures alone for a short period of time alone does not imply that space cooling will be used. This has been evidence by a case study in from Finland, where monitored temperatures up to 32 °C have been found, however, no mechanical cooling was installed. [77]

The differences in the SC-related expectations and coping with summer weather can also be seen on the penetration of AC devices in Europe. As seen on Figure 7, the percentage of dwellings equipped with AC in Europe also shows diversity, even for countries with similar climate. For example, the climatic conditions of Italy and Croatia does not explain the difference in the number of buildings with AC devices. These ratios however are showing a growing trend, since 2000 the average 10% European penetration rate has increased to 19% in 2022. [78].

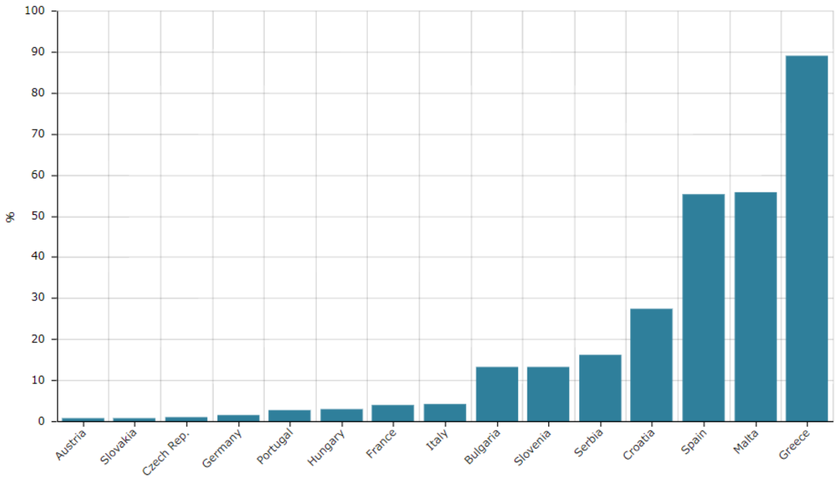


Figure 7. Share of dwellings with air conditioning (2010) Source: Enerdata [79]

As evidenced by this study, large-scale monitored data on space cooling setpoints in European countries is not readily available for dwellings. As seen above the literature contains some information on actual or preferred temperatures maintained in dwellings in summer, without the information whether this has been achieved by active or passive means. Thus, one should be careful not to take preferred temperatures as space cooling setpoints, as in some countries, the preferred indoor temperatures are actually higher than mean outdoor seasonal temperatures, which indicates that passive cooling, e.g. night time ventilation and shading is implemented. This the topic of implementing SC measures is further detailed in *D3.2 Analysis of behavioural interventions across Europe.*

Also, the literature seems to indicate that, as opposed to space heating, the information on "setpoints" might not be the most relevant indicator when SC demand in residential buildings is of concern:

- residential buildings in many cases do not have AC devices, or not in every room,
- occupants tend to operate AC devices intermittently, with setpoint temperatures that are not actually achieved
- in periods when space cooling is not activated, temperature tends to be higher than the setpoints implemented.

Understanding the correlation of preferred, actual and setpoint temperatures need to be studied in more detail for drawing conclusions on future space cooling demand, which is in the focus of the CoolLIFE project. To fill this gap of information, we have included specific questions on the actual, preferred temperatures and the temperatures implemented as setpoints on the SC devices within the country specific survey conducted for Hungary, together with the drivers on activating the SC devices. Please see the detailed analysis in the following section.

4.5.3. Findings from the CoolLIFE household survey

The full presentation of results and detailed analysis of the Hungarian household survey is done in Chapter 5 – Survey analysis. However, as temperature preferences are found to be inconsistent in the literature in the previous subsection, we find it important to present the most important findings of the survey on preferred temperatures, together with the relationship to perceived temperatures, perceived comfort, and air-conditioning schedules separately within this section, to help understand the interpretation of the available data.

Questions related to an average day in July, when no one from the household is on a holiday and everyone carries out his/her everyday activities, with the indication of the coldest room, if differences exist within the apartment were asked on:

- What is the usual temperature in your dwelling during summer on an average day of July?
- How do you feel the average temperature in your dwelling during summer in July?
- How comfortable do you find the average temperature in your dwelling during summer in July?
- What temperature do you aim for once you use air conditioning?

The goal was to identify the relationship between preferred temperatures and actual temperatures. This is important to assess the needs for space cooling. The results are illustrated in graphs below.

The usual temperature in the dwellings during summer on an average day of July when no one at the household is on holiday and everyone carries out his/her everyday activities has been investigated for three cases: 1. At daytime, when household members are at home, 2. At daytime, when no one is at home, 3. At night, when household members are at home. Results are presented on Figure 8. The temperature given by most of the respondents (mode value), and the value lying at the midpoint of the frequency distribution (median value) is the same for the first and the second case, thus for daytime independently of household members being at home or not. The mode value is 25°C and the median value is 24°C. The temperature somewhat differentiates at night, the mode value is 20°C and the median value 22°C. These values are in within the comfort range suggested for summer, in line with the expectations, and also similar to the results of the Enable.EU project above for Hungary. However, when asking the question of the preferred temperatures a tendency is seen for lower values (Figure 9). The median value for all three cases is 22°C.

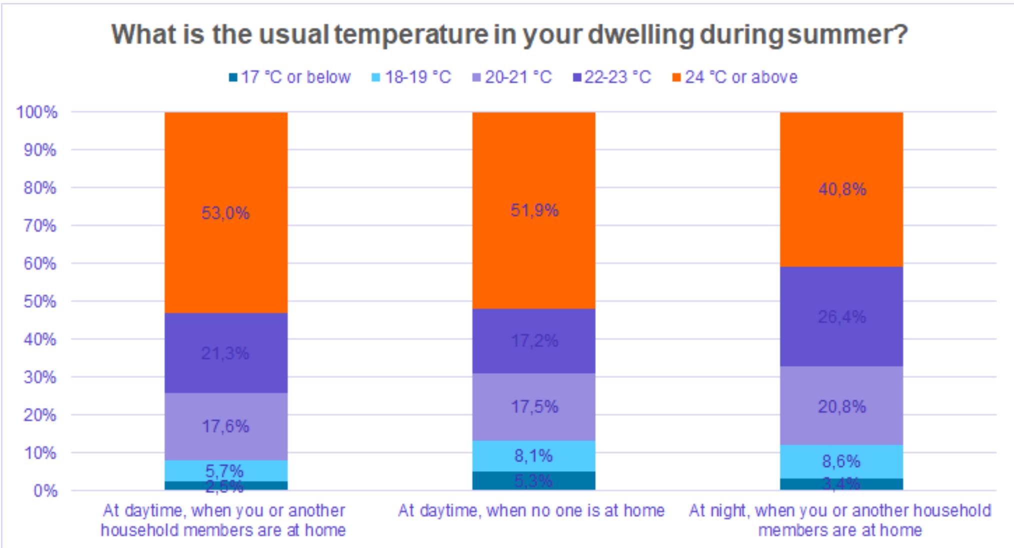


Figure 8. The usual temperature in the dwellings during summer on an average day of July, when no one at the household is on holiday and everyone carries out his/her everyday activities.

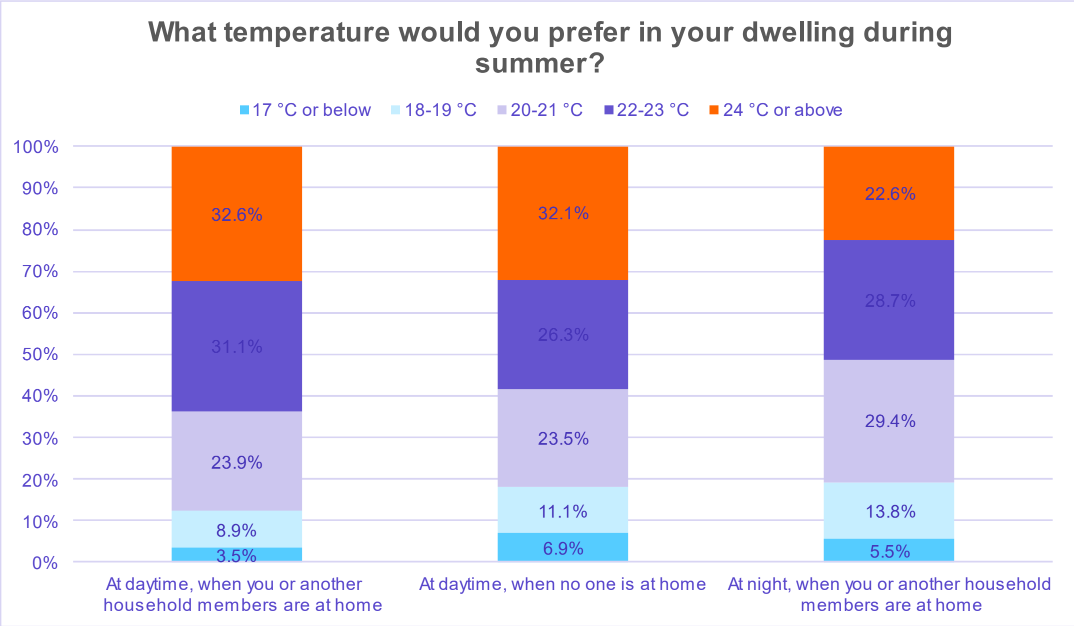


Figure 9. The preferred temperature in the dwelling during summer by occupancy.

Respondents were asked also how comfortable they felt with the temperature in their dwelling. Means of these scores by the actual temperature show that all in all up to 24°C the temperature is considered neither comfortable nor uncomfortable, mean values are close to the middle of the scale. Specific differences however reveal a temperature of 18°C is considered rather comfortable when household members are at home – both at daytime and at night – as the average is above value 3 in these cases. A turning point can be detected at a temperature of 25°C since the average scores of feelings of comfort decline sharply from this point on as the temperature rises.

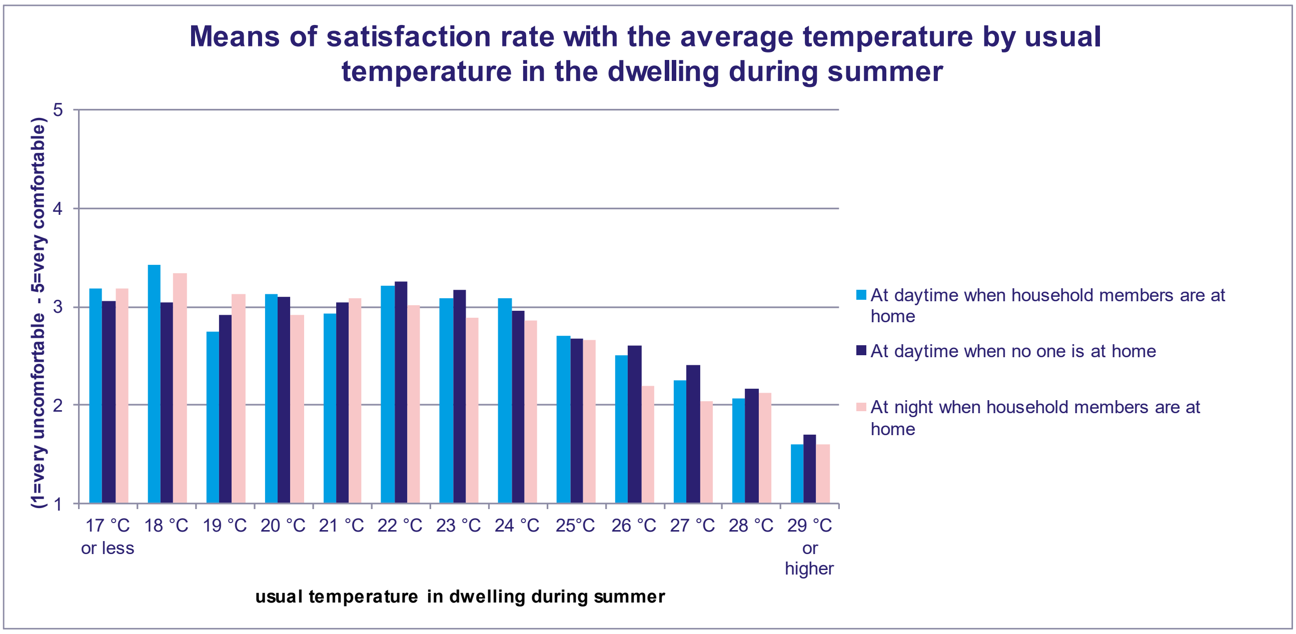


Figure 10. Means of satisfaction rate with the average temperature by usual temperature in the dwelling during summer.

The following two figures, present the relationship between preferred and actual temperatures both day and night. At daytime (Figure 11), those who have a relatively low temperature in their dwelling (18 °C- 17 °C or less) mostly desire the same temperature (68.2%; 60,7%). A smaller proportion of them would feel more comfortable with a higher temperature. The ratio of those preferring a warmer temperature in their dwelling is shrinking as the actual temperature in the dwelling rises. In contrast the proportion of those wishing for a colder temperature increases as the actual temperature in the dwelling rises. The turning point can be detected at a temperature of 25 °C in the dwelling as the greater part of the respondents who have 25 °C or more in their dwellings (65%-88.7%) wish for a colder temperature. Among respondents who have 20 °C in their dwelling in summer a significant part desires the same temperature (64.4%), the distribution of those longing for a warmer or colder temperature is almost equal (18.4% and 17.2%). As for people who indicated 19 °C or 21-24 °C as actual temperatures in their homes, they almost equally prefer the same temperature or a colder temperature.

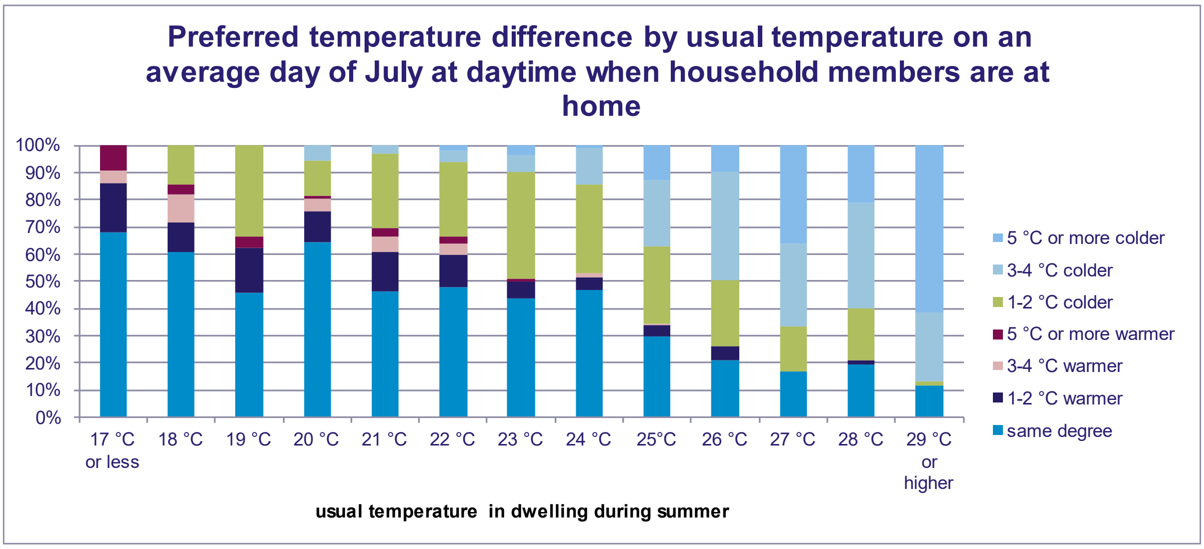


Figure 11. Preferred temperature difference by usual temperature on an average day of July at daytime when household members are at home

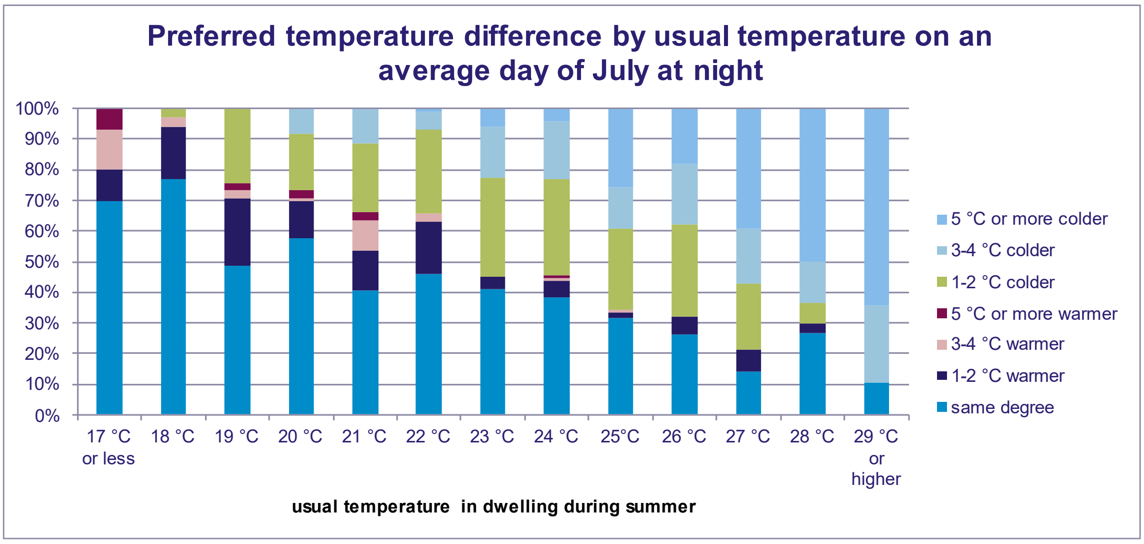


Figure 12. Preferred temperature difference by usual temperature on an average day of July at night.

At night (Figure 12) the trend is similar. The proportion of respondents preferring the same temperature as actually measured is the highest among those who have 18 °C or less (77,1%;70%) in their homes. The ratio of those wishing for a colder temperature is between 24.4% and 34.1% for those who have 19°C-22°C in their dwellings. A significant change in the tendency of preferred temperature outlines at 23°C in the dwelling at night. The proportion of those who prefer a colder temperature rises notably in this category (54.9%) compared to the previous one. The tendency of a growing proportion of respondents preferring a colder temperature continues further on. They represent almost 90% in the category of people who measure 29°C or more in their dwelling at night in summer. However, it is also seen that close to 30% of the people who reported to have 28°C in their dwelling prefer the same or even higher temperatures at nighttime. This value at daytime is only around 20% for this temperature.

As a conclusion, through our case study, we found that the mean preferred temperature in Hungarian households is 22°C-23°C during the summer season, which is somewhat lower than what is the actual temperature in their households. However, when respondents were asked how comfortable they felt with the temperature in their dwelling, up to 24°C the temperature is considered neither comfortable nor uncomfortable, while a turning point can be detected at a temperature of 25°C. Nevertheless, these cannot be considered as SC setpoints, as only around third (39.5%) of the dwellings are equipped with air conditioning units, which are not operated constantly. It is also seen that around 30% of the respondents who have 28°C at night prefer this temperature, while at daytime this portion is lower.

From the households that have air-conditioning, the majority (52.9%) of the respondents tend to turn on air conditioning in every case, or most cases, when they feel the dwelling uncomfortably warm. However, more than two-fifth (42.2%) of the sample uses air-conditioning only in case of extreme heat. As for the habits of the air conditioning use only 13.5% operate the SC the whole day, while 5.6% of the cases do not use it despite it is installed. The remaining percentages opt for different strategies of turning it on and off. The preferred setpoint was indicated between 20°C and 28°C among those who set a fix temperature. The mean value for adjusting the air conditioning is 22.4 °C, the median is 23°C, and however, the most frequent value 24°C. The majority of the respondents indicated that they set the SC device to a temperature between 22-25°C, each temperature indicated by a similar group size (16.6%-20.9%). Nearly 20% of the respondents set a temperature below 20°C. While the number of respondents are similar to those who prefer the these low temperatures, it is anticipated based on the above findings in section 4.5.2. that this setpoint is not always reached.

4.6. Critical review of the thermal comfort standards

It has been shown that the standardized values of the globally accepted thermal comfort criteria are all based on the same sources, the PMV-PPD indices developed by Fanger in the 1970s, which are meant to be used for building with controlled thermal environments. The occupants desired comfort conditions are limited to a very narrow range of scientifically determined parameters, designed for the resource-intensive air conditioning (AC) systems in buildings.

Although both European and US standards implement the adaptive comfort model for spaces without mechanical space cooling, which allow higher temperature ranges compared to what is required for spaces with active space cooling systems (mainly air conditioning systems), the adaptation of the comfort criteria to different groups or locations is missing.

As seen above, the concept of "thermal comfort" and its related expectations is deeply influenced by different factors and differs greatly between building occupants. The thermal comfort standards offer a set of criteria that when applied to an air-conditioned building will be widely accepted by most of the occupants on a statistical basis, however, the needs of individuals can vary from this widely. Especially in case of residential buildings, where the occupant has the freedom to directly adjust their thermal environment to their needs, the comfort range can vary from the standard.

The following shortcomings of the current standards have been found based on the literature review, that correspond to the findings of the review on the socially constructed concept of thermal comfort:

Shift between "comfortable" and "neutral"

A classic assumption for the PMV scale is that "slightly cool", "neutral", and "slightly warm", represent thermally comfortable or acceptable range. However, Schweiker et al [37] analysed whether laypersons perceive thermal comfort as researchers believe, and indicated that several studies have shown individual and contextual differences that do not support this assumption, a number of authors have proven the difference between comfort and neutrality. According to them: a German study found that PMV-PPD curves shifted to the right; a study with mostly English participants in winter showed a preference for warmer conditions and the neutrality did not represent the mid-point of the thermal continuum. A study on the Eastern Arabs' interpretation of ASHRAE thermal scale phrases showed that thermal sensations on the cold side of the scale were considered as comfortable. A wider analysis even showed that the PMV model predicted thermal sensation correctly only in one out of three times and that the PPD was not able to predict dissatisfaction rate, if PMV is used as input. It was also shown that the relationships between the observed thermal sensation and the observed percentage of unacceptability depend on climate, ventilation strategy, and building types. The percentage of dissatisfied was usually between 15–25% in the neutral zone.

Another study by Becker and Paciuk [23] examined predicted and actual thermal responses in residential buildings to determine a connection between indoor environmental and contextual variables (e.g., available control options, social factors), and thermal comfort perception. Significant disagreement was found between standard, predicted and the actual comfort (PPD and PMV) levels. The study showed that also having information on contextual factors, to more accurately predict the thermal response of an occupant, was essential.

Cândido et al. [45] studied effects of artificially induced heat acclimatization on subjects' thermal and air movement preferences. The argue that it is possible to physiologically acclimatize 'air-conditioning addicts' to warmer indoor environments without compromising their thermal acceptability.

Cultural/regional differences

Khovalyg et al *[80]* performed a critical analysis of the IEQ standards, also dealing with thermal comfort, and compared the global standards to what is implemented in China. They summarized that regional differences in climate, building typology, demographics and culture are not adequately covered in the standards. They suggest that it would be more appropriate for individual countries to use the concepts provided in standards such as EN and ISO and set "local" limiting values considering particular specifics of the region.
Kalmar *[81]* surveyed the subjective thermal sensation of individuals in a space with high ambient temperature (30°C) for two hours from different backgrounds. He showed that while during the measurement period the environmental parameters remained unchanged, the subjective thermal sensation characterized by the Actual Mean Vote AMV decreased from average 1.5 to 1.0-0.5 depending on the group of people (sex and nationality). The change in the acceptance was the highest for the group of Nigerian men, and lowest for the Hungarian men. His findings were also interesting in light that according to his summary on the topic. In the early years researchers could not show

differences in the thermal sensation of people with different backgrounds. In 1953 Ellis *[82]* found no notable difference between the sensation of European and Asian subject. In 1970 Fanger explored the effect of the country where the subjects are from on the comfort equations. In his experiments Danish and Northern Americans were studied and concluded that the subjective temperature sensation was similar for the two groups. Fanger also analyzed results from previous research and concluded that the Europeans living in Nigeria and the Indians in Calcutta had the same thermal sensation.

As seen in the previous bullet point the shift of the comfortable and neutral zone can differ from country to country: the European studies showed a shift towards the warmer environment in winter, while the Arabic respondents shifted towards the cooler sensations.

Activity types covered

In the ASHRAE standard it is specifically stated that the requirements are not applicable to people with metabolic rates between 1.0 and 2.0 met (i.e. resting to walking slowly), and people who are neither sleeping nor reclining. The EN16798 comfort standard also does not differentiate the recommended design values for sleeping and waking people. However, it has been shown in many studies that sleeping required different comfort ranges; and this is also highly influences by sleeping habits (e.g. clo level of bedclothes).

The thermal comfort standards and guidelines presume sedentary, light activity and a neutral overall thermal sensation when predicting local thermal discomfort. Toftum found a clear impact of activity and overall thermal sensation on human sensitivity to air movement, that is not covered in the standards. [83] Shifts from seated to standing posture may result in an activity increase of 0.3 met corresponding to a decrease in preferred temperature of approximately 2.4°C [84].

In a theoretical study on thermal comfort model for sleeping environments, Lin and Deng [85] developed a comfort equation applicable to sleeping thermal environments by introducing appropriate assumptions and modifications to Fanger’s comfort model. Their comfort equation for sleeping environments contains five variables: air temperature, mean radiant temperature, water vapour pressure in ambient air, air velocity and a new variable called the total resistance/insulation provided by a bedding system. They observed that the effect of the latter variable on the optimum operative temperature was approximately 5.3°C per clo. They conclude that that the total insulation value provided by a bedding system significantly affects the thermal neutral temperature for sleeping persons.

Applicability to building without SC or intermittent use of SC devices

While adaptive comfort theory is included in the EN 16798 standard with a wider range of acceptable environmental parameters, these are only applicable to metabolic rates ranging from 1.0-1.3, and clothing values between 0.4.-1.0 clo, which is a narrow range compared to what is seen in e.g. residential buildings.

Novel methods towards the adaptive comfort evaluation in also heated and cooled buildings exist. Maximum temperatures in European office buildings to avoid heat discomfort has been studied by Nicol and Humphreys based on measure data from the project ‘Smart Controls and Thermal Comfort (SCATs)’, funded by the European Commission in 1997–2000. Based on the measurements of conditions in 26 offices in 5 European Countries (France, Greece, Portugal, Sweden and the UK) comfort ranges in correlation to outdoor running mean temperatures have been suggested for free-running and heated and cooled buildings [64]. This paper provides a novel approach towards defining thermal comfort ranges in mechanically conditioned spaces compared to the standards, as based on the field measurements they argue that thermal adaptation also influences preferred temperatures in buildings which are being heated or cooled, despite the indoor temperature being largely decoupled from the outdoor temperature.

Zhang et al [76], who also completed field measurements on indoor comfort and perceived air quality to map thermal acceptance suggest a novel approach towards SC by mixing mechanically cooled and passive solutions. Namely, they suggest that buildings should be free-running between 19.5-25.5 °C, then ceiling fans and personal control fans should be used, while AC cooling should be used over 30 °C, to bring environmental conditions outside the thresholds within them. They also argue that within air temperatures from 21 to 27 °C there is no obvious best temperature for productivity, while beyond this range, productivity declines in most of the studies. Implementing this approach is not aligned with the standards, but implementing this in commercial buildings could have a potential when reduction of SC demand is concerned.

The metabolic rate

The metabolic rate is an input for the calculations of PMV are also standardized in the calculations. This value shows a large variation among occupants and is dependent on the weight, height, body surface area, but as stated above, also on the food that is eaten. While the calculation methodology of Fanger does allow for an input of different metabolic rates, the simplified suggestions in comfort standards that are taken as a bases in the design cannot address the variations of the metabolic rate that is seen in reality, neither the adaptation strategy by drinking cool/hot drinks, or having a shower.

Increased metabolic rate can occur from arriving to a building as well. Bourdakis et al [86] argue that most people will have an increased activity (higher than sedentary) coming to work. This may result in a feeling of warmth arriving in an office controlled for sedentary comfort. In their experiment they showed that a little lower temperature than the comfort range may improve comfort when arriving in the office and at the same time increase the potential use of night-space-cooling. They suggest that in countries where most people commute on foot or by bike, the room air temperature at the beginning of the occupancy period could be 20°C – 21.5°C, namely lower than EN Standard 15251 suggests. It should then increase steadily at a rate of 1.5K/0.5h to reach the comfort range of 23°C – 26°C.

Temporal adaptation

While the standards are relevant for spaces where people spend at least 15 minutes, the adaptation to comfort conditions by time is not addressed. In his measurements, as indicated above, Kalmar proved that the subjective thermal sensation of the individuals in the high ambient temperature space increased during the measurement period even with unchanged environmental parameters. The subjective thermal sensation characterized by the AMV decreased from average 1.5 to 1.0-0.5 over the two-hour experiment, depending on the group of people (sex and nationality). The change in the acceptance was the highest for the group of Nigerian men, and lowest for the Hungarian men.

4.7. Conclusion

In this section we have presented and analyzed the meaning of thermal comfort from the standardized approach and also from the occupants' perspective, the so-called socially constructed concept of thermal comfort. We have identified simplifications in the standard methodologies that cannot address the complexity of the thermal sensation of each individual, and also can have limitations regarding space types due to their typical usage, e.g. in residential buildings thermal comfort when sleeping is not addressed.

We have collected the available data on the regional differences in traditional practices to cope with hot weather and also the available data on preferred temperatures and setpoints for dwellings around Europe. As there is a lack of reliable data on this field we have extended the desk-based literature review with the findings of the CoolLIFE survey in regards to the temperature expectations, preferred space cooling setpoints, and satisfaction with room temperatures. In the next section further information from the survey will be presented on the inhabitants' approach to maintaining acceptable summer thermal conditions and the passive and active measures implemented by the respondents.

5. Survey analysis

We have conducted a literature review on the occupant behaviour surveys available in Europe and have found that surveys that are representative and target occupants in residential buildings are not available. Hence, conducting a targeted survey provides valuable insight on the user behaviour that helps understand the occupants' actions towards space cooling. In the next section information on the data collected within the survey is presented on the inhabitants' approach to maintaining acceptable summer thermal conditions and the passive and active measures implemented by the respondents. The survey also serves as a basis for identifying occupant behaviour patterns in implementing space cooling techniques and passive measures as well as adaptation techniques to cope with high summer temperatures. The patterns regarding the lifestyle and user behaviour interventions have been analyzed in detail in *D3.2 Analysis of behavioural interventions across Europe*.

5.1. Sample data

The survey was conducted online using a pool of 165,000 possible respondents from a survey panel of a market research company. The panel was created using incentives to reward participation in the survey. Unique personal links were sent to the respondents of the panel. The data collection lasted one month between mid-April and mid-May 2023.

The sample consisted of residents 18 years and older. A quota sample was used with a combination of age, gender, education, region (NUTS1) and settlement type. Respondents were selected randomly. The response rate was high: 99.9% of the respondents completed the entire questionnaire.

5.1.1. Location and characteristics of dwelling

Of the households in our sample, the largest share is located in cities and small towns (32.1%) and a much smaller share (28.7%) in rural villages. 22.6% of dwellings are located in the densely built-up areas of large cities, while 15.9% in the suburbs or on the outskirts of a large city. Farms are included in the sample with a share of 0.8%.

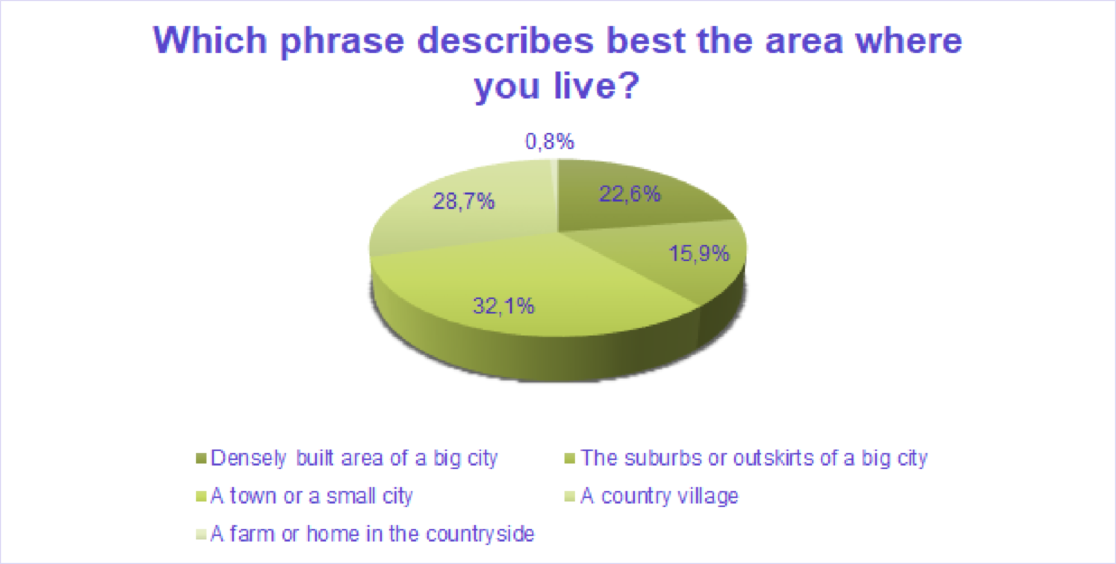


Figure 13. Respondents' distribution by size of the settlements.

Housing type and size

The sample reflects the Hungarian situation: 58.7 % of the housing stock are single-family houses. 3.9 % of the total sample lives in detached single-family houses (e.g. semi-detached houses, terraced houses) and 0.5 % in non-residential buildings or holiday homes. The share of flats in multi-family buildings in prefabricated construction is 21.3 %, in non-prefabricated construction 15.6 %.

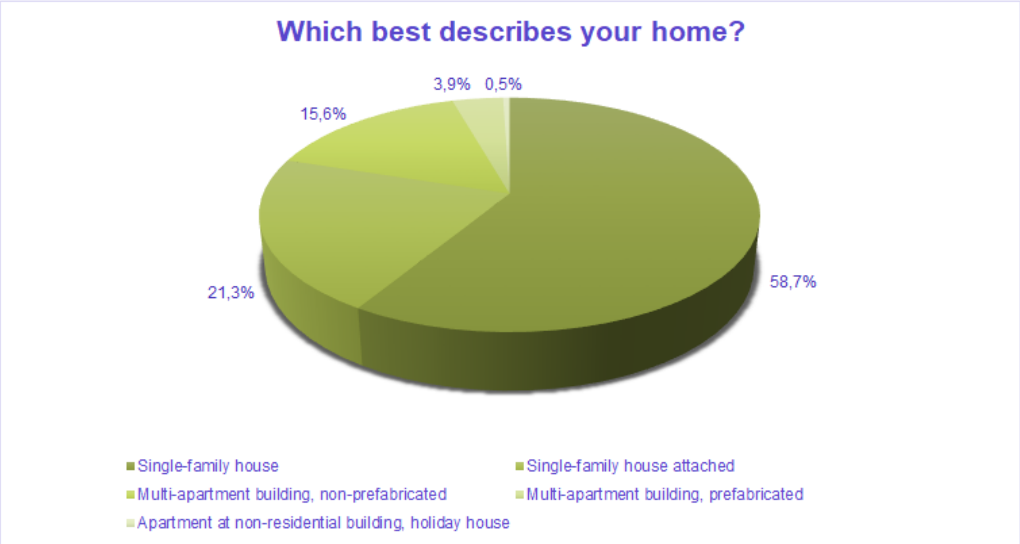


Figure 14. Building typology.

51.8% of the buildings surveyed contain one flat. The share of houses with more than 10 flats is relatively large (32.2%), with 2-3 flats it is 9.8% and with 4-9 flats 6.2%. The number of storeys was only asked for the non-family houses. The percentage of buildings with one storey is 31.2%, with 2-3 storeys 22.2%, with 4 storeys 18.3%, with 5-9 storeys 11.7% and with 10 storeys and more 1.5%.

13.9% of the residents do not know, when their flat or house was built. The largest share (21.3 %) of houses were built between 1970-79. The share of houses built in the previous decade (1980-89) is 16.9% and that of houses built after 1990 is 17.9%. The remaining 14.8% were built between 1960-69, and 15.1% before 1960.

We did not receive information on the size of the flats from almost one fifth of the sample (19.4%). The majority of respondents (20.2%) who were able to tell us the size of the dwelling they live in, gave the size of 50-59 square meters. This is the type of flat of which there are the most in Hungary. The share of flats or houses with less than 50 square metres is 16.5%. The share of flats with a living area of 60-79 square metres is 18.8%, while 14.9% with 80-99 square metres. The share of flats with 100 square metres apartments is 11.9% and more than 100 square metres is 17.7%.

Based on the composition of the rooms of the examined apartments, we found the following: 26.5% of the apartments had at least 1 open-kitchen. The proportion of apartments with a traditional, separate kitchen is 81.1%. 36.8% of households had at least one dining room. 37.5% of the apartments had no separate living room. 58.4% had 1, and 4.1% had several living rooms. 7.8% of households indicated that they did not have a separate bedroom. The proportion of dwellings with one bedroom is 30.7%, with two bedrooms 36.8% and with three 19.3% and with more than three 5.4%. In 18.5 % of the flats there is at least one separate study

Insulation of dwelling, space heating and space cooling systems, and smart meters

Regarding the insulation of the dwellings, we found that insulated windows (68.9%) and insulated doors (52.2%) were the most common. External or internal insulation of the walls was carried out in almost half of the dwellings (46%). Insulation of the roof was reported in one third of the houses (34%), and of the attic in 28.1%. The insulated basement was mentioned least often (11.9%).

The spatial distribution of insulation use showed that the highest proportion of attic insulation is most common in the outskirts of large cities (39.2%) and in villages (35.4%), in single-family houses (37.9%) and in dwellings built after 1990 (50.6%), as well as in buildings with a floor area of more than 100 square metres (50.2%).

Roof insulation was used mostly in the outer districts of large cities (45.9%) and in houses built after 1990 (54.4 %). Exterior and interior insulation was used to a large extent in dwellings in the outer suburbs of large cities (56.7%) and in houses built after 1990 (61.7%).

The isolated basement is most frequently found in densely built-up areas of large cities (15.9%).

Insulated windows have mostly houses built after 1990 (78.9%). Insulated doors were also installed in homes built after 1990 (61.9%) and in homes with an area of more than 100 square metres (68.9%).

Modern space cooling and heating systems are found in only a few households. 5.3 percent of the houses have solar panels, another 2.6 percent had solar collectors and 3.7 percent had heat pumps installed.

Heat pumps are mainly installed in houses built after 1990 (6.1%). Solar panels and solar collectors are typical mainly for single-family houses (4% and 6.7%) and flats with an area of more than 100 square metres. (6.7% and 8.4%)

When examining additional space cooling, heating and control devices, it was found that air conditioners that can be used for both space cooling and heating are used to a great extent in downtowns (31.4%) and in the suburbs of the large towns (34.0%) They are typically more frequently than average in houses built after 1990 (40.0%).

The most common method of optimising energy consumption is the use of energy-saving light bulbs. It is used by 86.6% of households. Energy-saving lamps were most frequently used in houses built before 1969 (91.0%).

Among the control devices, the wall-mounted room thermostat is the most common (25.7%). One tenth of households (9.9%) have a portable thermostat. Almost as high is the share of users of other smart devices that control space cooling or heating (9.7%). Room thermostats are most frequently used in the outskirts and metropolitan areas of large cities (35.4%), in single-family houses (32.8%), in buildings built after 1990 (42.2%), and in flats with an area of 70 to 99 square metres (32.6%) and in flats with an area of more than 100 square metres (40.3%). The use of a portable thermostat is most characteristic of single-family homes (12.4%) and flats with more than 100 square metres (15.1%).

In another question, we specifically asked about the existence of individual smart meters. The smart electricity meter was mentioned in the largest proportion (10.6%). This was followed in order by the smart heating meter (7.6%), then the smart gas meter (5.1%). The largest share of smart space heating and cooling control devices was used in homes built after 1990 (16.1%). When examining the details of smart meter use, we found that smart electricity meters were installed more frequently than average in single-family homes (12.5%) and in buildings built after 1990 (15.6%). Smart gas meters were mainly installed in densely built-up areas of large towns (8.4%). And the smart heating meter is installed in the inner (13.3%) and outer districts (11.9%) of large towns, in apartment buildings (12.2%), in flats built after 1990 (11.7%).

Two percent of the dwelling cannot be heated at all. Of the heating appliances, the most common are those used for space heating (38.4%), including individual heaters powered by gas, electricity, oil or solid fuels. This is followed by boilers and radiators installed in the dwelling (32.3%). District heating used by 20.8 % and boilers and radiators by 8.9 % supplying several apartments. 12.2 % of the dwellings also use air conditioning for space heating. Underfloor or in-floor heating was reported in 6.4 % of the dwellings.

Among the energy sources used for heating, piped natural gas is the most common (50.9%). LPG gas in a container was mentioned by 0.8%. In addition, a significant proportion of solid fuel (wood, coaler coke, pellets) is used by 29.8%. District heating serves 21.0% of the dwelling, while electricity is used for heating in 21.5%. The use of geothermal energy is still very low (1.2%). 2.4% of the respondents indicated that they also use waste for heating.

41.9 % of the radiators in the households are equipped with adjustable valves. There commonly used in the suburbs of large towns (49.1%) and in apartment buildings (48.5%); they were installed mainly in dwellings built between 1970 and 1989 (46.5%) and after 1990 (55.6%).

Household composition, tenure, and home office

After the Covid-19 pandemic, the home office is becoming commonplace in more and more households. 19.3% of households work from home four or more days a week, 6.4% 2-3 days and 3.4% one day. However, in 70.9% of households this is only occasionally or never the case.

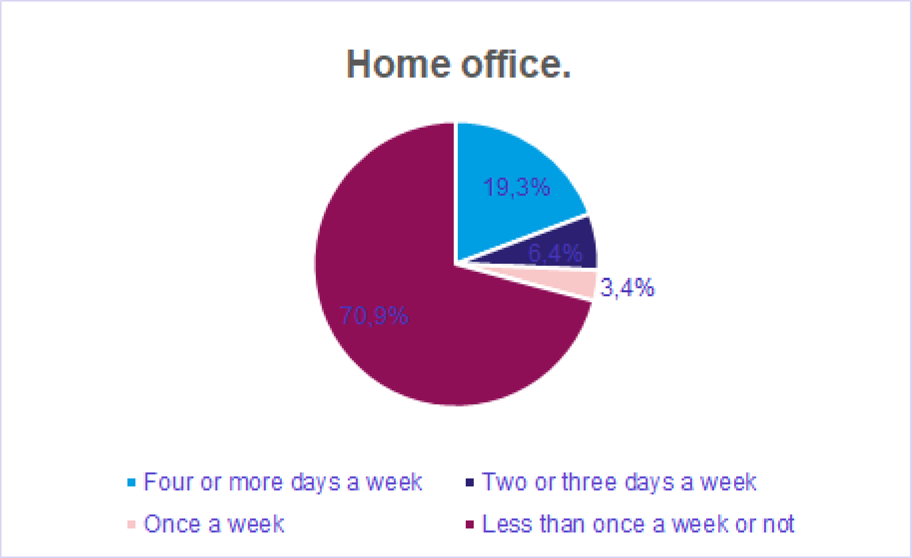


Figure 15. Dwelling occupancy in context of home office during Covid-19 pandemic.

The ownership structure of the dwellings reflects the character of the Hungarian residential property market. A significant proportion of the flats are privately owned (84.7%). The share of private rentals is modest (11.5%) and the share of public rentals is low (3.1%). Only 0.7% mentioned another legal form (e.g. housing co-operative, etc.).

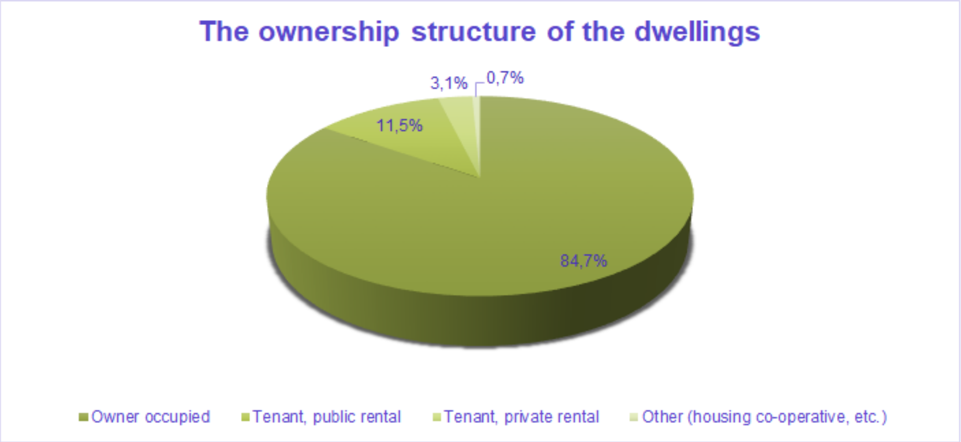


Figure 16. The ownership structure of the dwellings.

Looking at the number of occupants of the dwellings, we find that households with 2 persons accounted for the largest share (38.2%) in the sample. This was followed by households with 3 persons (22.6%) and households with 4 or more persons (22%). The share of one-person households was the lowest (17.3%).

Composition of the household members by age: Children aged 3 years or younger lived in 11.4% and aged 4-17 years in 20.2% of households. Adult residents (18-64 years) of employable age lived in 85.6% of the households. People aged 65 and older lived in 32.7% of the dwellings.

5.1.2. Characteristics of respondents

The breakdown by gender reflects the gender ratio in Hungary: 46.6% of respondents are men and 53.4% are women.

The youngest age group (18-29 years) account for 18.1% of the sample. The share of 30-39 year olds is 19.4% and that of 40-49 year olds is 16.2%. Among the older age groups, 17.7 % of 50-59 year olds and 14.5% of 60-69 year olds are represented in the sample. The share of the oldest (over 70 years) is 14.2%.

In terms of education, 51% of the sample have at most primary education (no formal education or below primary education); 31.3% have secondary and post-secondary non-tertiary education and 17.7% have tertiary education.

Looking at the current employment status of the respondents, we find that the largest proportion (44.6%) reported full-time employment. The share of part-time employees is 6.2 %, that of employees in their own company is 2.9%. The second largest group was pensioners with 28%. Among the inactive, the proportion of those at home with small children is 5.7%; the proportion of students is 2.2%. The share of unemployed is 5.9%, that of public employees (employed for no longer than 3 months) is 1%. The remaining 3.5% of the sample placed themselves in other categories.

A relatively large proportion (26%) of households have a person who spends a lot of time at home for health reasons. Household members who take care of small children or other family members at home were reported by 14.7% of the respondents.

In the last two decades, fewer and fewer people in Hungary have answered questions about income. Therefore, the question was asked in different ways.

For the questions on the income situation of the household, 43.8% of the respondents answered the open question. Another 34.3% answered on the basis of the predefined income categories. A relatively large proportion of respondents (21.9%) did not answer this question. Using this data, we sorted the answers into the predefined categories and arrived at the following result: The percentage of households with an income of less than 200,000 HUF is 19.7%, with an income of 201,000-300,000 HUF is 17.3% and 15% have an income of 301,000-400,000 HUF. The proportion of respondents with an income of HUF 401,000-500,000 was 9.4%, while an income between HUF 500,000 and 1 million was typical for 13.3%. 3.5% of the respondents had a household income of more than 1 million HUF.

According to the households' subjective assessment of their income situation, the relative majority (45.2%) get by on their current income. A quarter of households (25.5%) have difficulties, while 12.1% often have difficulties. However, 17.2% of the sample live comfortably on their current income.

Figure 17. Which of the descriptions below comes closest to how you feel about your household's income nowadays?

In order to be able to pay their energy bills, 12.8% of the surveyed households received some kind of financial support from public institutions (including so-called social tariffs) in the last 12 months.

5.2. Results of the survey

5.2.1. Patterns of energy demand

Temperature and preferences

Most of the Hungarian respondents (84.6%) are able to measure the temperature in their apartment, almost 60% in every room, another 25.6% in specific rooms. Those who cannot measure the temperature in their apartment represent only 15.4% in the sample.

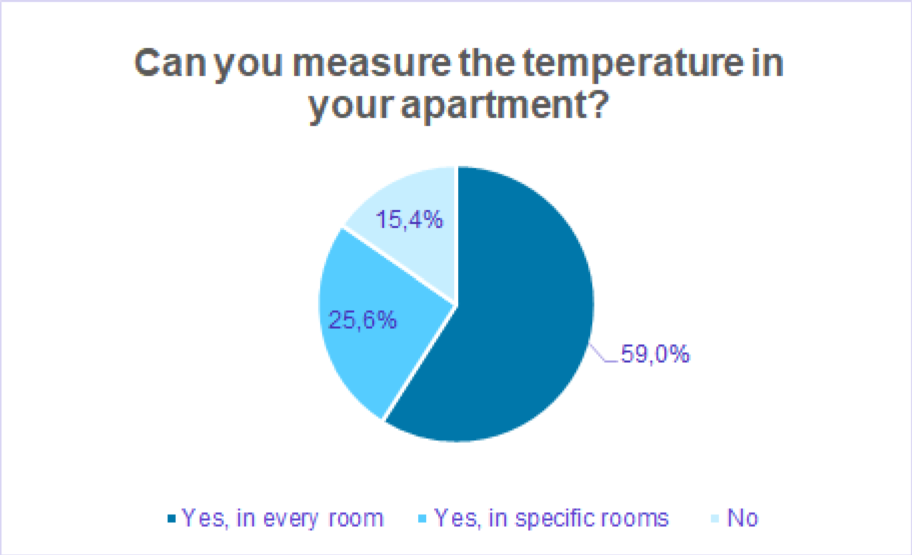


Figure 18. Possibility of measuring the temperature in the dwelling.

The most common device to measure the temperature among the respondents is the thermometer (analogue or digital) (71.0%), which is followed by the room thermostat for 16.4%. Measuring the temperature by a space cooling device (e.g. air-conditioner) applies for 10.0% of the cases. Less common device to measure the temperature is the appliance thermostat (portable) for 8.9%. Other answers than the listed ones were given by only 1%. These answers include for example a weather station or an air purifier.

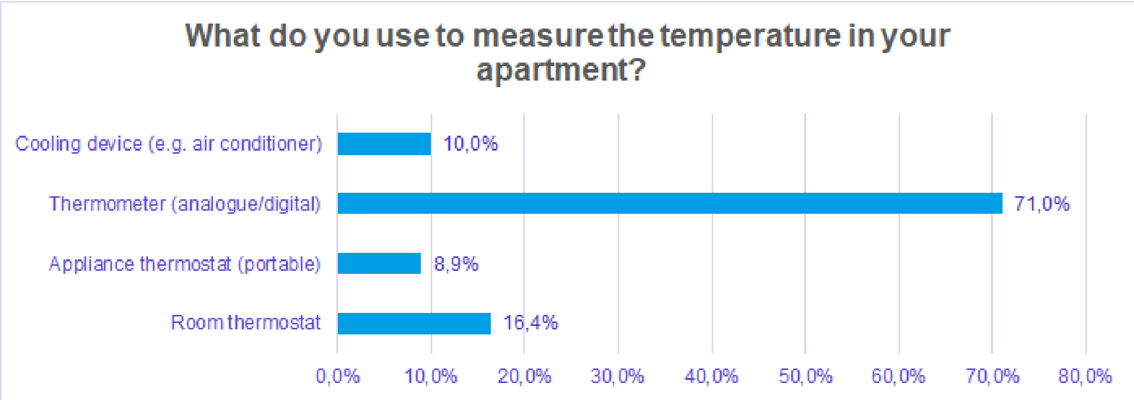


Figure 19. Device of measuring the temperature in the dwelling.

When it comes to changing the temperature in the apartment in any way most people consider how hot or cold they feel themselves (59.7%). One third (33.4%) of the sample considers how hot or cold other members of the household feel when they change the temperature. The temperature measured by a device is indicative for changing the temperature for 28.6% of the respondents and for only 24.9% is the less spending on space cooling the information they consider when they change the temperature. A small part of the respondents (9.9%) cannot change the indoor temperature at all.

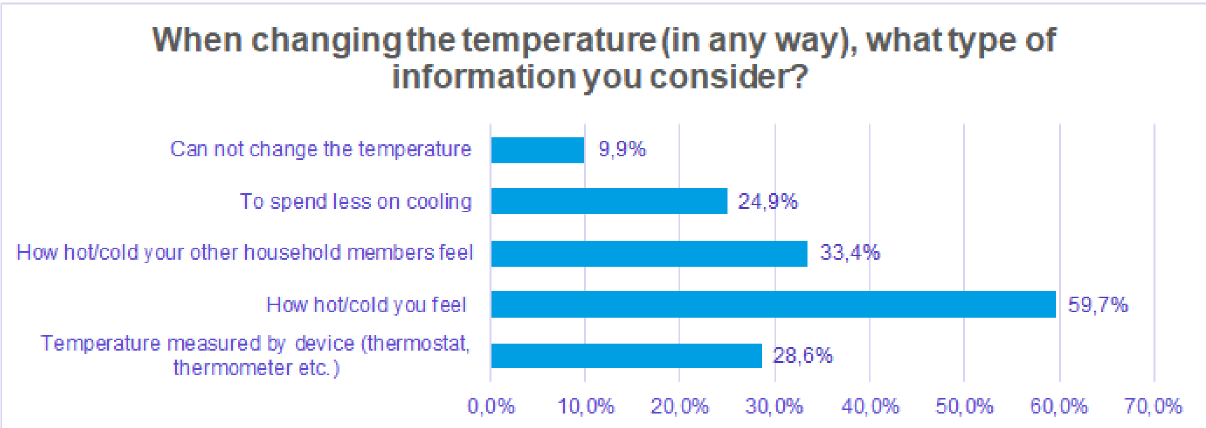


Figure 20. Type of information considering on when changing the temperature.

The usual temperature in the dwelling during summer on an average day of July when no one at the household is on holiday and everyone carries out his/her everyday activities has been investigated for three cases: 1. At daytime, when household members are at home, 2. At daytime, when no one is at home, 3. At night, when household members are at home. The temperature given by most of the respondents (mode value), and the value lying at the midpoint of the frequency distribution (median value) is the same for the first and the second case, thus for daytime independently of household members being at home or not. The mode value is 25°C (picked by 15.5% when any household member is at home, and by 13.9% when no one is at home) and the median value is 24°C. The temperature somewhat differentiates at night, the mode value is 20°C (17.4% of the respondents picked it) and the median value 22°C.

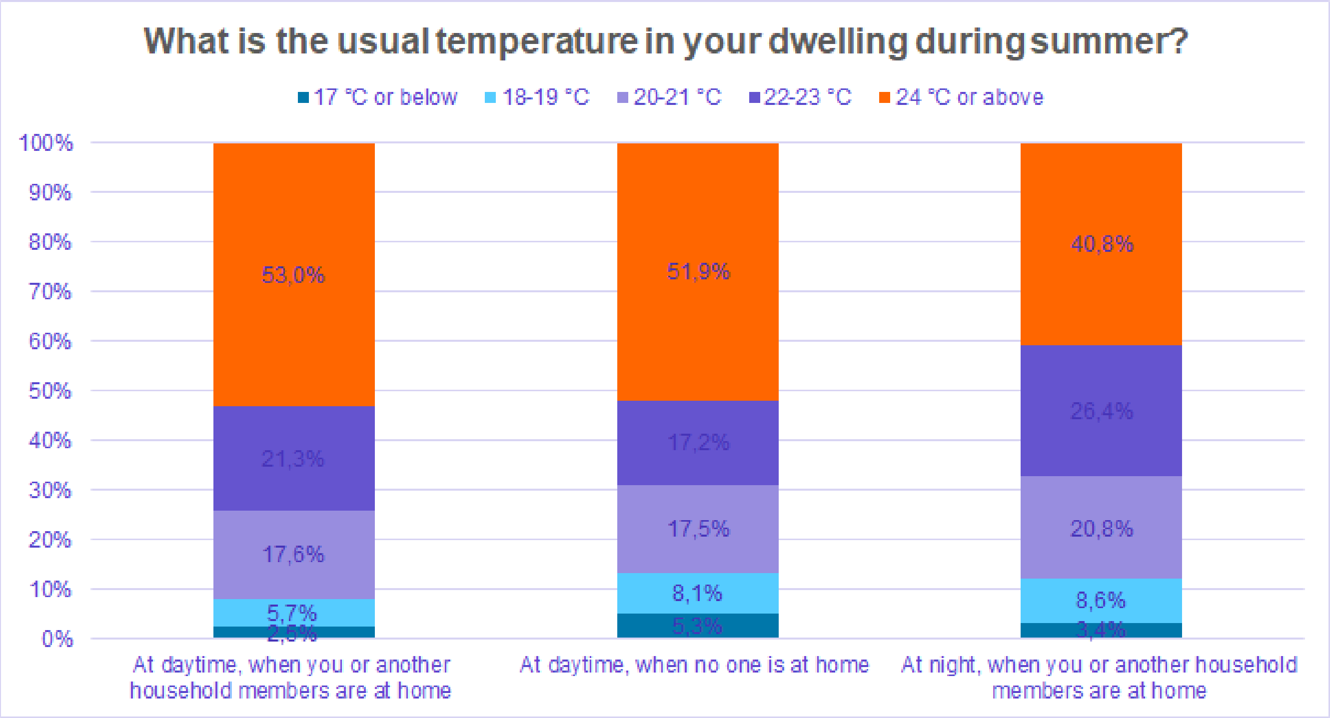


Figure 21. The usual temperature in the dwellings during summer on an average day of July, when no one at the household is on holiday and everyone carries out his/her everyday activities.

When analysing the usual temperature in the dwelling during summer on an average day of July at daytime by age groups we found that there seems to be a tendency of young adults (18-39 years old) to keep rather a moderate temperature (median value: 23°C, mode value 22°C) while among elder adults (40-59 years old) and the elderly (60-x years old) a slightly higher temperature (median value: 24°C, mode value: 25°C) is more common. The same tendency applies for the daytime when no one is at home, but at night also a moderate temperature reveals for the elderly (median value: 23°C, mode value 22°C).

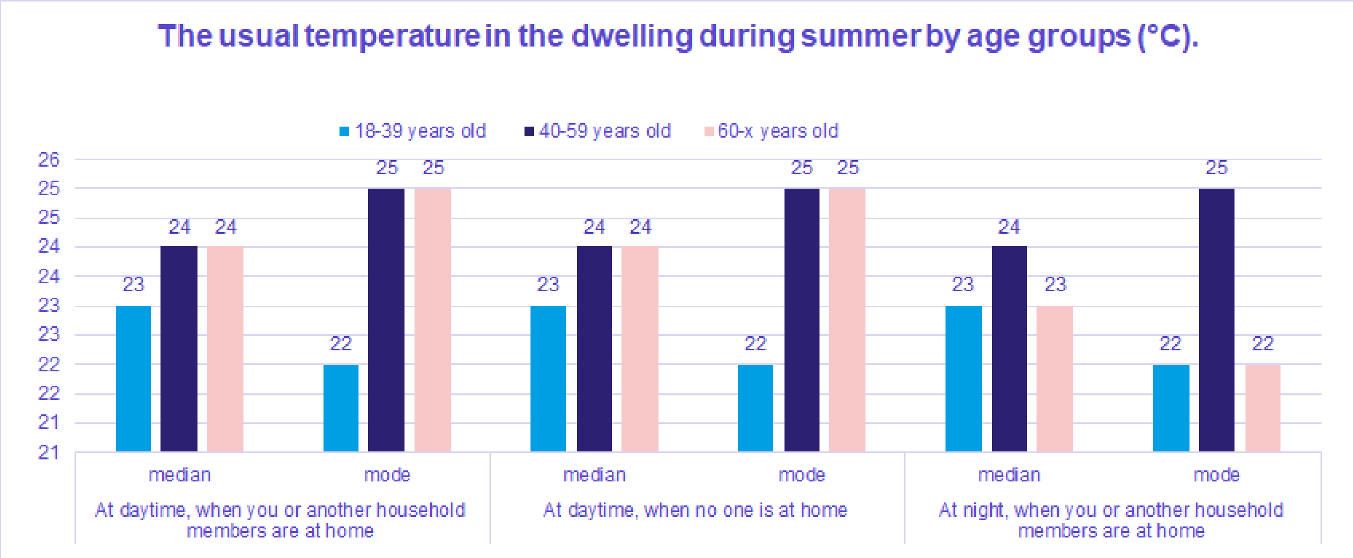


Figure 22. The usual temperature in the dwelling during summer on an average day of July by age groups.

Respondents were also asked about their preference regarding the temperature in their dwelling during summer on an average day of July in the abovementioned three cases. The mode values and the median values reflect preferences for a lower temperature. The median value for all three cases is 22°C. The mode value for daytime when any household member is at home is 22°C (picked by 17.4% of the respondents). The most frequent value chosen for daytime when no one is at home is 20°C, and for night also 20°C.

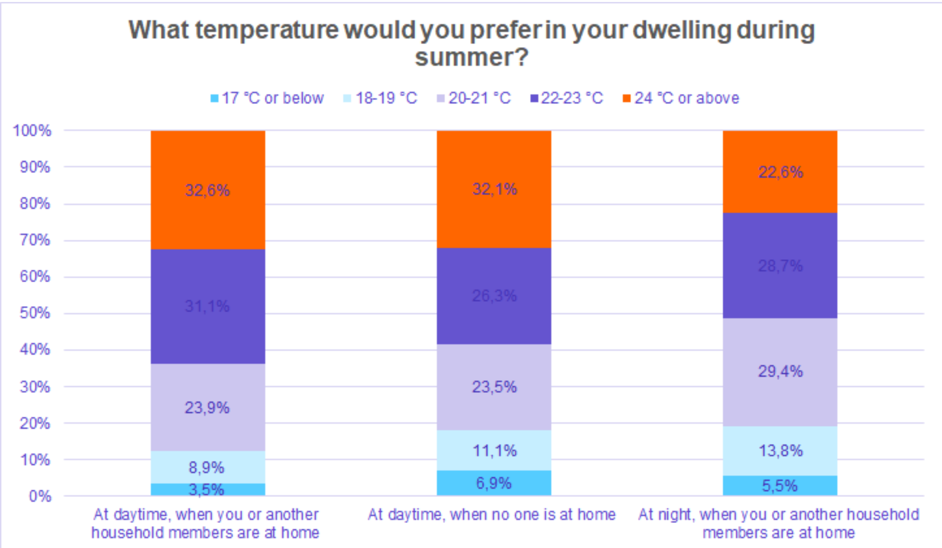


Figure 23. The preferred temperature in the dwellings during summer on an average day of July, when no one at the household is on holiday and everyone carries out his/her everyday activities.

The preferred temperature also shows some differences by age groups. Among young adults (18-39 years old) the most frequent preferred temperature at daytime (irrespectively of someone being at home or not) is 22 °C and for the night 23°C. The mode value is the same (22°C) for people aged 40-59 years at the daytime when household members are at home, however most of them opted for a preferred temperature of 20°C at daytime when no one is at home and also for the night. The most frequent value for the elderly is slightly higher for the daytime (24°C), but lower for the night (20°C).

There is a correlation between the actual temperature in the dwelling and the preferred temperature in summer at daytime when household members are at home. Those who have a relatively low temperature in their dwelling (18°C-17°C or less) mostly desire the same temperature (68.2%; 60.7%). A smaller proportion of them would feel more comfortable with a higher temperature. The ratio of those preferring a warmer temperature in their dwelling is shrinking as the temperature measured in the dwelling rises. In contrast the proportion of those wishing for a colder temperature increases as the actual temperature in the dwelling rises. The turning point can be detected at a temperature of 25 °C in the dwelling as the greater part of the respondents who have 25°C or more in their dwellings (65.0%-88.7%) wish for a colder temperature. As for people who measure 19°C or 21-24 °C in their homes, they almost equally prefer the same temperature or a colder temperature. Among respondents who have 20°C in their dwelling in summer a significant part desires the same temperature (64.4%), the distribution of those longing for a warmer or colder temperature is almost equal (18.4% and 17.2%).

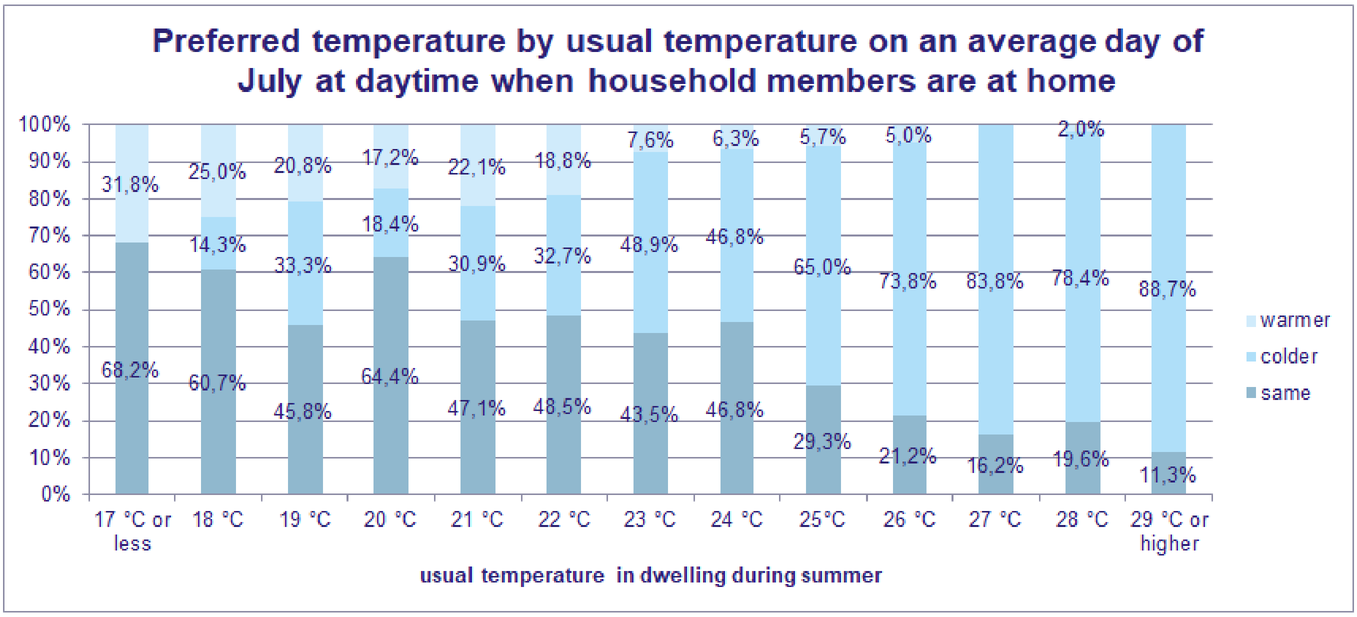


Figure 24. Preferred temperature by usual temperature in the dwelling in summer at daytime when household members are at home.

As for the difference between the actual and preferred temperature, the tendency shows that the higher the actual temperature in the dwelling the bigger is the difference for a colder temperature.

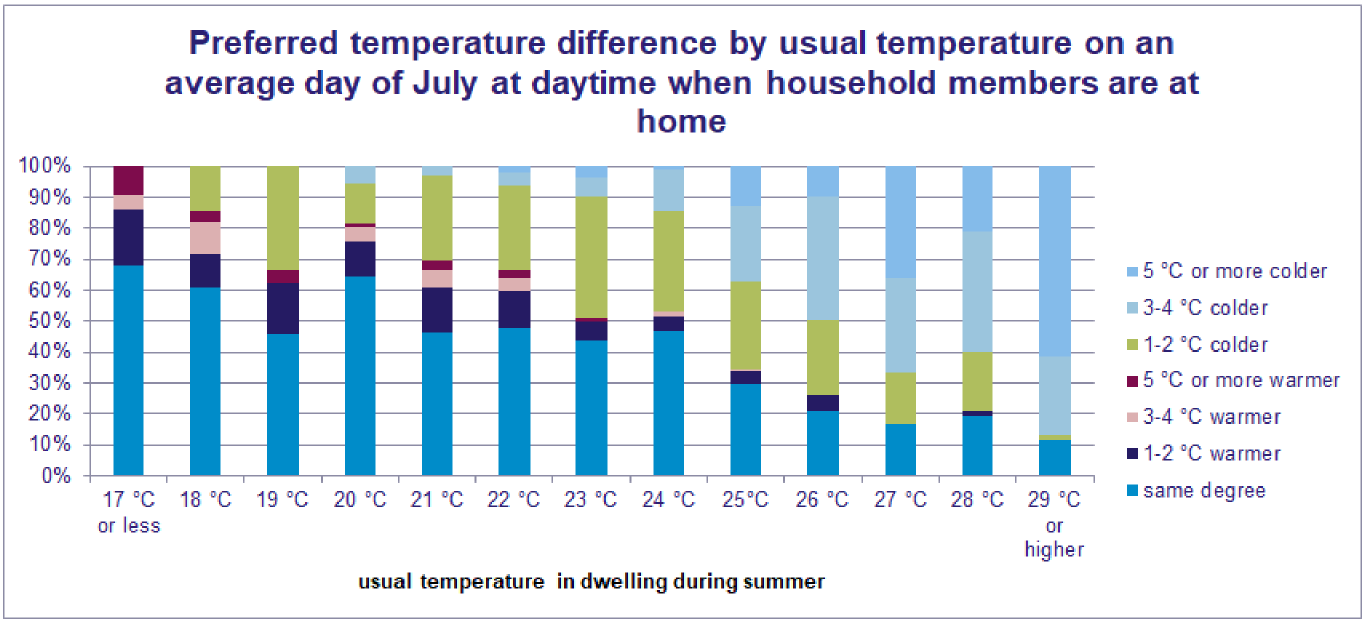


Figure 25. Preferred temperature difference by usual temperature in the dwelling in summer at daytime when household members are at home.

As an overall tendency it has been revealed that the desired temperature difference at daytime when no one is at home is smaller compared to when someone is at home. For instance, the ratio of those wishing for a colder temperature of at least 5°C is smaller in the categories with a relatively higher temperature in the dwelling (25°C or more) when no one is at home compared to when someone is at home.

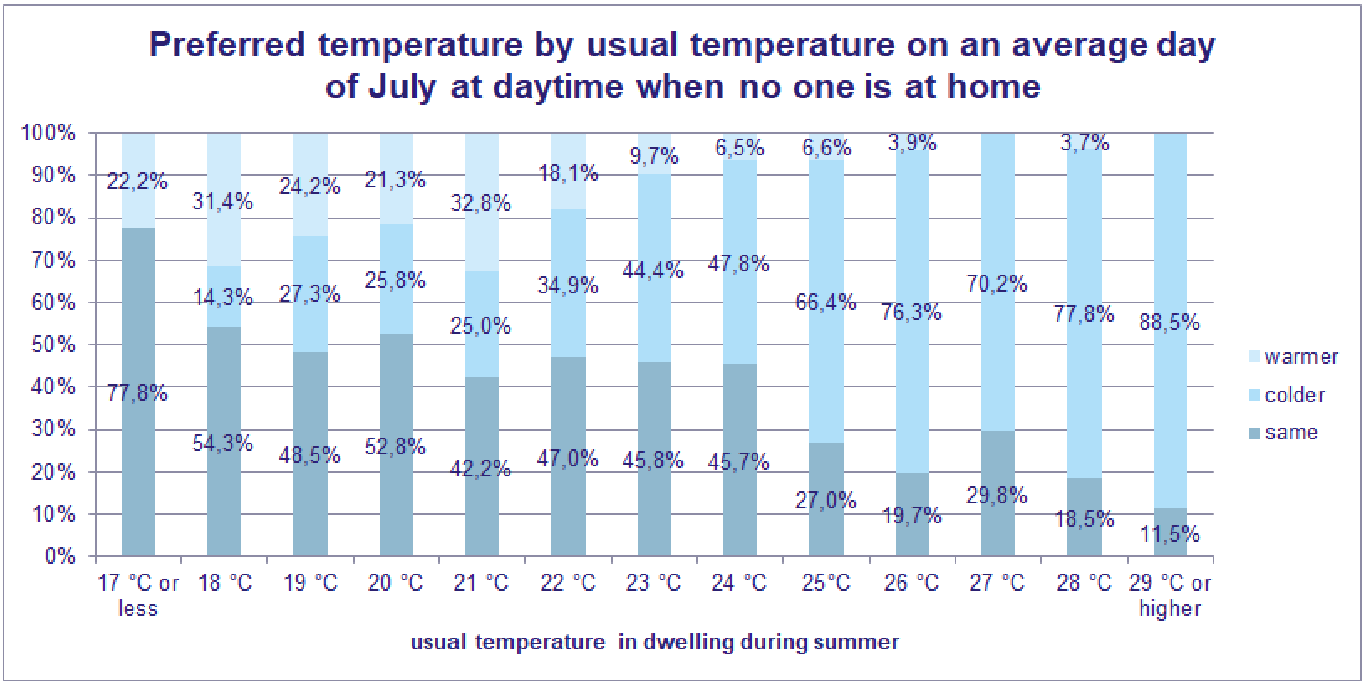


Figure 26. Preferred temperature by usual temperature in the dwelling in summer at daytime when no one is at home.

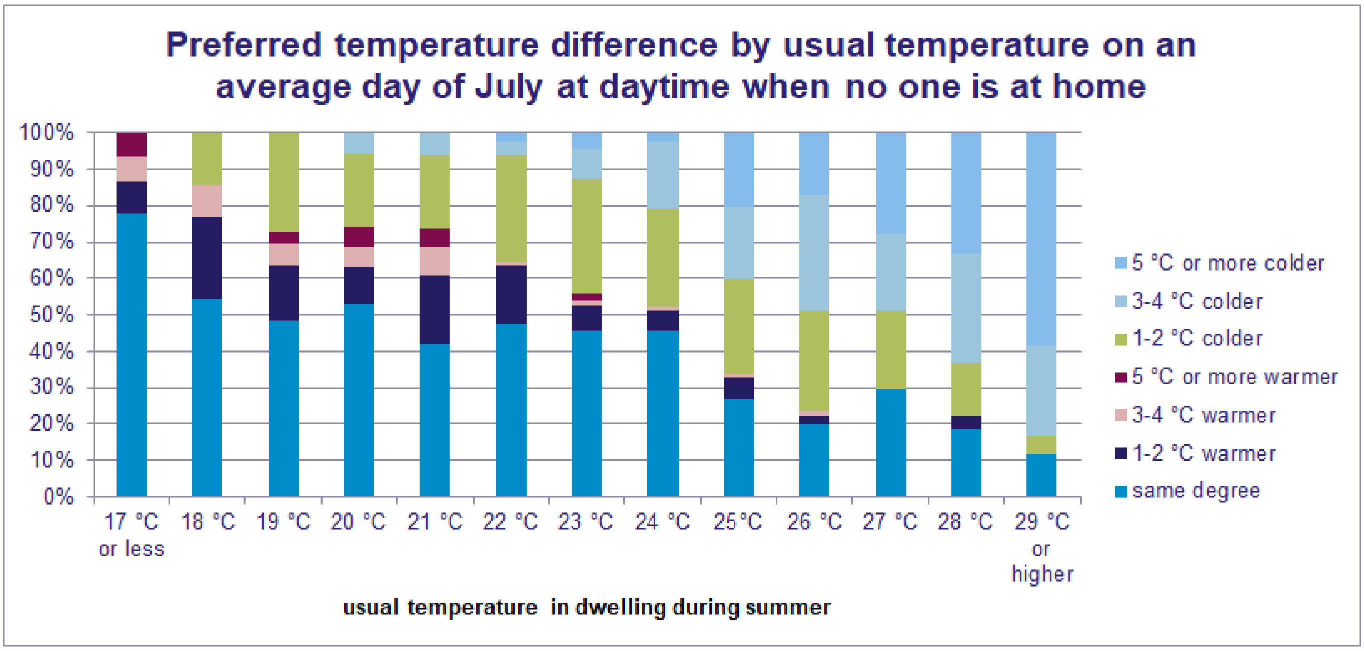


Figure 27. Preferred temperature differences by usual temperature in the dwelling in summer at daytime when no one is at home.

At night the preferred temperature is rather a low temperature compared to the daytime as the proportion of respondents preferring the same temperature as actually measured is the highest among those who have 18 °C or less (77.1%;70.0%) in their homes. The ratio of those wishing for a colder temperature is between 24.4% and 34.1% for those who have 19°C-22°C in their dwellings. A significant change in the tendency of preferred temperature outlines at 23°C in the dwelling at night. The proportion of those who prefer a colder temperature rises notably in this category (54.9%) compared to the previous one. The tendency of a growing proportion of respondents preferring a colder temperature continues further on. They represent almost 90.0% in the category of people who measure 29°C or more in their dwelling at night in summer.

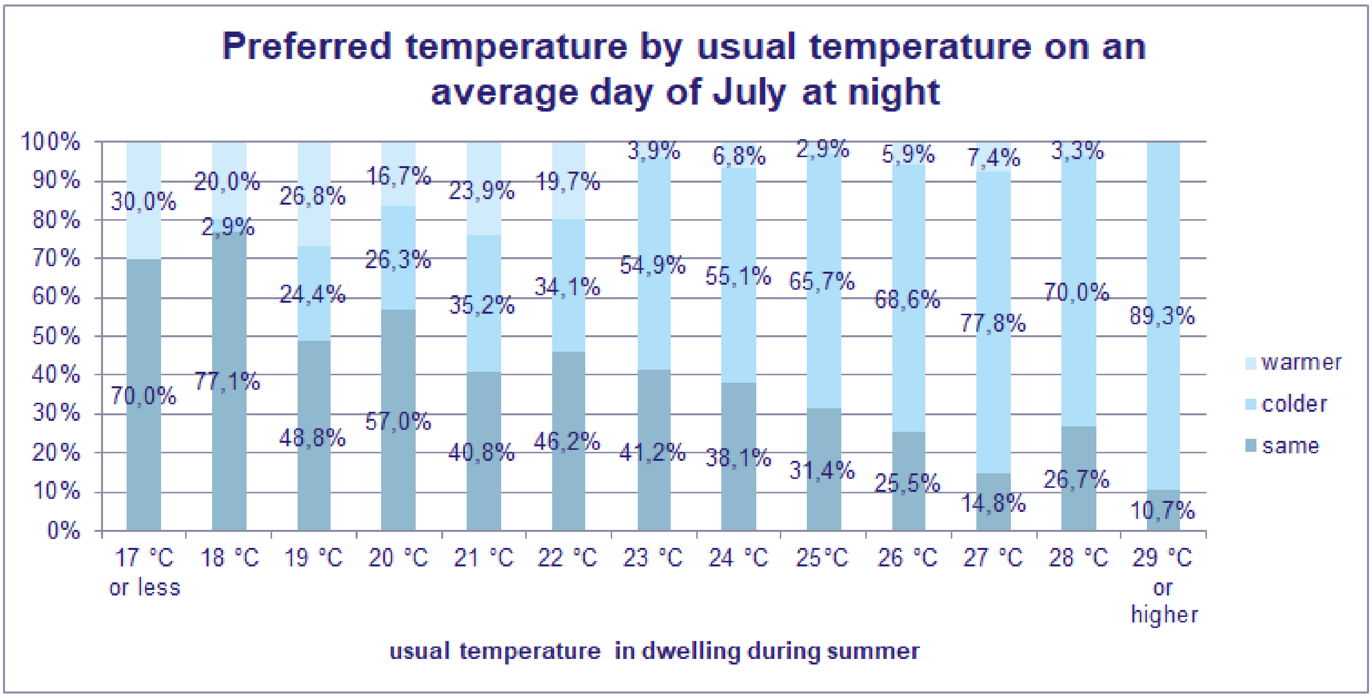


Figure 28. Preferred temperature by usual temperature in the dwelling in summer at night.

As for the distribution of preferred temperature difference at night we found that among those who have a rather high temperature in their dwelling – 25 °C or more – the proportion of respondents preferring a lower temperature by at least 5°C is higher.

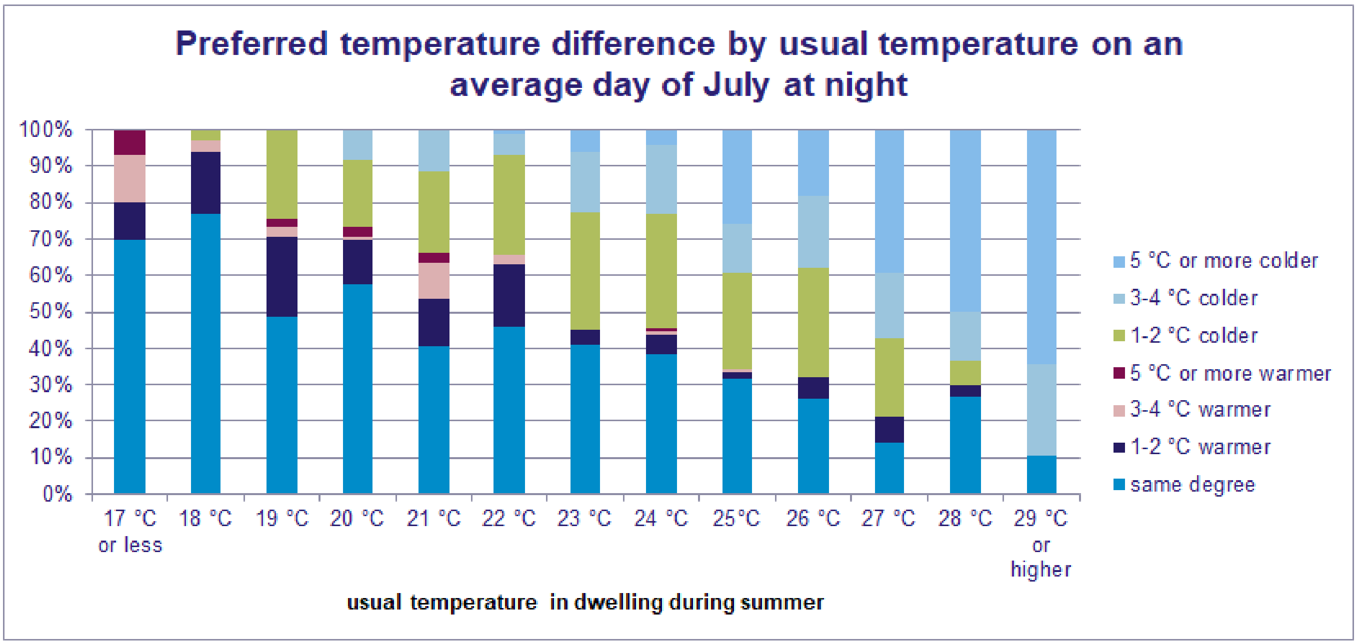


Figure 29. Preferred temperature differences by usual temperature in the dwelling in summer at night.

The tendency regarding the correlation between the actual and preferred temperature in the dwelling remains mostly the same at daytime when no one is at home: the higher the temperature in the dwelling, the bigger the proportion of those wishing for colder temperature. The turning point again is detectable at 25°C when the proportion of those desiring a colder temperature rises significantly. However, compared to the tendency at daytime when someone is at home a difference has been revealed at daytime when no one is at home. Namely among respondents who have a relatively low temperature in their homes (18-21°C) the proportion of those who prefer a warmer temperature is higher when no one is at home. As for the 'coldest' dwellings where the actual temperature is 17°C or less, the ratio of those who desire the same temperature is about 10% higher when no one is at home (77.8%) compared to when someone is at home (68.2%). Another remarkable difference has been found for those who have 27°C in their homes when no one is at home. A higher proportion of them (29.8%) wishes for the same temperature when no one is at home compared to the case when someone is at home (16.2%).

Respondents were asked how they felt about the average temperature in their dwelling during summer in July. The answers ranged from 1=very warm to 7= very cold. The temperature has been considered very warm by 21.8% of the sample. Altogether 41.2% told that they felt rather warm (frequency of value 2 and 3) about the temperature in their dwelling in July. Neither warm nor cold (value 4) has been chosen by 27.5% of the respondents. Less than 10.0% considered the temperature in their dwelling in July rather cold or very cold (values 5-7).

The next question investigated how comfortable people found the average temperature in their dwelling in July. Answers were given on a five-point scale (1=very uncomfortable, 5= very comfortable). The biggest part of the sample found the temperature neither comfortable nor uncomfortable (45.5%). Altogether one third of the respondents (33.8%) found the temperature rather uncomfortable or very uncomfortable. 14.0% considered the temperature rather comfortable and only 6.7% answered that they found the temperature in their dwelling during summer very comfortable.

When comparing the feelings about the average temperature in the dwelling in July with the feelings of comfortability about it a positive correlation outlines. Those who feel that the average temperature in their dwelling is rather warm or very warm tend to feel mostly uncomfortable about this temperature at the same time. And those who feel that the average temperature is rather cold or very cold mostly feel comfortable about it.

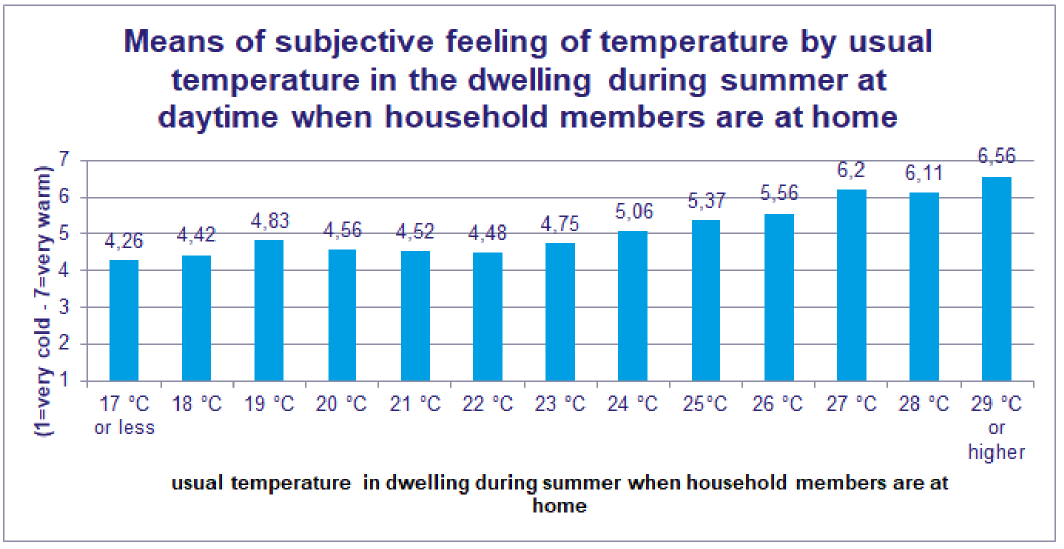


Figure 30. Subjective feeling of temperature in the dwellings at daytime when household members are at home.

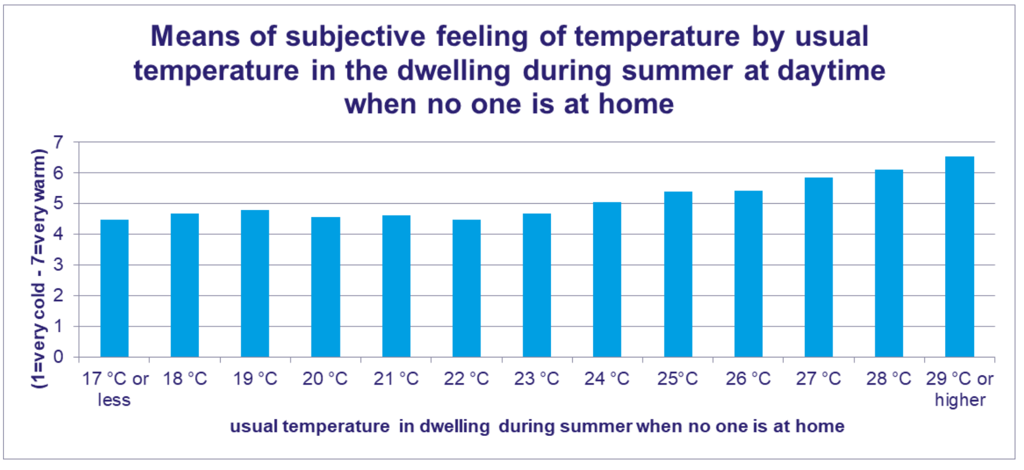


Figure 31. Subjective feeling of temperature in the dwellings at daytime when household members are not at home.

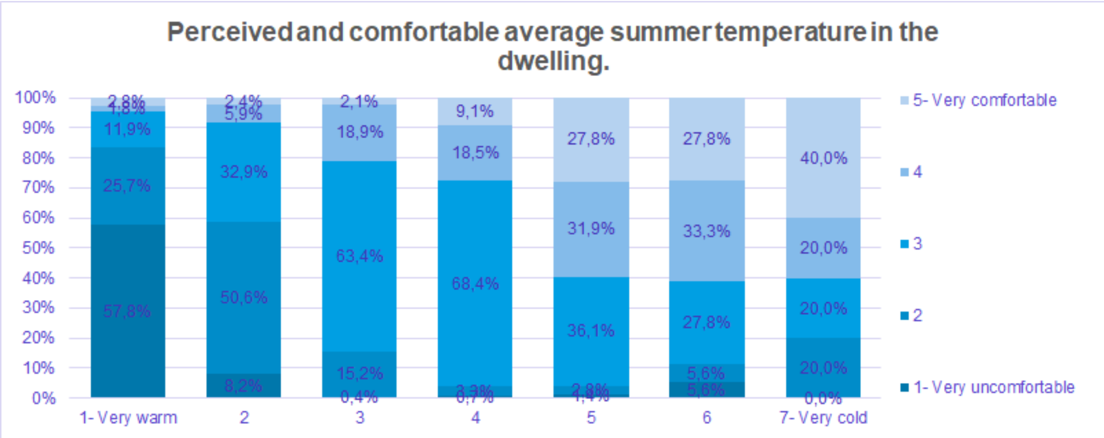


Figure 32. Perceived and comfortable average summer temperature in the dwellings.

The relationship between the subjective feeling of the temperature of the dwelling and the actual temperature in the dwelling shows that lower and moderate temperatures (17°C to 22°C) are considered neither cold neither warm, as the mean values are close to value 4 which was the middle of the scale. Little differences can be detected in some cases for the different parts of the day. For example, 18°C and 19°C in the dwelling are considered rather somewhat warmer at daytime than at night. The opposite is true for a degree of 20°C and 22°C which temperatures are considered on average somewhat warmer at night than at daytime. This pattern also applies for 23°C in the dwelling; the mean of subjective feeling of this temperature reaches value 5 in case of the night. At a degree of 24-26°C the means of subjective feeling increase slightly, and at 27°C there is a noteworthy rise in the means, they pass value 6 implicating that a temperature above 27°C in the dwelling is mostly considered warm or even very warm in all parts of the day.

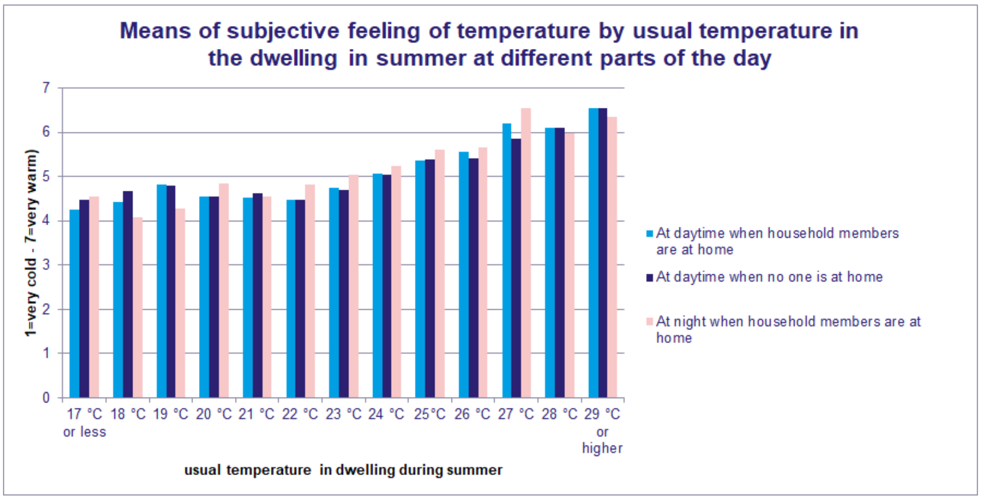


Figure 33. The relationship between the subjective feeling of the temperature of the dwelling and the actual temperature in the dwelling (means).

Respondents were also asked how comfortable they felt with the temperature in their dwelling. Means of these scores by the actual temperature show that all in all up to 24°C the temperature is considered neither comfortable nor uncomfortable, means are close to value 3, the middle of the scale. Some differences however reveal. A temperature of 18°C is considered rather comfortable when household members are at home – both at daytime and at night – as the average is above value 3 in these cases. A turning point can be detected at a temperature of 25°C since the average scores of feelings of comfort decline sharply from this point on as the temperature rises.

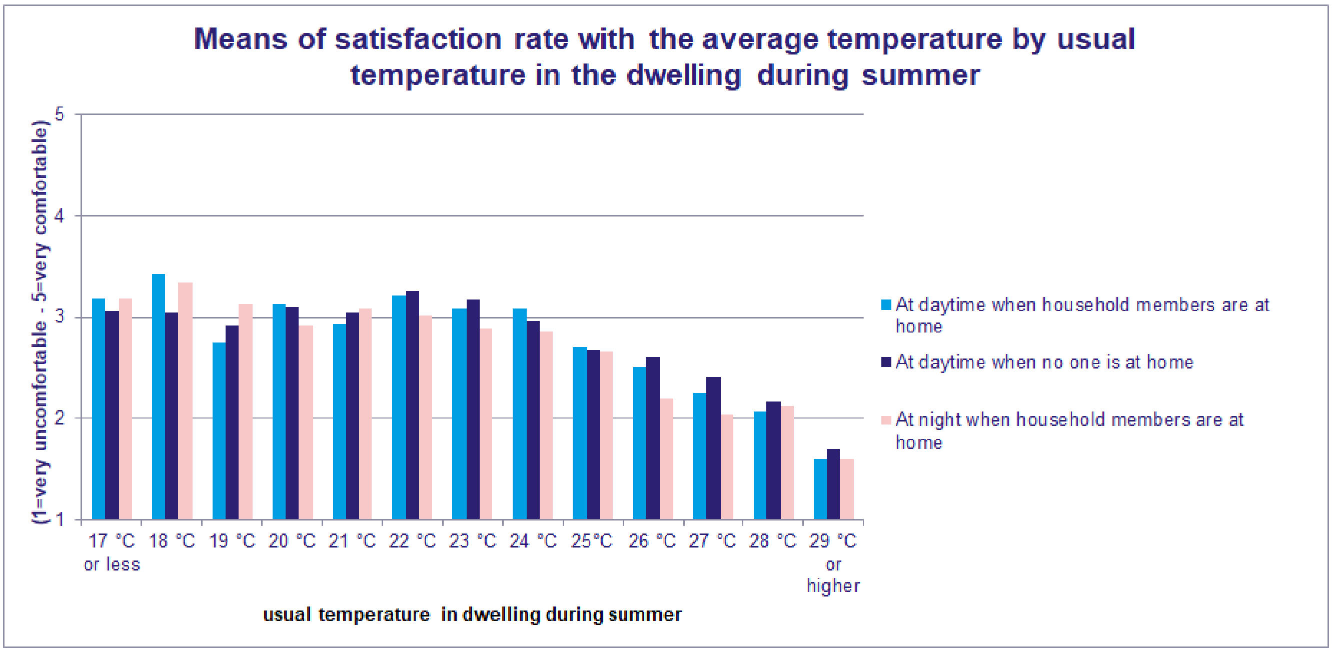


Figure 34. The relationship between the subjective feelings of comfort with the average temperature by usual temperature in the dwelling during summer (means).

5.2.2. Schedules of occupancy

In order to more accurately quantify how many people there are at home in the households during the different periods on an average weekday in summer in July (when no one at the household is on holiday and everyone carries out his/her everyday activities) the mean values have been analysed but measured as percentage values of the overall size of the households (mean = 2.62)[1]. For the different periods a slightly U-shaped pattern has been revealed: weekday early morning (6:00-8:00) 78.2% (2.0 persons on average) of the household members can be found at home, then weekday morning (8:00-12:00) and lunchtime (12:00-14:00) the values decrease to 57.3% (1.5 persons on average). Weekday early afternoon (14:00-17:00) already 70.2% (1.8 persons on average) of the household members can be found at home, and the percentage values increase in the rest of the time periods as weekday afternoon (17:00-19:00) 84.0% (2.2 persons on average), in the evenings (19:00-22:00) 89.7% (2.4 persons on average) and at night 93.0% (2.4 persons on average) of the household members are at home.

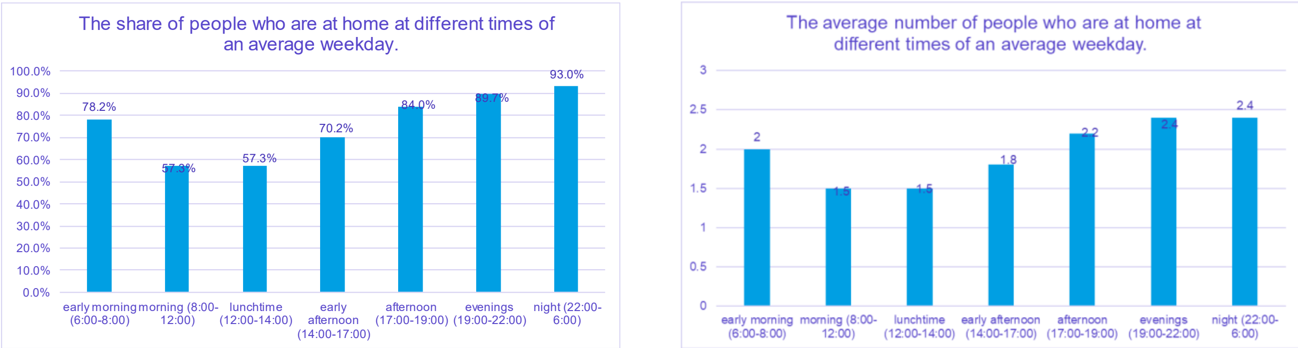


Figure 35. The share of people who are at home at different times of an average weekday.

Regarding weekends a similar pattern has been explored as the share of the members at home is higher in the early and later periods, and lower in the active periods of the day, however an overall difference is that at weekends more members of the households can be found at home. Regarding the first item of the question in this case again the data is missing, but weekend early morning (6:00-8:00) 90.5% (2.3 persons on average) of the household members are at home, while in this case morning (8:00-12:00) the value is lower; 83.2% (2.2 persons on average). In the long time period of weekend afternoon (12:00-19:00), 81.0% (2.1 persons on average) of the household members can be found at home, which increases to 88.2% (2.3 persons on average) in the evenings (19:00-22:00) and to 92.8% (2.4 persons on average) at weekend night (22:00-6:00).

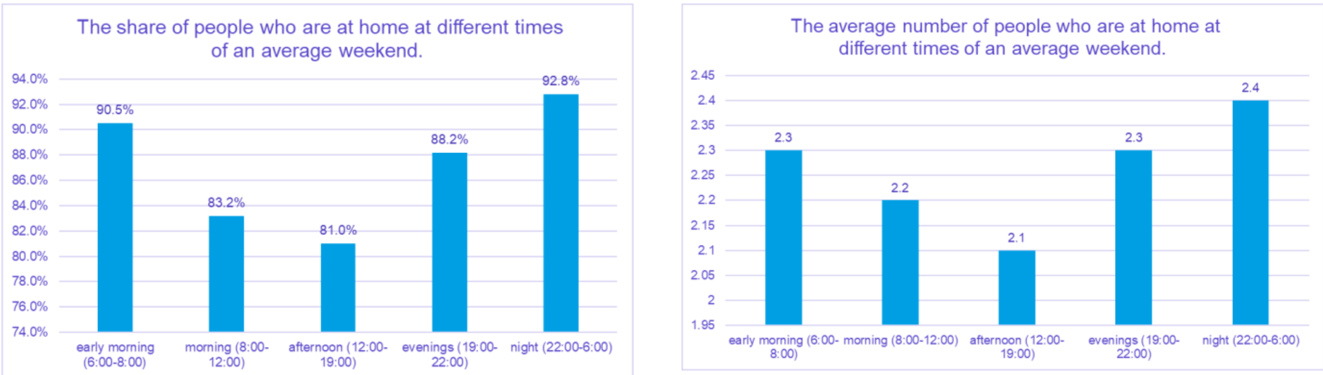


Figure 36. The share of people who are at home at different times of an average weekend.

To explore the temporal resolution of occupation and practices regarding space cooling, the respondents were asked to think of a hot summer day in July, Wednesday afternoon, when household members are not on holiday and carry out their daily activities.

On average 2.2 household members – 84.0% of the overall average household members size – are at home on such a summer day. According to the data (std. dev. = 1.287), both the median and mode are 2 persons. In case of 4.8% cannot be found no one can be found at home in this part of the summer period, essentially one-fourth of the sample (24.7%) said that only one person is at home, and more than one-third of the respondents (37.9%) answered that two people are at home. In the case of a further 18.8% three members can be found at home, that is, for more than eighty percentage (81.4%) of the sample the members of the households being at home is between one and three persons. 9.4%, 2.5% and 1.2% replied that three, four or five members of the household are at home. The share of higher values (7, 9, 10 people being at home) is below one percentage.

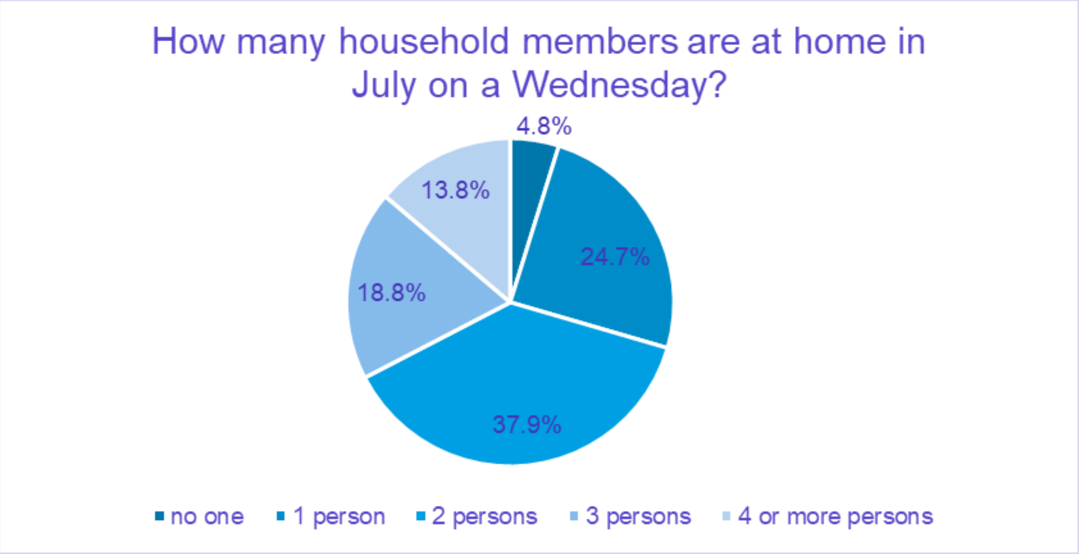


Figure 37. Occupancy of the dwellings on an average weekday.

The next question focused on the possible activities the household members do at home in July on a Wednesday afternoon. They mostly do household chores (73.7%), study (61.4%) and take a sleep/rest (48.7%) based on the multiple activity options included in the survey. More than one-third (39.4%) of them do non-physical leisure activity (e.g. watching TV, browsing the Internet), approximately one-fourth (26.7%) do non-physical, and almost one-fifth of the household members at home even do physical work (19.5%) and 13.2% do the gardening in this presumably hot period. The 'other activity' option – in this case not needed to be described in detail in the questionnaire – has been chosen by 8.1%, and the least frequent activity type proves to be doing exercises (7.5%).

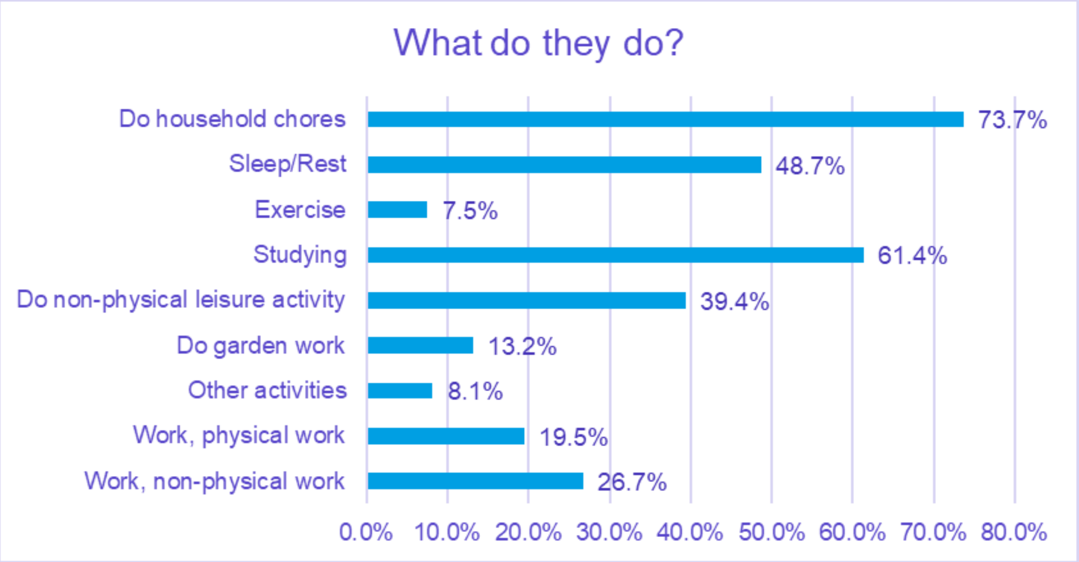


Figure 38. Possible activities the household members do at home in July.

As for the rooms occupied by the household members during the nominated period in July the bedroom (71.6%) and the kitchen (67.6%) have the highest shares according to the multiple answer data. In the case of more than half of the respondents the living room is occupied (55.2%), and a more than one-fourth rate (27.0%) use the dining room, and the open-kitchen is also mentioned with a similar, higher than one-fifth share (22.9%). The respondents prove to occupy the study room the least (13.8%) in this hot summer period.

Sunshine and shading

Before exploring the space cooling techniques of the rooms occupied, we revealed which rooms receive direct sunlight. Among the six rooms investigated the bedroom is mentioned dominantly (70.4%) to receive direct sunlight, followed by the living room and the kitchen as the second most frequent options with similar proportions (45.7% and 44.0% respectively). The rooms suitable for eating have also similar shares: dining room is mentioned by 23.2% and open-kitchen by one-fifth of the respondents (20.0%) to receive direct sunlight. Finally, the room to study is chosen with the lowest share (11.7%) again regarding this question.

In winter, the proportion of sunny rooms naturally decreased, but their order did not change. Even in winter, most sunlight reaches bedrooms (65.3%), living rooms (63.6%) and open-kitchens (63.4%). Study rooms (57.6%) and dining rooms (50.9%) have a slightly lower share of sunlight. Kitchens receive the least amount of sunlight (43.0%).

More than half of the houses (55.5%) have no foliage that would cast shade on any of the exterior walls or windows of the house. 26.0% of the houses have shade in summer, 18.5% also in winter. When looking at the natural shading of flats and houses, it was found that single-family houses (28.2%) and flats built before 1969 (32.1%) are generally only shaded in summer, while apartment buildings (61.6%) and flats built between 1970 and 1989 (60.1%) are not protected by natural shading.

Among the artificial forms of shading, manually controlled rolling shutters are used in the largest (68.3%). The proportion of electrically controlled rolling shutters in the smallest proportion (3.5%). A common shading method is the use of thick curtains, 38.0% of homes have them. Due to their construction 23.4% of the flats are shaded by their own balcony or overhang. 12.6% of the apartments have fixed external shading (i.e. sun sail), 7.2% have their movable version. 8.4% of the apartments have awning, and 4.5% have blinds.

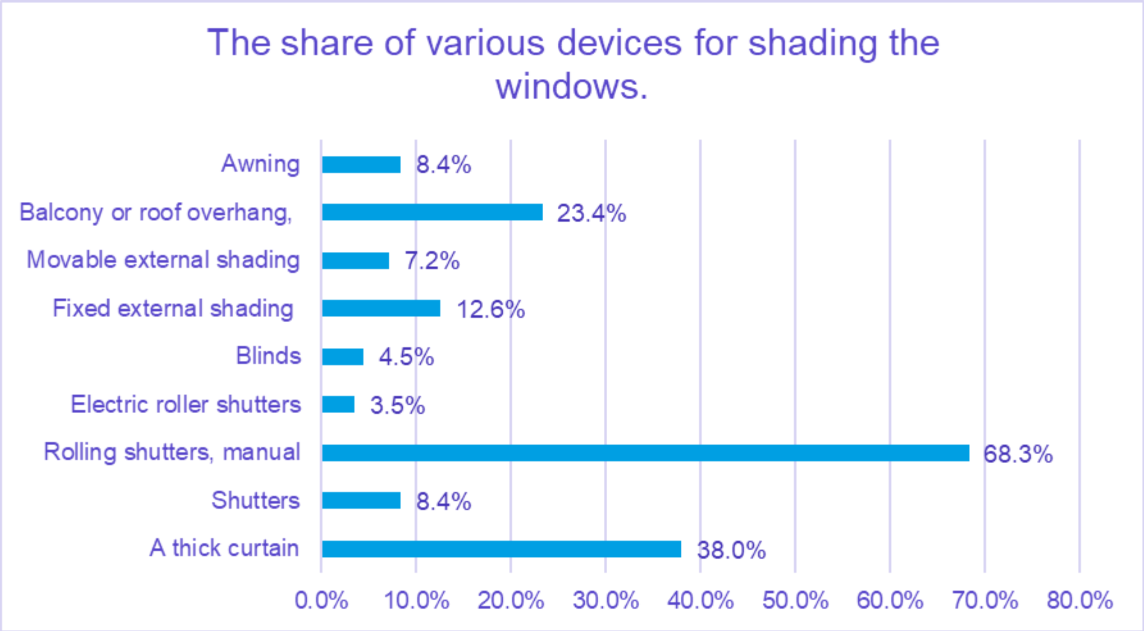


Figure 39. Distribution of possible shadings for windows.

Regarding the devices used for shading, we found that thick curtains are mainly used for shading in dwellings in inner areas of large cities (45.4%). Manual shutters are used mainly in rural towns (74.1%) and in houses built between 1970 and 1989 (75.4%). Electrically controlled shutters were found mainly in the inner areas of large cities (6.6%). Fixed outdoor shades (canopies, sun sails) are mostly used in single-family houses (16.5%). Blinds were mainly used in the outskirts of large cities (14.8%) and in dwellings built after 1990 (13.9%). Roller shutters are typical for single-family houses (5.6%).

Space cooling techniques

As for space cooling techniques in a hot summer day described in the investigation almost everyone (97.1%) applies wearing lighter clothing, but opening or closing of the windows (86.0%) and shading (82.7%) also prove to be wide-spread techniques, and also a relatively higher share of the respondents mentioned moving less, resting (76.1%) and taking a cold shower or bath (69.6%). 56.3% use fan as an option to cool down the temperature, more than one-third go into another room (38.5%), and 35.5% of the respondents mentioned the turning on of the air conditioning.

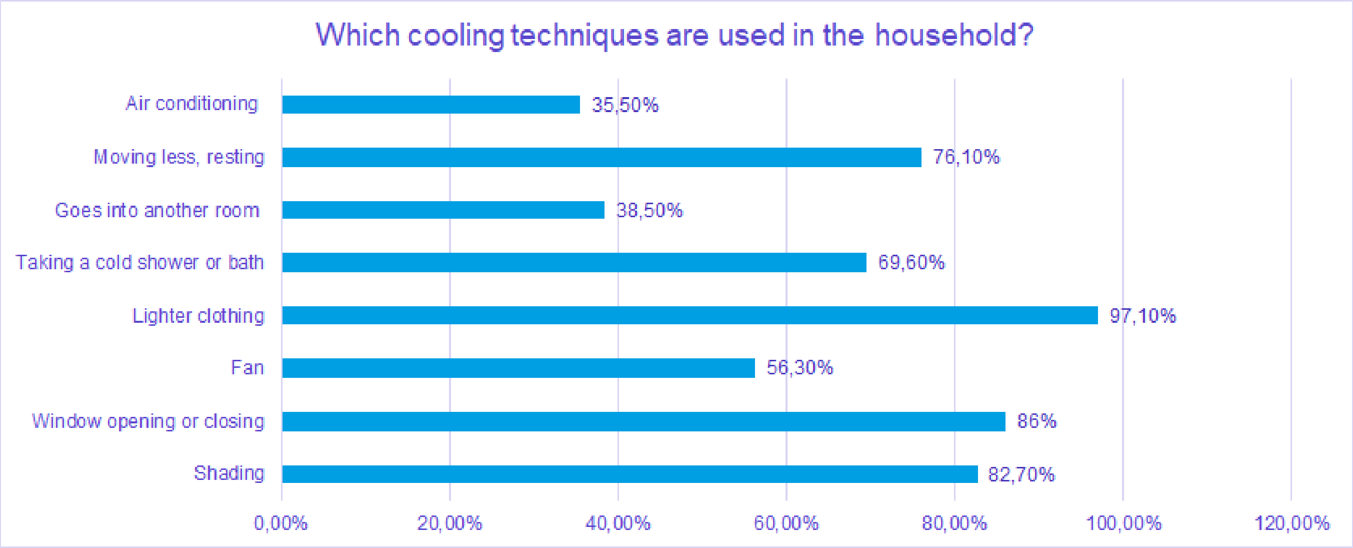


Figure 40. Applied space cooling techniques in the dwellings.

Those who choose to use the air conditioning dominantly (13.5%) set a temperature of 25 °C, and a similar 13,3% make the device on 24°C. A further 12.4% and 12.7% aims a temperature of 22°C and 23°C respectively, and still one-tenth of the respondents answered to set a temperature of 26 °C. Some mentioned rather low temperature values – 15°C, 16°C, 17°C (2.3%, 1.7%, 3.5% respectively) – but also relative higher values also appeared (28°C, 29°C and 30°C 2.5% and 1.7% respectively). As an overall pattern the air conditioning is used at an average temperature of 22.67°C (std. dev. = 3.268), the median is 23°C.

Before leaving the apartment and no one stays at home, on such a hot day, the 68.8% of the respondents shade the window(s), furthermore the window(s) are closed by 45.1%, and more than one-fourth of the respondents (26.9%) turn the fan off[2]. About one-tenth of them do not do anything before leaving the home empty (11.9%) or open the windows (9.4%). The air conditioning is turned off by 14.5% and only 2.4% adjusts the temperature of the air conditioner. These 8 respondents adjust the air conditioner to an average temperature of 22.85°C (std. dev. = 3.985), both the median and the mode is 25°C, only one person said 26°C, and similarly one respondent each adjusts the air conditioner to lower temperatures as 15°C, 18°C, 20°C, 21°C.

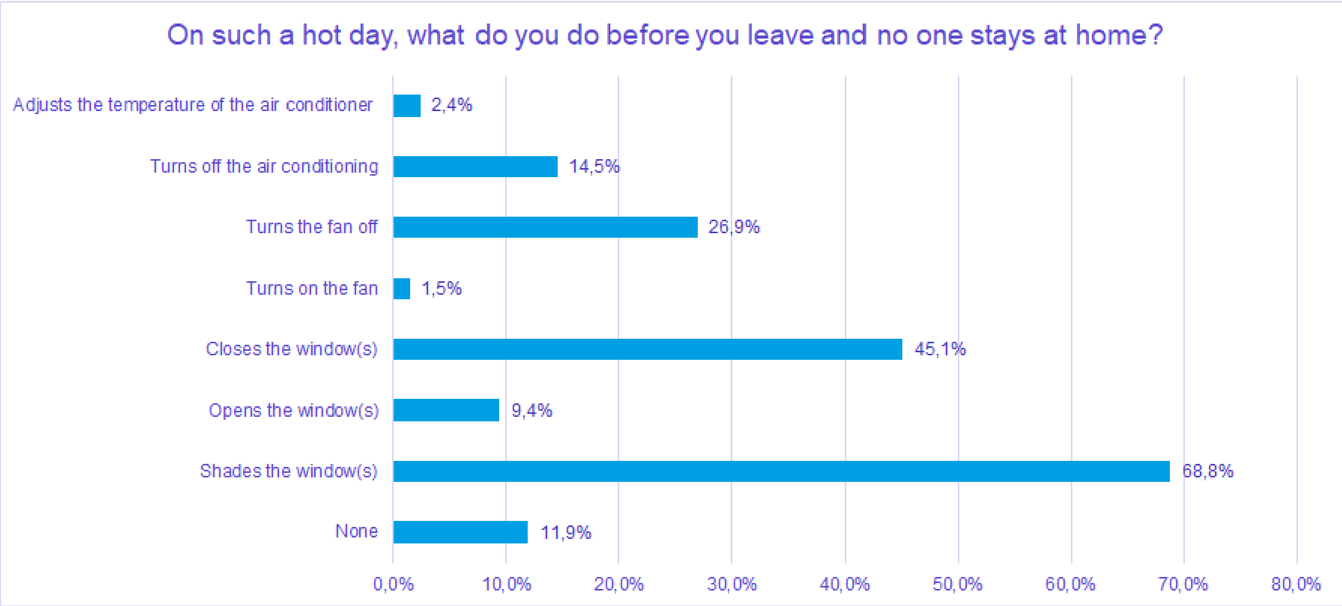


Figure 41. Measures before leaving the dwelling and no household member stays at home.

5.2.3. Air conditioning systems use

The proportion of dwellings equipped with air conditioning units is 39.5%. There may be more than one air conditioner in a household. The pattern is as follows: the share for combined space cooling and space heating devices is 27.3%. Another 11.3% mentioned air conditioners for space cooling, and 10.8% portable air conditioners. Air conditioners that can only be used for space cooling are more likely to be found in built-up areas (16.8%) and on the outskirts of large cities (17.4%), as well as in houses built after 1990 (18.9%).

Patterns of use of air conditioning systems

The use of the air conditioner has been explored more precisely in the following questions. First the motivations for turning on the air conditioning have been revealed. Based on the answers the highest share (52.9%) of the respondents tend to turn on air conditioning in every case, or most cases, when they feel the dwelling uncomfortably warm. However, more than two-fifth (42.2%) of the sample uses air conditioning only in case of extreme heat. Only 5 respondents (4.1%) said that they turn on the air conditioning system only when the outside temperature reaches a certain degree.

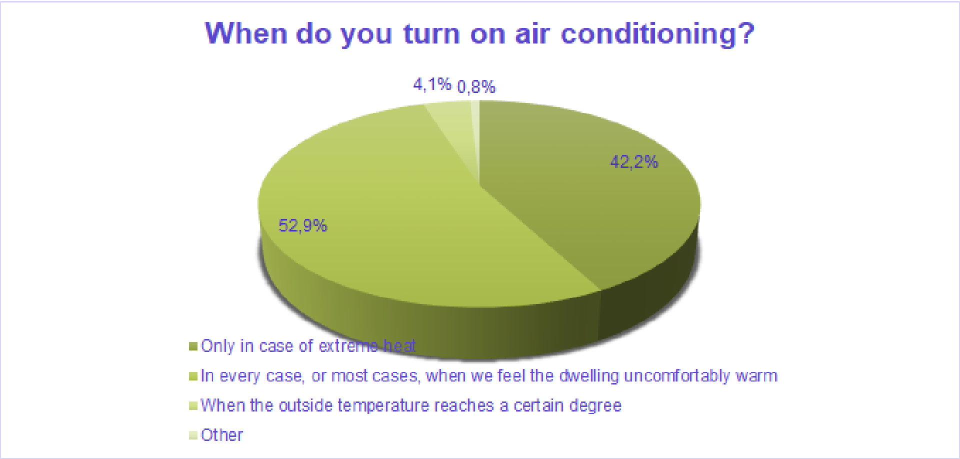


Figure 42. The reasons for turning on air conditioning.

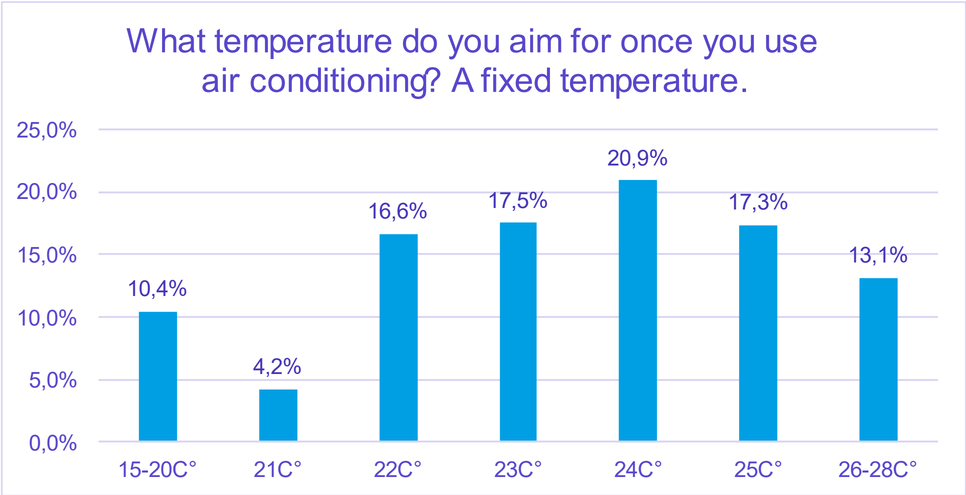


Figure 43. The preferred indoor temperature when setting the air conditioner on a fixed temperature.

The majority of the respondents adjusts the air conditioning to a fixed temperature (53.7%), and the rest of the sample (46.3%) choose to decide about it depending on the outside temperature. The mean value for adjusting the air conditioning (number of respondents is 61) is 22.4 °C (std. dev. = 2.99), the median is 23°C, and the most frequent value is also a similar temperature: 24°C (twelve respondents marked this value). Also twelve respondents (19.7%) set a temperature below 20°C (the lowest value being 15°C), and approximately one-fourth of the respondents (25.4%) use the air conditioning at a higher temperature compared to the mode value: most of them (8 respondents) apply 25°C , and the highest temperature set is 28°C. 52 respondents use air conditioning based on the difference between the inner and outside temperature. The mean value for this difference is 7.2°C (std. dev. = 4,221[!]), the median is 6°C and the mode is close to the former one; 5°C. Thus, most of the respondents (twelve persons) prefer a space cooling of the apartment by 5°C compared to the outside temperature, however some apply only a rather moderate difference (1-2 °C), and also just a few respondents apply a rather high difference of 15 °C, 18 °C and even 20 °C when setting the air conditioning.

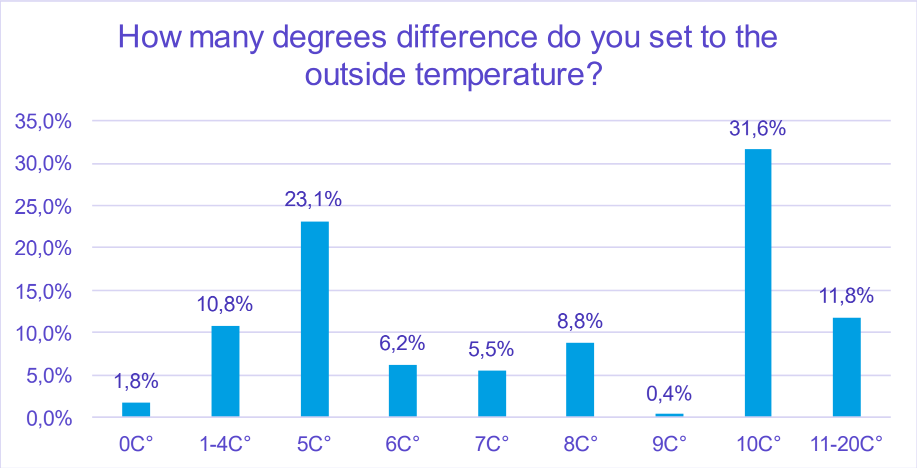


Figure 44. Adjusting the appliance to the outside temperature.

As for the habits of the air conditioning use, for the six possible answer options we analyse the multiple structure. Based on the cases of the survey the highest proportion of the respondents (33.8%) use air conditioning only during the warmest part of the day, but an essentially same rate (33.5%) tends to use air conditioning according to their comfort with an attitude to rather switch it from time to time on and off. The air conditioning is used only until the dwelling cools down to the set temperature in the case of 30.0% of the respondents, but a 13.5% make the air conditioning work all day, or most of the day. In contrast, 5.6% of the cases do not use the air conditioning during the day. One respondent has chosen the other answer option and said that the air conditioning is used before going to sleep.

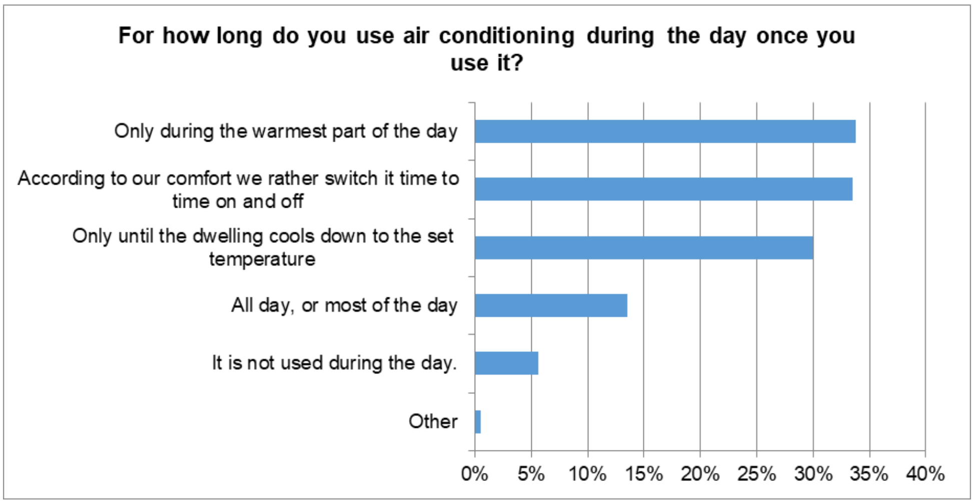
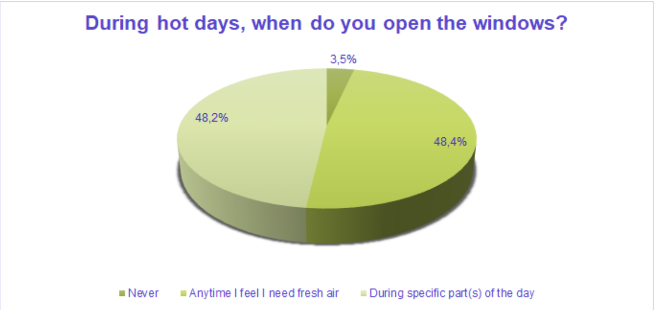


Figure 45. Length of time using air conditioning

Regarding the concerns about the environmental impact of air conditioning measured on a five-point scale, the responses are dominated by the middle of the scale: 39.4% are neither concerned nor unconcerned. Altogether 37.9% of the sample are rather not concerned or not concerned at all and only 22.8% prove to have higher concerns: 4 and 5 values have a share of 14.2% and 8.6% respectively.

The next question explored how comfortable the respondents and their household members are with using air conditioning. The majority of the respondents (113 valid answers have been counted in this case) seem to be rather comfortable with using air conditioning as 54.2% find it a perfectly good solution. A further 43.0% of the respondents feel not, or not completely comfortable with it, because of the environmental impact, they use it because they have no other effective means of space cooling their homes. Only 2.9% (3 respondents) find that air conditioning is not, or not entirely a good solution for other reasons. One of the reasons why they don't feel comfortable with it is the constant noise, or because it cannot be used to heat the flat, and one respondent complained about particulate matter.

Other space cooling techniques than air conditioning have been investigated in the next few questions. As for using the windows to cool the apartment during hot days only 3.5% of the sample said that they never use this way to moderate the temperature. The other two different options are followed by an identical rate: 48.4% of the sample said that anytime they feel they need fresh air the windows are opened, and 48.2% apply this method differently during specific part(s) of the day. These 482 respondents gave an overall number of 959 answers regarding the six possible options. Based on the responses the windows are being opened mostly at dawn (34.2%) and at night (31.,4%), and also almost a one-fifth share opted for the "after dusk" option (17.3%).



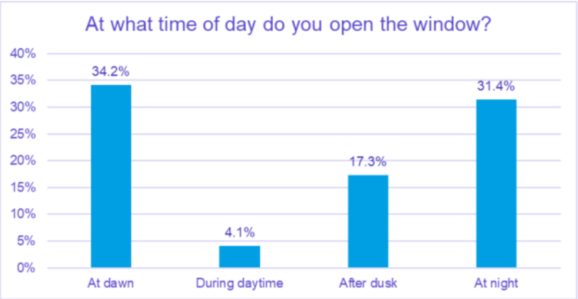
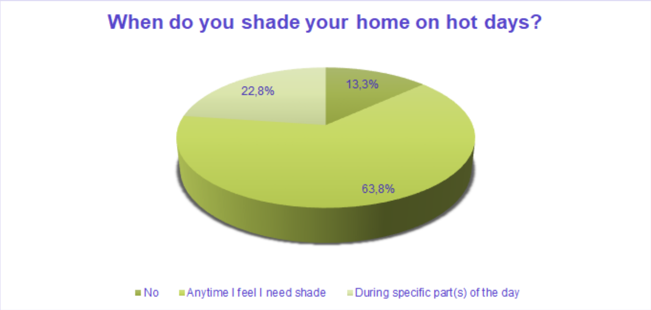


Figure 46. Window opening behaviour triggers, and periods of opening the windows during hot days (among who open it at a specific time of the day).



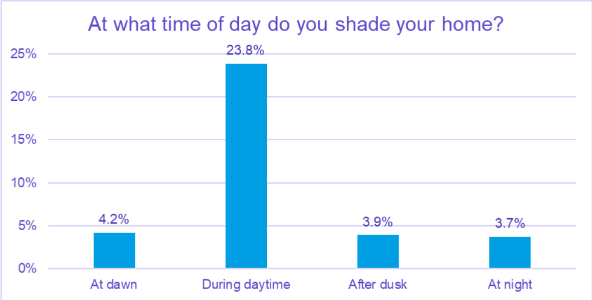


Figure 47. Shading operation behaviour triggers and periods of shading the windows during hot days (among who open it at a specific time of the day).

Shading the home is another space cooling technique on hot days, and most of the respondents (63.8%) do it anytime they feel they need it. Almost one-fourth of the sample (22.8%) answered that they apply shading during specific part(s) of the day, and only 13.3% does not shade the home. The 228 respondents gave a total number of 462 answers for the six options of applying shading during different parts of the day. In contrast to the former space cooling technique of opening the windows, the shading proves to be most frequent in the morning and during the day (32.9%) and also a further 31.6% of the responses were given for the afternoon. 23.8% of the respondents do shading during daytime, and in the mostly shady and inactive periods of the day this technique is not rather frequent: only 4.2% of the responses were given for dawn, and 3.9% and 3.7% for dusk and for the night respectively.

The application of several other different techniques has been investigated regarding space cooling on hot days. The respondents of the survey have chosen a total number of 6782 (combinations of) the options. Dominantly respondents wear lighter clothing (96.6%) and open the windows during the coldest part of the day (92.7%), in a similar proportion close window shutters during daytime (79.,8%), drink cold beverages (77.,6%) and do not open window during the hottest time of the day (76.2%). Also, relatively frequent options are to avoid using the oven (71.0%) and avoid activities which require physical activity (70.4%), or even have a siesta (66.7%). In 59.,9% fan use is mentioned as an option for space cooling on hot days.

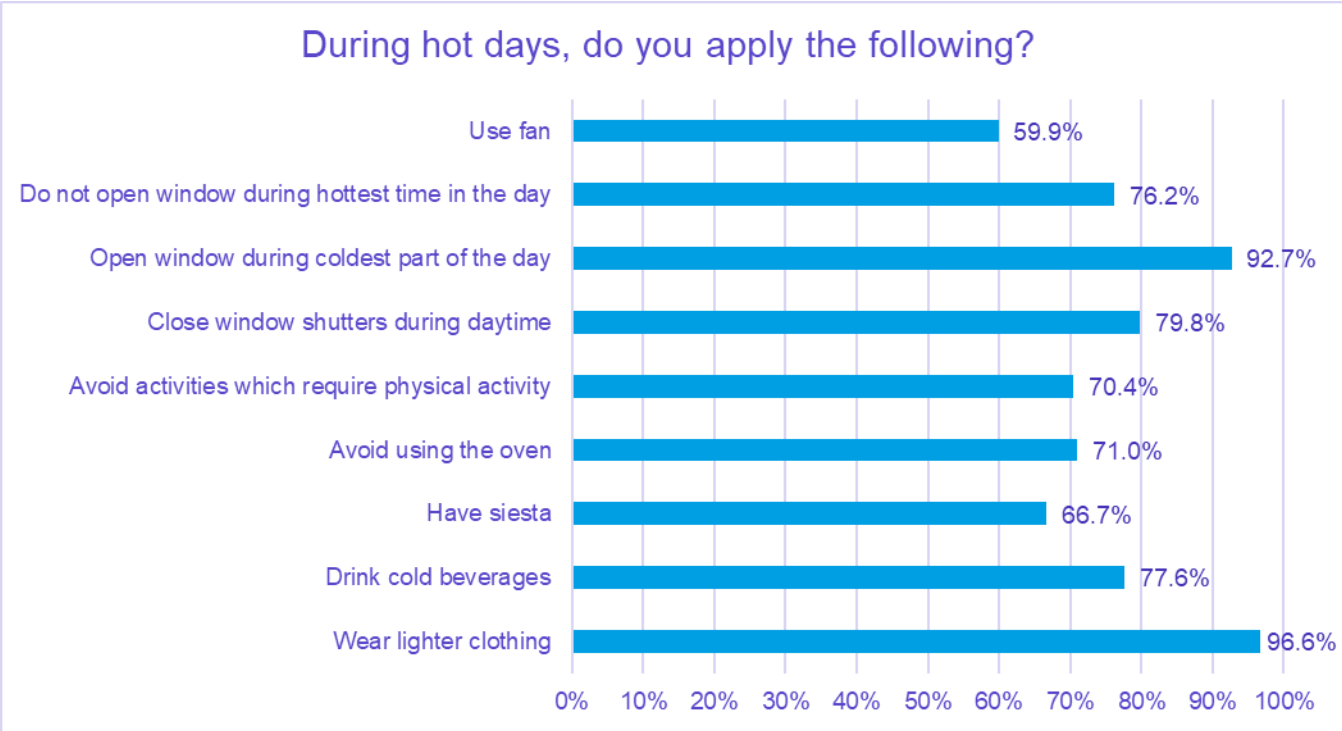


Figure 48. Different techniques the hot days.

Those who mentioned to use a fan on hot days mostly do so (53.7%) only when someone is using the room. Approximately one-third (31.6%) use the device when a household member is close to the fan, and only some (14.7%) chose to leave it on for longer periods either there is a household member close, or not.

6. Conclusions and remarks

This report has reviewed the different dimensions influencing thermal comfort of building occupants. Now more than ever, the need for occupant-centric building design becomes evident. Our literature review shows that people's perception of thermal comfort depends on both internal and external factors: from inherent physiological variables (such as gender, age, metabolism, among others), to psychological experiences (personal relations, perception of control), behavioral variables (level of activity, clothing), or simply personal preferences, this internal dimension only makes up half of the equation. External factors such as the surrounding physical environment (design, materials, colors, textures) and the heavy influence of society and culture in behaviors and choices need to be considered in building design and operation.

In this report, the main argument we have put forward is that thermal comfort first and foremost is a socially constructed phenomenon. While this insight is hardly novel to the field of comfort studies, we have aimed to provide a detailed illustration of this in the specific domain of space cooling. More concretely, we have highlighted the concept's dynamically evolving nature as a function of time, space, and context. The importance of time is exemplified by the dynamic feedback loop between space cooling expectations and space cooling infrastructure: the more societies become equipped with air conditioning infrastructure, the more expectation of lower optimal indoor temperature is experienced, which in turn feeds back into the deployment and availability of space cooling technologies. Some of the examples that we used to illustrate the importance of space in occupants' thermal comfort perceptions are comparatively straightforward: individuals who reside in warmer regions tend to feel comfortable in warmer indoor environments, including their households and offices. Finally, contextual determinants of thermal comfort include the financial incentives and the social environment in which occupants find themselves when deciding on their clothing choices, activity levels, and social behaviors.

Specifying the various dimensions of how thermal comfort is a socially constructed phenomenon is not merely an academic enterprise which is interesting in its own right but it also has fundamental ramifications for the practicalities of space cooling demand management and the design of solutions. For example, a perfectly calibrated building model designed for Scandinavian citizens might have limited applicability for a Mediterranean market and a failure to properly specify the parameters of the thermal comfort – air conditioning availability feedback loop might severely mislead our predictions for aggregate space cooling demand in the future. As a result, it would be desirable for international standards to reflect such variations in the model outcomes in order to provide more precise space cooling solutions for occupants in Europe and beyond.

More generally, we shall wrap up this report on an optimistic note. In the broader discourse on the energy transition and achieving carbon neutrality by 2040, much of the focus has been on innovation and the design of new technologies or the efficiency and performance of the existing ones. By contrast, there has been comparatively limited attention to the appropriate policy mix to nudge people toward reducing energy demand. Taking such a socially constructed view of human behaviour in the context of space cooling opens up a lot of possibilities for how energy demand can be reduced given the right changes in the social environment where individuals are embedded. Alternatively put, the "magic bullet" with the potential to help us cross the finish line before it is too late might not lie in the realm of technologies but rather in the hands of policy-makers with the power to shape the social environment and citizens' everyday behaviour, as a beneficial side effect.

7. References

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Annex I. - Questionnaire for surveys

1. Location and characteristics of dwelling

1. Which phrase describes best the area where you live?

- *Densely built area of a big city*
- *The suburbs or outskirts of a big city*
- *A town or a small city*
- *A country village*
- *A farm or home in the countryside*

2. Which best describes your home?

- *Single-family detached house*
- *Single-family house attached to one or more houses (e.g. duplex, rowhouse)*
- *Multi-apartment building, non-prefabricated*
- *Multi-apartment building, prefabricated*
- *Apartment at non-residential building, holiday house*

FOR ALL CATEGORIES OUTSIDE SINGLE-FAMILIY DETACHED HOUSES:

3. How many apartments does the building contain?

- *2-5*
- *6-9*
- *10+*

4. Please indicate the number of floors in the building

5. As far as you know, when was your home built?

- *Before 1950*
- *1950 to 1959*
- *1960 to 1969*
- *1970 to 1979*
- *1980 to 1989*
- *1990 to 1999*
- *2000 to 2009*
- *2010 to 2023*

6. What is the size of your apartment?

- *Up to 42 m^2*
- *43-65 m^2*
- *66- 90 m^2*
- *91- 120 m^2*
- *121-200 m2*
- *More than 200 m^2*

7. How many of the following rooms are there in the flat?

- *Living room with kitchen*
- *Kitchen*
- *Living room(s)*
- *Sleeping room(s)*
- *Study*
- *Bathroom*
- *Other*

8. What is the tenure of your apartment?

- *Owner occupied*
- *Tenant, public rental*
- *Tenant, private rental*
- *Other (housing co-operative, etc.)*

2. Household characteristics

9. How many people live in this household for at least 6 months of the year? (Including you)

_ _ person

10. How many household members are:

- *Between 0-3 years of age*
- *Between 4-17 years of age*
- *Between 18-64*
- *65 years of age and above?*
- *Living with a disability?*
- *Living with acute illness?*
- *Unemployed?*
- *At home taking care of children, or elderly relatives?*

11. Do you, or anyone in your household work from home on a regular basis?

- *Yes, four or more days a week*

- *Yes, two or three days a week*
- *Yes, once a week*
- *Yes, less than once a week*

3. Schedules of occupancy

12. On an average summer day of July or August – when no one at the household is on holiday and everyone carries out his/her everyday activities – at which of these times are you or someone else in your household regularly at home?

(Multiple answers possible)

- *All day/all the time*
- *Weekday Until 8am*
- *Weekday morning (9-12:00)*
- *Weekday lunchtime (12:00-14:00)*
- *Weekday afternoon (14:00-17:00)*
- *Weekday 5pm till 7pm*
- *Weekday evenings (7pm onwards)*
- *Weekend daytimes*
- *Weekend evenings*
- *Highly variable*
- *Weekday mixed between mornings and afternoons*

4. Energy use, energy efficiency-related questions

13. Does your home have any of the following?

(Multiple answers possible)

- *Attic insulation*
- *Roof insulation*
- *External wall insulation*
- *Internal wall insulation*
- *Cavity insulation*
- *Insulated basement*
- *Insulated windows*
- *Insulated door*
- *Room thermostat*
- *Appliance thermostat (portable)*
- *Radiator(s) with adjustable valve*
- *Air conditioner for cooling and heating*

- *Air conditioner for cooling*
- *Heat pump?*
- *Solar collector*
- *Solar panel*
- *Energy-saving light bulbs*
- *Smart device for the control of heating and cooling (apart from thermostat)*
- *Portable electric heater(s)*
- *Portable air conditioner*

14. Does your home have any of the following “smart meters”?

By smart meter we mean devices which record every consumption in real time and send this information to your utility company and in some cases include also a monitor to see (and control) your energy usage.

- *Electricity smart meter*
- *Gas smart meter*
- *Heating smart meter*

15. Please indicate how many rooms you have where the sun shines in during winter and summer at these times. (Only the premises entered in question 7 are displayed.)

When is the main exposure of the living room/kitchen area

		morning (until 12:00)	lunchtime (12:00-14:00)	afternoon (14:00-17:00)	evening (17:00-)
A.	Winter				
B.	Summer				

bedrooms

		morning (until 12:00)	lunchtime (12:00-14:00)	afternoon (14:00-17:00)	evening (17:00-)
A.	Winter				
B.	Summer				

16. Which room gets the most sun?

    - *Living room with kitchen*
    - *Kitchen*
    - *Living room(s)*
    - *Sleeping room(s)*
    - *Study*
    - *Bathroom*
    - *Other*

17. Is there any foliage casting shadow on any of your external wall(s) and/or window(s)? (E.g. Tree, creeper)

    - *Yes, all year round*
    - *Yes, during summer*
    - *No*

18. Are your windows or some of your windows equipped with:

    - *A thick curtain*
    - *Shutters*
    - *Rolling shutters, manual*
    - *Electric roller shutters*
    - *Venetian blinds*
    - *fixed external shading*
    - *movable external shading*
    - *balcony or roof overhang,*
    - *awning*

5. Space cooling related comfort requirements

19. Can you measure the temperature in your apartment?

    - *Yes, in every room*
    - *Yes, in specific rooms (please specify?)*
    - *No*

IF TEMPERATURE MEASUREMENT IS FEASIBLE:

20. What do you use to measure the temperature in your apartment?

(Multiple answers possible)

- *Room thermostat*
- *Appliance thermostat (portable)*
- *Thermometer (analogue/digital)*
- *Heating/cooling device (e.g. storage heater dial, air conditioner)*
- *Other, please specify: ....*

21. When changing the temperature (in any way), what type of information you consider?

(Multiple answers possible)

- *Temperature measured by device (thermostat, thermometer etc.)*
- *How hot/cold you feel*
- *How hot/cold your other household members feel*
- *To spend less on cooling/heating*
- *Other, please specify:...*

22. What is the usual temperature in your dwelling during summer on an average day of July or August? (When no one at the household is on holiday and everyone carries out his/her everyday activities. – If different in specific rooms, indicate the warmest.)

	24 °C or above	23 °C	22 °C	21 °C	20 °C	19 °C	18 °C	17 °C	other
	29							17	
At daytime, when you are at home									
At daytime, when you are not at home									
At night, when you are at home									

23. What temperature would you prefer in your dwelling during summer on an average day of July or August? (When no one at the household is on holiday and everyone carries out his/her everyday activities. - If different in specific rooms, indicate the warmest.)

	24 °C or above	23 °C	22 °C	21 °C	20 °C	19 °C	18 °C	17 °C	other
	29							17	
At daytime, when you are at home									
At daytime, when you are not at home									
At night, when you are at home									

6. Thermal comfort and practices, incl. coping strategies with hot weather

Now think about the average temperature in your dwelling during daytime, in summer in July, when you are at home.

24. How do you feel the average temperature in your dwelling during summer in July or August (If different in specific rooms, indicate the coldest):

1. Very warm 2 3 4 5 6 7. Very cold

25. How comfortable do you find the average temperature in your dwelling during summer in July or August: (If different in specific rooms, indicate the coldest):

1. Very uncomfortable 2 3 4 5. Very Comfortable

26. When do you turn on air conditioning?

(Only ask those who ticked air conditioning in question 14)

- *Only in case of extreme heat*
- *In every case, or most cases, when we feel the dwelling uncomfortably warm*
- *When the outside temperature reaches a certain degree —> **What degree?** .... °C*
- *Other, please specify:.........*

27. What temperature do you aim for once you use air conditioning?

- *A fixed temperature —> **What temperature?** ...... Celsius*
- *It depends on the outside temperature —> **How many degrees difference do you set?** ..... °C*

28. For how long do you use air conditioning during the day once you use it?

- *All day, or most of the day*
- *Only during the warmest part of the day*
- *Only until the dwelling cools down to the set temperature*
- *According to our comfort we rather switch it time to time on and off*
- *Other, please specify:.....................................*

29. How concerned you are about the environmental impact of air conditioning?

1 not at all   2   3   4   5 very concerned

30. How comfortable are you, and your household members with using air conditioning?

- *We are perfectly comfortable with using air conditioning.*
- *We are not, or not fully comfortable with air conditioning, but have no other effective means of cooling our dwelling.*

31. During hot days, when do you open the windows?

- *Never*
- *Anytime I feel I need fresh air*
- *During specific part(s) of the day —> IF YES: **When?** (Multiple answers possible)*
    - *At dawn*
    - *During daytime*
    - *After dusk*
    - *At night*

32. During hot days, do you use shading for your dwelling?

- *No*
- *Anytime I feel I need shade*
- *During specific part(s) of the day —> IF YES:* ***When?*** *(Multiple answers possible)*
    - *At dawn*
    - *During daytime*
    - *After dusk*
    - *At night*

IF THE DWELLING IS EQUIPPED WITH FAN :

33. When do you use fan on hot days?

- *Never*
- *Only when someone is using the room*
- *Only when a household member is close to the fan*
- *We leave it on for longer periods either there is a household member close, or not*

34. During hot days, do you apply the following?

(Multiple answers possible)

- *Wear lighter clothing*
- *Drink cold beverages*
- *Have siesta*
- *Avoid using the oven*
- *Avoid activities which require physical activity*
- *Close window shutters during daytime*
- *Open window during coldest part of the day*
- *Do not open window during hottest time in the day*

7. Temporal resolution of occupancy and practices

Now think about a hot summer day in July, Wednesday, at 11:00 am. Assume you are not on holiday, and household members carry out their everyday activities.

35. How many household members are at home?

- *.... person*

36. What do they do?

(Multiple answers possible)

- *Work, non-physical work*
- *Work, physical work*
- *Do household chores*
- *Do garden work*
- *Do non-physical leisure activity (e.g. watching TV, browsing the Internet)*
- *Exercise*
- *Sleep/Rest*
- *Other*

37. Which rooms they occupy?

(Multiple answers possible)

- *Living room(s)*
- *Sleeping room(s)*
- *Study*
- *Kitchen*
- *Bathroom*
- *Other*

38. Which rooms receive direct sunlight?

(Multiple answers possible)

- *Living room(s)*
- *Sleeping room(s)*
- *Study*
- *Kitchen*
- *Bathroom*
- *Other*

39. What cooling techniques do you (any of the household members) apply?

(Multiple answers possible)

- *Shading*
- *Window opening or closing*
- *Air conditioning —> **if yes, what is the preset temperature?** .... °C*
- *Fan*
- *Lighter clothing*
- *Taking a cold shower or bath*
- *Change position or activity level*
- *Other*

40. In such a day, what would you do when no one would be at home?

(Multiple answers possible)

- *None*
- *Shading*
- *Window opening or closing*
- *Air conditioning **—> if yes, what is the preset temperature?** .... °C*
- *Fan*
- *Other*

8. Drivers behind traditional and other energy use behaviors

41. How important these considerations are to you, when you try to decrease your energy use?

	Not at all important	Somewhat important	Neither important or not	Rather important	Very important
To decrease my energy expenditures	1	2	3	4	5
To contribute to the fight against climate change	1	2	3	4	5
To reduce my electricity bill	1	2	3	4	5
To maintain a comfortable environment for my activities	1	2	3	4	5

9. Environmental attitudes, agency in tackling climate change

42. Please indicate how much you agree or disagree with the following statements about climate change:

RANDOMISED ITEM ORDER

	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree
Climate change will have profound impact on next generation’s life	1	2	3	4	5
Environmental impacts are frequently overstated	1	2	3	4	5
It is primarily governments’ task to counteract climate change through environmental policies	1	2	3	4	5
I can contribute to tackling climate change if I run a lifestyle with smaller environmental impact.	1	2	3	4	5
Environmental issues should be dealt with primarily by future generations	1	2	3	4	5
I am willing to make compromises in my current lifestyle for the benefit of the environment	1	2	3	4	5
Most of the people important to me tries to make sustainable lifestyle choices	1	2	3	4	5
Environmental issues will be resolved in any case through technological progress	1	2	3	4	5

It is too late to do anything about climate change	1	2	3	4	5

43. In the last month, how often did the following apply to you:

	Never	**Sometimes**	**Often**	**Usually**
You felt rested?	1	2	3	4
You felt lonely and isolated?	1	2	3	4
You felt safe and protected?	1	2	3	4
You found yourself in situations of conflict?	1	2	3	4
You found you did things you really liked?	1	2	3	4
You felt tired?	1	2	3	4
You were full of energy?	1	2	3	4
You felt mentally exhausted?	1	2	3	4
You felt lighthearted?	1	2	3	4
You had trouble relaxing?	1	2	3	4

10. Household characteristics (cont.d.)

44. What is your gender?

- *Male*
- *Female*

45. What year were you born?

- *……….year*

46. What is your nationality? If other than Hungarian, how many years have you been in Hungary?

47. What is the highest level of studies you have completed?

- *No formal education or below primary*
- *Primary education*
- *Secondary and post-secondary non-tertiary education*
- *Tertiary education first stage, i.e. bachelor or master*
- *Tertiary education second stage (PhD)*

48. What best describes your current employment status?

- *Employed full-time*
- *Employed part-time*
- *Long time not employed (more than 3 months)*
- *Retired / pensioner*
- *Student*
- *Other economically inactive person*

49. Which of the descriptions below comes closest to how you feel about your household"s income nowadays?

- *Living comfortably on present income*
- *Coping on present income*
- *Finding it difficult on present income*
- *Finding it very difficult on present income*

50. Has your household or any member of it received any financial aid from a public institution, which has helped you to pay your energy bills in the last 12 months (incl. so called social tariffs)?

    - *Yes*
    - *No*

51. What was the average total monthly income of your household, after tax and compulsory deductions, from all sources, over the last 12 months? If you don't know the exact figure, please give an estimate.

    - *................ (local currency)*

IF REFUSES TO ANSWER:

52. Can you indicate which is the income range of your household?

[income ranges to be predefined for each country]

Annex II. - History of thermal comfort theory

Based on the work of Teitelbaum et al. [26] the development of comfort theory is summarized in more detail:

In 1876 Osborne defined a list of descriptive terms for the assessment of sensible temperature using a 20-scale comfort vote approach [28] but this had not yet been done under controlled conditions and the required conclusions could not be finalized. In 1910 the Chicago Commission on Ventilation was founded to study the application of technology to ventilating larger office buildings, streetcars, motion picture theaters and classrooms. The unique part of the experiments done in 1914 involved the room occupants' assessments of the thermal environment of the classroom, introducing the phrase Comfort Zone or Zone of Comfort for the first time, based on only temperature and humidity values.

In 1911, Willis H. Carrier [29], known as the Father of Air Conditioning, established the scientific foundation of air conditioning with his paper titled "Rational Psychrometric Formulae." This ground-breaking work marked the end of relying solely on empirical formulas derived from simultaneous measurements of dry bulb, wet bulb, and dew-point temperatures. As summarized in [26], although the psychrometric chart started as a method of characterizing the properties of air as it moves through a comfort conditioning system, the chart has – misleadingly – been used as a means of assessing comfort in the occupied space. The psychrometric chart has primary emphasis on only two aspects of thermal comfort: sensible and latent energy of air. In 1923 Houghten and Yagloglou performed an experimental research on "Determining Lines of Equal Comfort" by evaluating the perception of 130 subjects; both sexes were represented and an effort was made to get as many types of clothing as possible worn by the subjects, as long as it was "normal" clothing for them. Based on the lines of the psychrometric chart they defined the effective temperature as 64°F (17.8°C) and the comfort range between 62°F (16.7°C) – 69°F (35.6°C).

Effective temperature with standardized clothing and moving air was investigated by Yaglou and Miler (1925) [30]. The result was the new psychrometric chart and nomogram, illustrating the nature of the "neutral point" where the effects of moving air have no effect on body heat storage. This work represented the first attempt at empirically correlating variables, aside from just air temperature and relative humidity, that influenced thermal comfort within a meaningful framework. Their research gave way to similar subsequent studies.

The same authors in 1929 added a refinement to the effective temperature chart including seasonal variation in the comfort zone; however, experiments demonstrated that these were due to unrecognized clothing differences.

Numerous other indices appeared with the intention of simplifying or improving the definition of comfort. Many of these involved physiological processes and radiant temperature measurements which are usually not observed at the standard weather station.

In 1932, Vernon [31] replaced the dry bulb thermometer with the black globe thermometer explicitly with the intent of measuring the effect of radiation on thermal comfort. Bedford in 1934 [87] pointed out that the black globe thermometer in the context of measuring the mean radiant temperature alone was not sufficient to establish comfort and developed an equivalent temperature framework for air velocity, globe thermometer temperature, and air temperature. However, radiation was again considered a fixed parameter. Consequently, Carrier and Mackey corrected the original psychrometric data for radiation exchange not considered in the original study in 1937 [29].

However, not all research was done with the goal of improving the understanding of comfort to help developments in the air-conditioning industry. Victor Olgyay in 1963 published “Design with Climate” as a response to the popularization of manufactured air that was central to the modernism movement [32]. The charts showed the relationship between humidity, temperature, and comfort, also incorporating further climatic factors. The comfort temperature range covered 20°C to 30°C, however, strategies to maintain thermal comfort outside this range were also provided. Levels of radiation were indicated, necessary to offset the decrease in temperature below the lower boundary of the comfort zone. While in the comfort zone shading is necessary to maintain reasonable level of comfort, the comfortable temperature can be decreased by up to 10°C with appropriate shading. Likewise, to retain comfort up to around 10 °C above the zone, wind speed can offset the increase in temperature. A contour relating to metabolic rate was also included, indicating when light work was acceptable, for instance. Evaporative space cooling according to this chart is another means to retain comfort at high temperature values but low humidity.

Current widely adapted comfort models

The above models included a limited number of parameters that could describe the thermal environment more or less successfully, but these were not fully applicable to be applied to any condition. A groundbreaking change in the thermal comfort models that are adopted in the standards to date was done by Fanger.

Fanger comfort model (1970)

P.O Fanger in the 1970s published several works attempting to rethink thermal comfort including all thermal comfort variables, namely air temperature, relative humidity, mean radiant temperature, clothing level, air velocity, metabolic rate, and skin wettedness [3]. P.O Fanger introduced the widely used Predicted Mean Vote (PMV) model, which takes into account the following factors:

- **a.** air temperature,
- b. mean radiant temperature
- **c.** humidity,
- **d.** air velocity,
- **e.** clothing insulation
- **f.** and metabolic rate to predict thermal comfort.

Based on the PMV value, the calculation of the PPD (Predicted Percentage Dissatisfied) had also been introduced. His work made a great impact on the thermal comfort prediction methods used for the built environment, consequently, the currently used thermal comfort standards are based on his models. However, it is important to be aware that his model was intended for application by the HVAC industry in the creation of artificial climates in controlled spaces (Fanger 1970). Further on, the extrapolation of the model’s scope to all spaces intended for human occupancy, including those with natural ventilation, was a later development, and had been proven to be wrong through the research done by de Dear and Brager [33].

Local discomfort and Increased air velocity

A new element in the thermal comfort calculations was the consideration of local effects. The PMV and PPD indices express warm and cold discomfort for the body as a while. But thermal dissatisfaction may also be caused by unwanted space cooling (or heating) of one particular part of the body, which is called local discomfort. Local thermal discomfort has also been addressed in later work of Fanger [34]. This might be caused by draught, high vertical temperature difference between head and ankles, too warm or too cool floors, or by too high radiant temperature asymmetry. People engaged in light sedentary activity are the most sensitive to local discomfort.

The effect of air velocity on summer comfort is apparent and was tried to be incorporated in the early comfort models of Yaglou and Miler [30]. The air velocity in space influences the convective heat exchange between a person and the environment. The influence of this on the general thermal comfort of the body is expressed withing the PMV-PPD index and the local thermal discomfort due to draught. However, increased air velocity can be used to offset the warmth sensation caused by increased temperature, for which a dedicated calculation method has been developed. The benefits that can be gained by increasing air velocity depend on clothing, activity, and the difference between the surface temperature of the clothing/skin and the air temperature.

Adaptive Comfort Model (1998)

De Dear and Brager [33] developed the Adaptive Comfort Model, which acknowledges that people can adapt to a range of thermal conditions depending on factors such as outdoor climate, cultural expectations, and individual preferences. They described one of the predictions of the adaptive hypothesis as people in warm climate zones prefer warmer indoor temperatures than people living in cold climate zones, which is contrary to the static assumptions adapted previously. During their work, optimum indoor temperatures and prevailing indoor and outdoor temperatures were tracked. They found that by successfully accounting for behavioral adjustments, the so-called static model of comfort (represented by Fanger's PMV model) was demonstrated to be a partially adaptive model and appears suitable for application as it was initially proposed back in 1970 by Fanger himself—as an engineering guide in centrally controlled HVAC buildings, where occupants have little or no control over their immediate thermal environment. Occupants in naturally ventilated buildings were tolerant of a significantly wider range of temperatures, explained by a combination of both behavioral adjustment and psychological adaptation. These results formed the basis of a proposal for a variable indoor temperature standard.

They also concluded some reasons for discrepancies with previous data:

- diversity of Clo values, that represent the clothing insulation of the occupants
- Clo estimates also need to include the incremental contribution of chair insulation (the effect of an upholstered chair on the thermal sensation).
- Another source of error in field research appears to be the assumption that neutral always coincides with ideal (preferred). This was shown not to be the case for people in buildings with centralized HVAC system: Occupants were found to prefer a sensation slightly cooler than neutral in summer and slightly warmer than neutral in winter.

Adaptation within buildings was concluded by De Dear and Brager:

*“**Buildings with centralized HVAC**: adaptation is at work in buildings with centralized HVAC, but only at the biophysical (behavioral) level of clothing and air speed adjustments. HVAC building occupants appear to be adapted quite well to the conditions they are being given (22°C~24°C), but are intolerant of temperatures that fail to match these expectations.*

Buildings with natural ventilation: First, occupants appear tolerant of a much wider range of temperatures than in the centralized HVAC buildings and find conditions well outside the comfort zones published in Standard 55-92 (ASHRAE1992) to be acceptable. Physical explanations for the correlation between indoor comfort temperatures and outdoor climate, such as clothing insulation or indoor air speeds, accounted for only half the observed variance. By a process of elimination, we conclude that psychological adaptation in the form of shifting expectations — the subjective comfort set-points — account for the residual variation observed in the comfort temperatures of our database.

Our results were interpreted to indicate that occupants of HVAC buildings had become finely tuned to the very narrow range of indoor temperatures being presented by current HVAC practice. But there is potentially a very high energy cost to maintaining those narrowly defined comfortable thermal conditions. In contrast, occupants of naturally ventilated buildings had a greater scope of adaptive opportunity and were thus comfortable across a wider band of temperatures that more closely reflected the patterns of outdoor climate change.”

Current standards

The comfort theory developed as shown above was incorporated into standards that serve as guidance for engineers and designers to design and construct buildings, indoor environments that should be acceptable to the occupants at least on the statistical bases. The most important standards including thermal comfort models adapted for summer thermal sensation can be summarized as the following:

- ASHRAE Standard 55:2020: Thermal Environmental conditions for human occupancy

  The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 55 was first published in 1966 and is updated every 3-7 years based on current research, practical experience, and recommendations from designers, manufacturers, and end users. In 2004 the standard underwent significant changes with the addition of two thermal comfort models: the PMV/PPD model and the adaptive comfort model. The standard is in close agreement with ISO Standard 7730. It includes:

    - Fanger’s PMV model and established thermal comfort criteria. (since version 2004)
    - Adaptation (since version 2004)
    - Local discomfort criteria (since version 2004)
    - Elevated airspeed method (2010)
    - Adaptive comfort criteria, expanded for naturally conditioned spaces that have a mechanical cooling system installed (since version 2020)

   - New method for avoiding draft risk at the ankle region (since version 2020)

  While the ASHRAE standard is a standard developed in the USA, the requirements have been used globally, thus they are included in this report.

  Valid for:

   - healthy adults at atmospheric pressures in altitudes up to (or equivalent to) 3,000 m (9,800 ft),
   - people whose clothing insulation is between 0.0 and 1.5 clo, who are not wearing highly impermeable clothing,
   - metabolic rates between 1.0 and 2.0 met,
   - people who are neither sleeping nor reclining,
   - for indoor spaces designed for occupancy of at least 15 minutes.

- ISO 7730:2005 Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

  The first version was published in 1984 as Moderate thermal environments — Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. This standard incorporated Fanger's methodology of calculating PMV, PDD. The current version also includes the calculation methods for local thermal discomfort.

- CEN CR 1752:2000 Ventilation for buildings. Design criteria for the indoor environment

  This European Prestandard specified the requirements for, and methods of expressing the quality of the indoor environment for the design, commissioning, operation and control of ventilation and air-conditioning systems. For the purposes of this prestandard, the indoor environment comprises the thermal environment, the air quality and the acoustic environment. This prestandard covers indoor environments where the major concern is the human occupation but excludes dwellings. Although this standard has been superseded, it was worth mentioning as the 1998 version of this standard incorporated the criteria for local discomfort parameters (draught rate, radiant temperature asymmetry, vertical air temperature differences and floor surface temperatures) before the ASHRAE-55 and EN 15251 standards.

- CEN Standard EN 15251:2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. The European Committee for Standardization (CEN) introduced the EN 15251 standard, which outlines criteria for indoor environmental quality, including thermal comfort. It incorporated adaptive comfort principles and offers guidance for achieving optimal comfort conditions. It included 3 categories for the thermal environment. The standard has been withdrawn in 2019 as requirements are integrated into EN 16798-1:2019.

- EN 16798-1:2019 - Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics - Module M1-6

  Requirements on thermal comfort have been incorporated from the standard EN15251. The major change compared to the EN 15251 standard was that the standards were split up into a normative part (Part 1) and a technical report (Part 2). Further technical changes are the introduction of a category IV, inclusion of daylight factor and occupant schedules.

  Criteria for heated and/or mechanical cooled buildings shall be based on the thermal comfort indices PMV-PPD (ISO 7730) with assumed typical levels of activity and typical values of thermal insulation for clothing (winter and summer). Based on the selected criteria a corresponding design operative temperature interval shall be established. The values for dimensioning of space cooling systems shall be the upper values of the comfort range during cooling season (summer) and values for dimensioning of the heating system shall be the lower values of the comfort range. The design criteria shall be used for both the design of the buildings and the HVAC systems.

  Selection of the category is building, zone or room specific, and the needs of special occupant groups such as elderly people (low metabolic rate and impaired control of the body temperature) shall be considered. For this group of people it is recommended to use category I requirements. Instead of using operative temperature as the design criterion the PMV-PPD index can be used directly. In this way the effect of increased air velocity and effect of dynamic clothing insulation can be taken into account. Category I is used for spaces for very sensitive and fragile people, while Category II is the normal level of expectancy. A normal level would be Medium. A higher level may be selected for occupants with special needs (children, the elderly, people with disabilities). A lower level will not provide any health risk, but may decrease comfort and requirements are aligned with ISO 7730

  Default criteria for the indoor operative temperature in buildings without mechanical space cooling systems are presented in the standard. The upper limits shall be used to design buildings and passive thermal controls (e.g. orientation of glazing and solar shading, thermal building capacity, size and adjustability of operable window, etc) to avoid overheating. The values for dimensioning of space cooling systems shall be the upper values of the comfort range during cooling season (summer).