D3.3. Multiple, socioeconomic impacts of sustainable space cooling

Cool LIFE

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List of Acronyms

AB	Apartment Block
ABM	Agent-based Modelling
AC	Air conditioning
AMV	Actual Mean Vote
BCVTB	Building Control Virtual Test Bed
BEM	Building Energy Modelling
BPE	Building Performance Evaluation
BPS	Building Performance Simulation
CBA	Cost Benefit Analysis
Clo	Clothing factor
COMBI project	Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe Project
DNAS	Drivers, Needs, Actions, and Systems
DP	Design Parameters
ECM	Energy Conservation Measure
EM	Engineering Method
EMS	Energy Management System
EPC	Energy Performance Certificate
FM	Facility Management
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
GHG	Green House Gasses
IAQ	Indoor Air Quality
IDP	Integrated Design Process

IED	Integrated Energy Design
IED^N	Integrated Energy Design Process at Neighbourhood Scale
MFH	Multi Family House
MI	Multiple Impacts
MICAT	Multiple Impacts CAlculation Tool
ML	Machine Learning
NR	Non-Residential
OB	Occupant Behaviour
obFMU	Occupant Behaviour Functional Mockup Unit
obXML	Occupant Behaviour XML
OPA	Occupant Presence and Actions
PD	Percentage Dissatisfied [%]
PMV	Predicted Mean Vote [%]
POE	Post-Occupancy Evaluation
PPD	Predicted Percentage of Dissatisfaction [%]
RCP	Representative Concentration Pathway
SC	Space cooling
SFH	Single Family House
SM	Statistical Method
TUS	Time Use Survey
NR	Non-Residential
WWR	Window-to-Wall Ratio
XML	eXtensible Markup Language

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Keywords list

- Occupant Behaviour
- Thermal Comfort
- Energy Modelling
- Sustainable Space Cooling
- Multiple Impacts

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Executive summary

Occupant behaviour (OB) has an impact on the space cooling energy demand in both residential and non-residential buildings. Occupants can interact with the buildings and adapt to changing internal thermal conditions to avoid discomfort in the summer season. Within the CoolLIFE project, deliverables *D2.1 Taxonomy of space cooling technologies and measures* [1], *D3.1 Knowledgebase of occupant-centric space cooling* [2] and *D3.2 Analysis of Behavioral Interventions Across Europe* [3] have explored the effects of Occupant Presence and Actions (OPA) on the building space cooling needs and showed the possibilities to shift occupant behaviour to more sustainable practices in a qualitative way. Comfort lifestyle and user behaviour measures have been categorized into environmental adjustments, personal adjustments, physiological adaptation and behavioural adaptation. Generally, it has been recognized that occupants' adaptive behaviour on passive measures, which are mainly provoked by various environmental conditions, are stochastic but with some predictability through identifying triggering factors.

The current deliverable focuses on the quantification of OPA on the energy use of residential and non-residential buildings on the building scale, and the multiple impacts and social co-benefits when behavioural interventions are implemented on a larger scale.

In the first part of the deliverable state-of-the-art methodologies and tools for OPA modelling, such as presence and movement in the buildings, and actions covering practices for thermal adaptation, interactions with windows, shading and air-conditioning devices, and other equipment, including lighting are collected. Their possibility to help the accurate modelling of space cooling (SC) related OPA is assessed. The main model types, data collection methodologies for data-driven models, and applied mathematical models to develop stochastic or rule-based OPA models are summarized. Through reviewing the scientific methodological frameworks such as the IEA's Annex 66 [4] and Annex 79 [5], we have collected more than 150 examples for OPA models, that can be used to quantify SC-related behaviour. For each model type, we have identified the OPA action types, building types and geographical conditions the models have been based on, and integration possibilities with existing energy prediction tools, to help energy modellers in finding appropriate OPA models when SC demands need to be quantified. It can be concluded that most of such models have been developed in such European countries which do not have the highest space cooling loads (e.g. Switzerland, UK, Germany, etc.). Window opening is the OPA described by the highest number of papers (35%) while for air-conditioning use (AC) only a limited number of models exist (8 models), mainly for China. As for the building functions, offices are highly represented in existing OPA models (80%), followed by residential buildings (17%), and a few examples of educational buildings (5 models). As a standard approach, incorporating OPA models that are not based on simple rule-based algorithms needs custom coding to be applied in the building energy simulation environments, however, more than 75 models have already been standardized using a so-called, 'occupant behaviour XML' (obXML) language, that can be integrated into the building simulation workflow through the occupant behaviour Functional Mockup Unit (obFMU).

The collection of these models and the state-of-the-art methodologies give the building simulation experts a palette of possible behavioural actions and tools to integrate OPA in energy predictions in more sophisticated ways when SC demand prediction is targeted. However, as the stochastic occupant behavioural models have been developed on a sample of building occupants, implementing these models does not directly reduce the prediction uncertainty. To close the performance gap, a lot needs to be done to have ready to use models that are based on empirical data.

For example, it is hard to find realistic occupancy data, as these are not available for most of the European countries. Policymakers can help the development of such databases. Good examples exist where through Time use Surveys

(TuS) large scale data-collection for residential buildings was done, which can serve as a basis for development of different occupancy profiles for energy simulations.

As the next step, based on these results, guidelines have been developed on how OPA could be addressed during a design process, to reduce the prediction uncertainties of OB. Taking the Integrated Design Process (IDP) and the Integrated Energy Design Process at Neighbourhood Scale (IED^N) methodologies as the starting point, step-by-step guidance is given on what actions are needed to incorporate the behavioural aspects of the existing or unknown future occupant(s) at a given project phase. The following actions have been identified as important steps to be taken:

- incorporate occupant assumptions early,
- establish effective communication mechanisms,
- identify occupant heterogeneity,
- conduct participatory design process,
- multiple occupant behaviour profiles,
- enhancing building performance through post-occupancy spatial design optimization,
- continuous improvement and research.

On neighbourhood scale, the identification of occupant heterogeneity is even more important. The multidisciplinary questionnaire developed and published within *D3.1 Knowledgebase of occupant-centric space cooling* [2] is a useful resource in setting up a survey to gather OPA inputs also addressing socio-economic characteristics.

As a next step, based on the findings of D3.1 and D3.2 typical, possible occupant behavioural measures in residential and non-residential (NR) buildings have been defined, which serve as a basis for the development of as inputs for energy simulations. The CoolLIFE project focuses on space cooling demand in the residential sector, which is also reasonable from the OPA perspective. Residents have a wide range of options and tools to adapt to thermal discomfort conditions and can freely interact with their environment in returning to a state of thermal satisfaction, thus the influence of OPA on the SC demand is the highest, which also results in high uncertainties. However, in NR buildings, the temporal and special aspects of space use, and functional requirements or standardized internal operational conditions limit the freedom of occupants to a smaller number of behavioural measures, which is reflected in the approach taken in the project. The findings of the previous deliverables served as a basis for defining typical occupant behavioural measures in residential and commercial buildings, simulation and quantification of energy performance in selected scenarios using parametric analysis in Grasshopper and EnergyPlus and analysing their individual and integrated impact on energy use in buildings.

The scenarios have been developed considering several aspects. 6 countries were selected for the analysis, where the countries' exposure to the effects of climate change and aspects of vulnerability, energy poverty and space cooling demand were taken into account, and scenarios were constructed with different current and future climatic conditions (RCP4.5, 2020, 2050, 2080), and three building archetypes (multifamily house - MFH, single family house – SFH and apartment building - AB) and renovation levels (existing state, usual retrofit, advanced retrofit) have been used as boundary conditions.

For residential buildings, after analysis of the individual effects of the OPA actions, scenarios with different occupant behaviour profiles and indoor thermal comfort expectations, reflecting user lifestyles and attitudes towards energy-saving habits and different adaptations to heatwave events were defined: i) Baseline, i.e. unconscious, when the user relies on the mechanical SC device to ensure thermal comfort, regardless of the possible passive or adaptation opportunities; ii) Mitigative, where occupant reacts to a discomfort condition by prioritizing passive and adaptive behavioural measures; iii) Adaptive, when occupants adopt behavioural measures to prevent a discomfort condition. Behavioural measures applied in these three profiles cover occupant presence, window opening, shading control, adaptative or controlled thermal environment, lighting and equipment use. Where existing, standards served as the basis of the baseline scenarios, and contrasted with realistic behavioural profiles. In the has been seen, that the OPA models that existing are limited to specific OPA types and of geographical territory, hence within the definition assumptions needed to be done.

The simulations showed that when realistic occupancy schedules based on the available TUS data were used for the simulations, space cooling demand was reduced by up to 6 kWh/m^2.

From the individual effects of OPA measures, the reduction of internal loads through lower appliance power density and limited usage hours has the highest effect on the results. When power density is reduced from 10 W/m^2 to 4 W/m^2 and reduced operational schedule is applied, the average space cooling demand was reduced by nearly 20 kWh/m^2,year. This result confirms the significance of behavioural interventions targeting the reduction of energy used in electrical and heat generating appliances, to reduce space cooling demand. Motivating the residents to reduce electricity costs by monetary incentives, information campaigns or nudging has also been found to be a popular behavioural intervention that has well documented positive impacts in the literature. [3] It is advisable to implement such programs in the future as well to limit the space cooling loads.

The second most effective measure was applying conscious shading behaviour, that showed nearly 10 kWh/m^2 reduction in the annual SC demand for the Italian MFH case study. Reaching SC savings though shading requires more active involvement of the occupant, which might need different motivations. To utilize the potential lying in the use of shading, instead of conscious behaviour, building automation systems can relieve the occupant of this responsibility. It is however the responsibility of the policymakers to facilitate the adaptation of these behaviours by incorporating the installation of movable shadings into the building regulations.

As an individual effect, natural ventilation combined with night cooling could result in an average of nearly 5 kWh/m^2 reduction for the Italian MFH case study. However, this effect considers space cooling with constant setpoints, while when relaxing the thermal comfort requirements to the adaptive comfort limits, an additional effect can be seen, evidence during the simulation of the combined actions.

The simulations quantifying the combined effects of Mitigation and Adaptation behaviours showed that a huge potential lies in the occupant behaviour change to reduce space cooling demand. It is seen, that in comparison to the Unconscious behavioural scenario, the Mitigation scenario can reduce space cooling demands by an average of 69-84%, while the percentage reduction of the Adaptation scenario is between 97%-100%. Also, the range of the space cooling demand covering by the different behaviours and scenarios reduced by adapting more conscious behaviours, spreading from 31-48kWh/m^2 to 1-5kW/m^2.

The analysis of the boundary conditions showed that with climate change – as expected - SC demand will increase. The results however confirm that the increase is the highest in case of the Unconscious behaviour (4.10 kWh/m^2,year on average), while marginal if the Adaptation behavioural patterns are followed.

An additional finding is that with increasing envelope performance and applying advanced retrofit levels to the building stock, space cooling does not inevitably decrease. This confirms that future space cooling demand and energy use should be considered together with the requirements to reduce space heating demand, during policymaking.

For the commercial building sector, a similar quantification approach is followed, by adjusting the set of behaviours and number of scenarios to the space types considered. The combined effect of the behavioural measures could result in average 40%-76% space cooling demand reduction for hospital, hotel, educational and office space types. The highest savings can be achieved in office buildings, and the highest potential is in Stockholm, within the analysed scenarios.

A high potential here lies in the increase of space cooling setpoints. The literature review evidenced that in commercial buildings the space cooling setpoints are typically lower than what are the highest allowed temperature limits in the thermal comfort standards, and also lower than what is taken into account in the country specific legislation. Increasing the setpoint by 1 °C results in a reduction of annual space cooling demand of 0.5-12 kWh/m^2,year, depending on the selected building function and scenario, and can result in 5-68% reduction in the annual SC demand.

Shading and night-time ventilation have also proven to be effective measures. From the analysed building functions, the highest potential in reducing SC demand / or increasing thermal comfort by the effective use of shading lies in office buildings, where external shading is considered to be more widespread than in other building functions. The mean reduction of the SC demand is 39% for all office cases considered, ranging from 6-65% depending on the country, orientation, building construction, and other occupant behavioural settings. With night-time ventilation, educational and office buildings can utilize the free pre-cooling effect of lower temperatures the most.

The potential reduction of space cooling demand in the service sector resulted in the range of 67-84% for offices, 58-69% for educational, 38-48% for hospitals, and 48-69% for hotels for the spaces evaluated.

Finally, the multiple impacts and social co-benefits of behavioural interventions evidenced have been mapped and quantified. It has been concluded that in the literature, existing quantification models are more widespread for energy efficiency interventions (EEI) targeting the reduction of space heating energy use. As a first step, a map of impact chains was developed, including economic, social and environmental aspects. Root causes were identified. Space cooling and summer thermal comfort can be addressed through EEI (e.g. installing shading or active systems with better performance), behavioural measures (e.g. increasing setpoints), or lifestyle measures (reducing the need for SC demand).

Summer specific impacts of improving thermal comfort or reducing electricity used for space cooling have been identified as the following:

- *Social:*
    - *energy poverty*
    - *health: heat-related mortality and morbidity; health issues from overcooling, air pollution, well-being benefits from NbS*
    - *productivity*
- *Economic*
    - *energy intensity*
    - *gross domestic product*
    - *employment effects*
- *Environmental*
    - *nature resource use*
    - *emissions*
    - *import dependency*
    - *impact on RES targets*

It has been concluded, that the existing methodologies on the summer specific multiple impacts on a large scale are scarce, and new methodologies need to be developed to quantify the summer related social impacts. However, the impact map developed serves as qualitative indicator of policy-makers in non-energy impacts that are associated with sustainable cooling.

As a next step, building on the results of the quantification of building level space cooling, and on the findings of the collection of successful SC-related behavioural interventions evidenced in D3.2, building on the existing quantification frameworks, the multiple impacts arising from behavioural change have been quantified. By using the recent developments in this field, the comprehensive approach implemented in the Multiple Impacts Calculation Tool (MICAT), also building the COMBI methodology, has been used for quantifying the impacts of occupant behavioural intervention implemented in residential and non-residential sectors. The impacts arising from the reduction of electricity use are quantified namely: social impacts as avoidance of pre-mature mortality and lost working days due to air-pollution; environmental impact covering fuel savings, renewable energy share targets and reduction of additional capacities, and economic impacts such as impact on import dependency, is done for the EU-27 region as a whole and the five member states with the highest final energy use for space cooling: Spain, Italy, Greece, France and Germany. The results show that when reaching 12% electrical energy savings in residential and 6-15% savings in the relevant subsectors of non-residential buildings, premature mortality due to air pollution can be reduced by a number of 15 on EU-27 level, while the lost working days due to air pollution-related illnesses can be reduced by 4284 days annually for the same region. From the top 5 countries, the social impacts calculated are the highest for Italy. These values are low compared to the overall health risks associated with the PM2.5 pollution on the EU level, which could have reached as high as 238,000 premature deaths in 2020 according to EEA's estimates [6], however, still high when the individual is concerned. However, the as detailed above, heat-related mortality and morbidity impacts associated with summer conditions are not included in these values in lack of robust methodologies.

Reduction of the import dependency is generally low, the highest percentage is shown for Coal in Greece, where 1.5% reduction can be achieved. After monetization of the savings from the additional, multiple impacts, 3-12% additional savings above the direct savings from the reduced electricity use has been shown for the 5 Member States, and an average 7% for the EU-27 region.

1. Introduction

As described by the IEA [7] occupant behaviour is one of the six influencing factors of the energy performance of a building. Occupants' interactions with the energy system shape building operations and thus the energy use and indoor comfort, however, high uncertainties exist in the predicted actual energy consumption, partially attributed to OPA [8]. Therefore, increasing the knowledge base of occupant behavioural interventions is a key factor for the successful implementation of energy efficiency strategies in buildings.

The concept of energy-related occupant behaviour in buildings can be defined as occupants' behavioural responses to discomfort, presence and movement, and interactions with building systems that have an impact on the performance (energy, thermal, visual, and Indoor air quality - hereafter: IAQ) of buildings. Measures that can affect space cooling energy performance have been collected for the report *D2.1. Taxonomy of space cooling technologies and measures* [1] lifestyle and behavioural interventions cover environmental changes, e.g. operation of building elements (shading, openings), or turning appliances on/off, personal adjustments that change the sensation of comfort (e.g. changing clothing or taking cold drinks), and psychological adaptations (acclimatization). *D3.2. Analysis of behavioural interventions across Europe* [3] has summarized the lifestyle and user behaviour aspects of space cooling more in-depth: first, i) how people use building Space Cooling (SC) systems and what do they use to avoid/limit the need for active SC; and secondly, building on this ii) how this behaviour can be changed. The patterns of occupant behaviour (OB) based on a wide literature review on standards, and legislative and empirical data, were collected, which helps understand how the occupant is considered in the theoretical calculation of SC demand – and how they behave in reality.

As seen in D3.1 and D2.1 to maintain the physiological balance of the human organism, the behaviour reactions of the users are induced. Generally, it has been recognized that occupants' adaptive behaviour on passive measures, which are mainly provoked by various environmental conditions, are stochastic but with some predictability through identifying triggering factors. Comfort lifestyle and user behaviour measures have been categorized into environmental adjustments, personal adjustments, physiological adaptation and behavioural adaptation.

Occupant behaviour modelling in regards to building energy use has been researched since the 1980s. [9] With the increase in the available computational power and technical solutions, the application of more detailed mathematical models and higher spatial or temporal resolution for representing the actions of individual occupants has become possible, which allows advanced models to describe occupant's presences and actions, moving from static inputs for simple quasi-steady state energy calculations to dynamic hourly and sub-hourly models.

The first part of the current work focuses on mapping and collecting the available state-of-the-art occupant behaviour models. The goal is to: i) identify models, data, and computational solutions that are ready to use in predicting space cooling demand in the European context, ii) provide guidelines on how to integrate the OB aspects into the pipeline of building design and operation, to reduce the uncertainty in the prediction of space cooling energy use.

Secondly, building on the results of this chapter and previous deliverables, the current work aims at the quantification of direct energy benefits that can be gained by implementing behavioural measures in the context of summer thermal comfort and space cooling. The collected information in D3.1 and 3.2 on the behavioural aspects are used to quantify the reduction in space cooling demand due to behavioural change on the building level, for a wide variety of boundary conditions, through using energy modelling.

In addition to the direct costs and benefits of the building owner or operator when applying sustainable space cooling, including behavioural measures to reduce space cooling energy use, indirect impacts, including economic, social and environmental aspects beyond the usual measure of energy savings rise on a larger scale, which can be both positive or negative. As the literature on multiple impacts related to the building sector and stemming from energy efficiency interventions (EEI) is not specifically focused on space cooling and does not cover a wide range of behavioural measures, but energy efficiency interventions in general, there is a knowledge gap that needs to be addressed to appropriately consider the effect of implementing sustainable space cooling solutions. While the existing quantification models, e.g. the COMBI [10] or MICAT [11] have dedicated indicators that quantify the social impacts in winter from inadequate heating (e.g. avoided asthma cases due to the reduced exposure to indoor dampness or Excess winter morbidity attributable to inadequate housing), the aspects of summer heat-related mortality or health-related issues from space cooling are not addressed.

To address these knowledge gaps, the current work maps impact chains related to a better performance in space cooling or summer thermal comfort, and aims at identifying root causes and impacts stemming from both space cooling targeted EEI actions (e.g installing shading or active systems with better performance), to behavioural measures (e.g. increasing setpoints) and lifestyle measures (reducing the need for SC demand). Based on the existing impact chains and summer-specific indicators collected, this work attempts to quantify the multiple impacts of behavioural interventions in this domain.

Building upon this information the current report is structured as the following:

Chapter 1 analyses and summarizes the State-of-the-art methodologies and tools for Occupant Behaviour modelling regarding SC energy prediction, amended with guidelines for the integration of OPA in the design process.

Chapter 2 includes the Quantification of behavioural interventions for space cooling reduction, for both residential and non-residential buildings.

In Chapter 3, the impact assessment of behavioural interventions has been developed and presented.

2. Methodologies and tools for Occupant Behaviour modelling

Occupant behaviour modelling has been researched since the 1980s. In the last four decades, several methods have been used to model occupants' presence and actions (OPA). [9] According to the computational power and technical solutions available, a wide range of methods have been applied with different levels of complexity, also corresponding to the goals and purpose of the calculations. With Energy Performance Certificates (EPCs) being mandatory for new buildings and major renovations around the EU countries, standardized energy prediction methodologies have become widespread. The calculation methodologies implemented in the country-specific EPC calculations range from simplified building energy modelling and dynamic simulation modelling. [9], [12] Simplified calculations are done under standard conditions, using steady-state or quasi-steady-state timesteps and monthly average weather data. These methodologies use daily average occupancy hours and occupant behaviour like window opening for natural ventilation, or activation of shading devices are only implicitly implemented through given ventilation air change rates or g-values considered constant over high periods of time. As the role of the EPC is to provide a comparable, verified energy performance rating of the building itself, it is not intended to, and is also not capable of taking into account the real needs/habits of building users, which leads to high gaps between the actual and predicted energy use.

Dynamic simulation methodologies are also available for calculating performance for given EU countries, which rely on dynamic inputs based on schedule or rule-based occupancy presence, and explicit or implicit behavioural actions. These methods allow multivariable calculations under actual operational conditions and hourly weatherly data, returning results not only for annual energy performance but also on the hourly level. International standards like ASHRAE 90.1 and EN16798-1 have been developed to provide hourly profiles for internal conditions and OPA. These simulation methods provide a platform for incorporating also custom-defined OPA schedules, rules, or other inputs that can help replicate the more flexible and seemingly unpredictable way occupants behave. However, to do this, realistic inputs are needed.

The simulation of energy demand, and especially cooling demand on a neighbourhood or urban scale is also challenging. Swan et al distinguish top-down, bottom-up statistical and bottom-up engineering methods [13] Top-down approaches are widely used for supply analysis based on long-term projections of energy demand by accounting for historic response, they cannot incorporate behavioural aspects explicitly. Bottom-up approaches however are capable of accounting for behavioural aspects as well, hence the application of behavioural models on urban scale is also important. The current chapter collects the state-of-the-art methods, tools, and models that are available in the field of occupant behaviour modelling in the context of SC, both on building and neighbourhood scale.

2.1. State-of-the-art methodologies and tools for Occupant Behaviour modelling

Occupant characteristics can be distinguished into two groups: occupancy, which defines presence, and behaviour. The relationship between occupants and buildings as defined in Figure 1 [4] can be seen in Occupants on one hand move in or out, or within the building, causing not only an effect on the internal heat loads, but also determining the thermal comfort requirements within a particular space. Occupancy is also characterized by the number of occupants in a space, also defined as occupant density. On the other hand, occupants pursue actions that change the physical state of the building, by increasing the air-change rate or changing the solar transmittance of the transparent surfaces. While remote actions are becoming more and more available (e.g. using smartphone-based thermostats), in most cases the presence of the occupants is necessary to perform actions.

Occupant actions may be triggered by physical, physiological, psychological, or social phenomena, but are also influenced by external, or contextual impact factors. The occupant actions are influenced by comfort, culture or economy, which are hard to map and predict, however, in the context of energy efficiency are much studied by behavioural scientists. Behavioural change can be targeted through monetary incentives, but also through non-price interventions including nudges or information strategies, as detailed in *D3.2. Analysis of behavioural interventions across Europe* [3].

Through reviewing the scientific methodological frameworks such as the IEA's Annex 66 [4] and Annex 79 [5], and the latest scientific literature, we first explore how OPA can be defined through modelling methods, and characterize these in various means from how they address human behaviour, through what is the subject of control, what mathematical approach is followed. Afterwards, we will review how the models can be incorporated in dynamic energy simulations. Figure 2 shows the summary of how OPA models have been characterized within the literature.

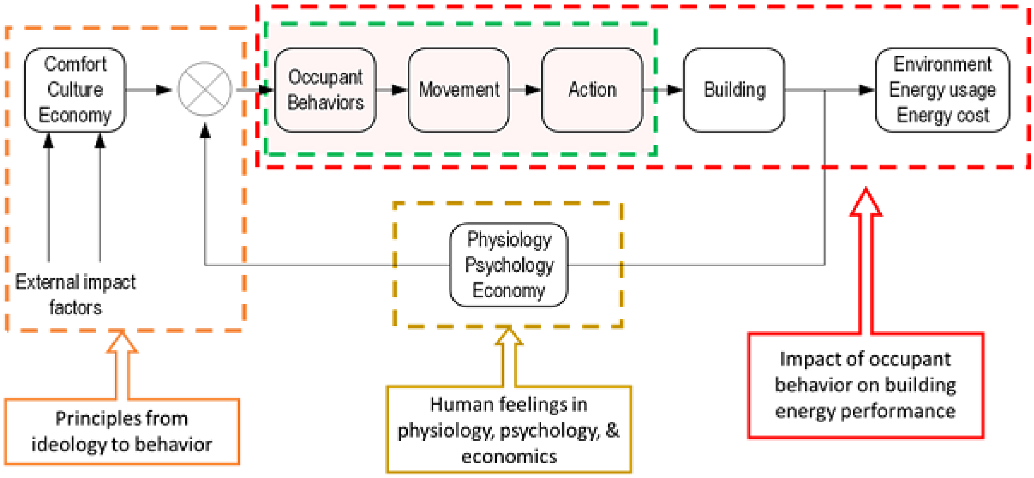


Figure 1. Relationship between occupants and buildings [4]

2.1.1. Review of state-of-the-art models types of determining OPA

Models can also be categorized into two types based on what is the subject of their control: implicit and explicit. Implicit models focus on rules related to physical systems rather than directly addressing occupants. They predict the states of building components that occupants commonly interact with. On the other hand, explicit models involve rules and logic associated with occupants, directly forecasting occupants' interactions with these building components. [14], [15] As described by [13], bottom-up Engineering Methods (EM) can be categorized as explicit models, as they rely on the dwelling characteristics, power ratings use characteristics and/or heat transfer and thermodynamic principles to calculate the energy use. On the other hand, statistical methods (SM) incorporate behavioural models only implicitly.

Occupant actions can be due to adaptive triggers when for example, environmental variables like glare motivate the user to take action in closing shading, however, many triggers exist that are independent of the conditions that can be defined through environmental characteristics and stemming from non-adaptive triggers, e.g. habits, as outlined on Figure 3 by O'Brien and Tahmasebi.[16] In the realm of literature, the modelling of occupant actions is also commonly classified into three distinct groups, as outlined by [17]. Literature identifies traditional behaviour models falling under these three categories, including building schedules [18], [19], weekly schedules, and building survival models [17], [20], [21].

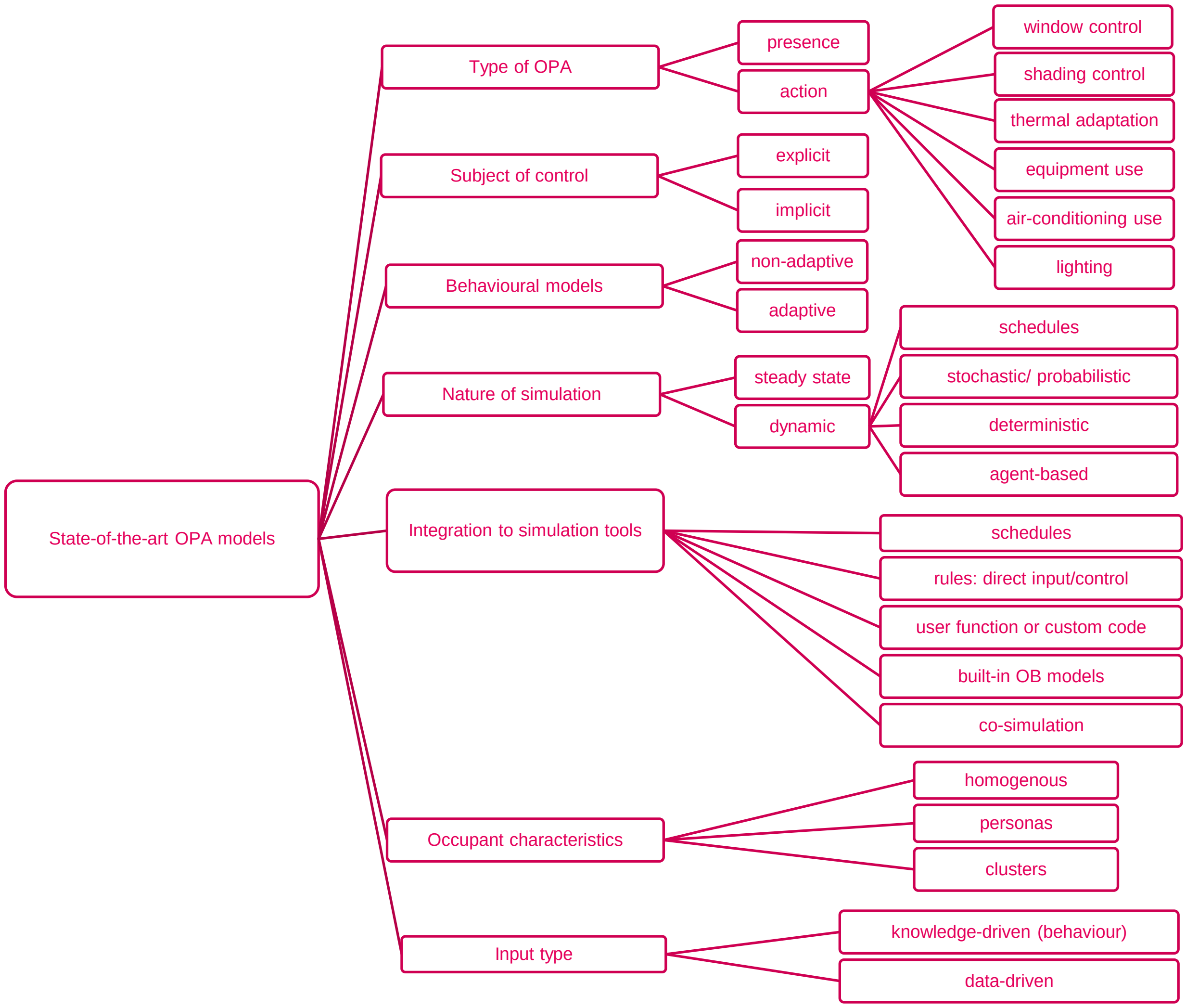


Figure 2. Characterization of state-of-the-art OPA models based on the literature review

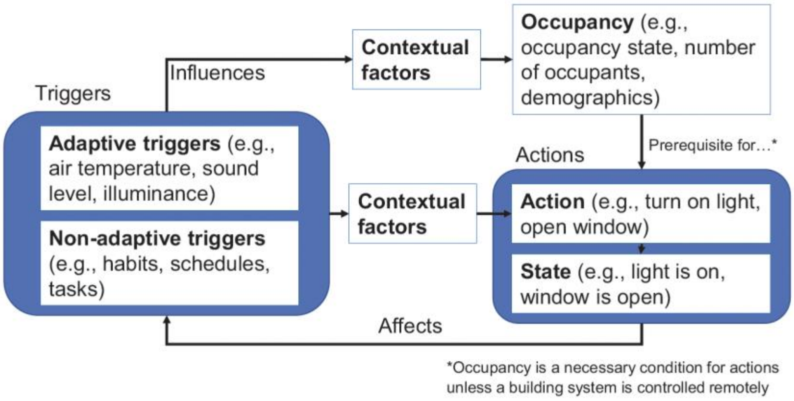


Figure 3. Relationship between actions, behaviours and triggers in buildings [16]

- Occupancy Models:

Occupancy models are designed to forecast various aspects of occupants' presence, encompassing arrival and departure patterns, as well as the duration of periods of vacancy or occupancy. These models aim to ascertain occupants' presence either by indicating the occupancy status at the space level or by quantifying the number of occupants within a building.

- Adaptive Behaviour Models:

Occupant actions falling into this category are primarily geared towards restoring occupant comfort. Examples include activities such as switching on lights, closing blinds, adjusting thermostats, utilizing windows, and making clothing adjustments.

- Non-Adaptive Behaviour Models:

Actions within this group are predominantly motivated by contextual factors rather than physical discomfort. Occupants engage in these actions to save energy, enhance outdoor views, or accomplish tasks. Examples encompass the use of plug-in appliances, turning off lights upon departure, and opening blinds.

The models based on their nature of how OPA is predicted have further been categorized by numerous authors [16] [22], and these models tend to be characterized by possessing one or more of the following possible and desirable traits:

- Deterministic/ non-probabilistic

Deterministic or non-probabilistic models operate on fixed values, such as constants or schedules derived from assumptions or empirical observations, as opposed to stochastic models that account for variability. In the context of occupant-driven control, deterministic models dictate occupant actions based on predetermined correlations with indoor and/or outdoor environmental conditions. [22] These deterministic occupant behaviour (OB) models serve as fixed inputs in building performance simulation (BPS) programs, similar to other variables like thermo-physical characteristics, lighting system power, and HVAC efficiency. While deterministic models offer simplicity, transparency, and reproducibility, they lack consideration for design and operational uncertainties.

When integrating deterministic inputs into BPS programs, modellers commonly employ direct input or control logic, alongside built-in OB models. Alternatively, modellers may choose a data-driven deterministic control logic or custom code for simulation studies, eliminating the necessity for intricate co-simulation environments unless already in place. [22], [23]

- Stochastic/probabilistic

Stochastic models in occupant behaviour capture the inherent uncertainty and variability in environmental control actions, considering the diverse nature of occupant responses influenced by complex relationships among contextual factors, adaptive triggers, and non-adaptive triggers. These models introduce probabilities associated with environmental conditions or events, such as occupants opening windows when feeling hot or entering/exiting a space. Utilizing stochastic processes, these models reproduce occupancy and diverse behaviours within buildings, generating a probabilistic distribution of predicted outcomes across different timeframes, from timesteps to annual results. [9], [22], [23].

In building performance simulation (BPS) programs, the simulation process for stochastic OB models involves three key steps. Initially, the OB model is incorporated as probabilistic inputs into BPS programs, following specific approaches (direct input, built-in model, user function or custom code, and co-simulation), outlined later in the review. The simulation is then run multiple times, and for each run, the simulated probability of behaviour is matched with a set of randomly generated numbers to determine the actual behaviour condition—whether a space is occupied or an adaptive action is performed. To preserve stochastic patterns, the behavioural action is activated and simulated only when the simulated probability exceeds the randomly generated number.

The mathematical model used to generate stochastic models is manifold. The application of Markov chains in occupant behaviour modelling is well-established, with early examples in 2008 by Richardson et al. [24] and Page et al. [25] utilizing first-order Markov chains to generate stochastic synthetic occupancy patterns. These models predict adaptive actions' likelihood in a timestep, considering explanatory variables. Further mathematical models used in the literature are discrete-time Markov chain models, discrete-event Markov models, hidden Markov-chain models, and mixed-effect models.

- Agent-based

Agent-based modelling (ABM) is a technique that captures the dynamics of autonomous agents, their interactions, and the resultant impact on the entire system. This approach recognizes that occupants engage with buildings or each other through a series of decisions influenced by various conditions (e.g., IEQ, presence, or others' behaviour). Agents, representing entities like building occupants or households, possess attributes governing their interactions within a defined environment. ABM's unique capability to simulate individual decision-making enables the representation of real-world systems with intricate, nonlinear, and dynamic properties [26]. Each agent assesses the environment and the state of others, making decisions based on a set of rules, leading to the emergence of global system behaviour from micro-level actions and interactions. ABM shares characteristics with probabilistic methods, often incorporating probabilistic rules guiding agents' actions based on environmental information or interactions with other agents. For example, in a shared office with uncomfortable thermal conditions, a "person" agent might adjust thermostat settings based on group preferences through probabilistic interactions. Using ABM when the real-world system exhibits characteristics such as complex, nonlinear, or discontinuous interactions between agents, heterogeneous interaction topology (e.g., social networks), dynamic spatial considerations, a diverse population of agents, and complex behaviours involving learning and adaptation features [16], [26].

A further aspect is how the models are constructed, and what type of information serves as the input for defining the model logic and the values used.

- Knowledge-driven

Traditional models are considered "knowledge-driven", that take physical behaviour as a starting point and construct bottom-up models based on measurements or observations.

- Data-driven

In contrast to the traditional methodologies, data-driven modelling is an approach that centres on leveraging computational intelligence, specifically machine learning (ML) methods in building models. This methodology, as discussed [27], [28], aims to either complement or replace traditional "knowledge-driven" models that describe physical behaviour. The data-driven trait entails the generation of models based on measurements but uses more advanced methods, and adopts model-fitting techniques, such as regression.

Data-driven methodologies are often used in urban energy modelling, using statistical methods (SM) defined by Swan et al [13]. SMs utilize dwelling energy consumption values from a sample of houses and regress the relationships between the end-uses and the energy consumption. While submetering could contribute highly to the data precision distinguishing energy systems and defining OPA in more detail, OPA can be taken into account by utilizing conditional demand analysis or neural network methods implicitly, as done by several authors. [13] However, when using statistical methods, space cooling is often modelled together with other end uses, e.g. appliance and lighting. [13] Data-driven methodologies are also used when occupant presence in dwellings is derived from statistical data collected, e.g. Time Use Surveys (TUS) [29]. TUS is conducted voluntarily by national statistical offices and measures the amount of time people spend doing various activities, such as paid work, household and family care, personal care, voluntary work, social life, travel, and leisure activities. In the last 20 years, TUS has been used to collect also data on the location of the respondent, for example in Italy [30] and France [31] [32].

The generation of models form the collected data can result in a model where the same behaviour is applied to all occupants. There are however possibilities to involve different occupant characteristics from the data collected:

- Clustering

Clustering is often used to group data collected into subgroups of similar characteristics. This method involves classification of the survey, clustering and determination of the number of clusters. Clustering by unsupervised learning has also been used to generate archetypes for socioeconomically sensitive urban building energy modelling based on smart metering data. [33] The data collected in the TUS is from representative population samples and thus can be used to develop probabilistic or deterministic occupancy profiles representing the behaviour of a larger population as well. For example, a methodology for the identification of representative daily residential occupancy profiles for households with different numbers of occupants was developed and applied to UK households by Buttitta et al. [29] The methodology used data available from the UK TUS 2000 and through clustering, it identified 22 representative occupancy patterns for households based on the state of the occupants (home and awake, home and asleep and away).

- Personas

Regarding the types of occupants in the model, the most common approach is that based on the data collected a single behavioural model for the occupant is developed, without distinguishing between the possible occupant characteristics. As an alternative, the development of personas is a novel approach. Personas, archetypal characters are fictional, but representative occupants, that provide a compelling method for modelling occupant behaviour and beliefs, facilitating a more tangible and comprehensible representation for diverse stakeholders [23], [34] Clustering behavioural model data based on additional socioeconomic parameters and creating archetype personas has been implemented for urban energy modelling in for example [31] and [32].

2.1.2. Review of tools for OPA modelling

Increased model complexity necessitates more sophisticated implementation methods within building performance simulation (BPS) tools. The strategies for implementing occupant models can be classified into two distinct categories: those seamlessly integrated into BPS tools and those that independently generate inputs before integration (offline and stand-alone methods). [4], [16] A more detailed characterization is done by several authors, which can be concluded as the following:

- Direct input or control

In this method, users define occupant-related inputs alongside other model inputs using BPS program semantics. The direct input approach involves pre-calculating schedules based on correlations between environmental conditions and occupant actions, with minimal runtime communication between the pre-calculation module and the BPS program. Despite its ease of implementation, the direct input approach has limitations. It lacks flexibility, struggling to represent complex logic or algorithms for certain OB models. Additionally, the approach associates occupant controls with building systems or components rather than individual occupants, potentially leading to actions occurring when occupants are absent. The use of static set points for temperature and assumptions in pre-calculation can also compromise the accuracy of OB model predictions during the validation process.

- Built-in OPA model

In this method, OPA models are already embedded within BPS programs, often within dedicated software modules. While this provides a straightforward means to model specific OPA behaviours, there is a limitation to the number of built-in OPA models available in a few BPS programs, impacting the approach's flexibility.

Despite this limitation, some BPS programs are enhancing their capabilities by incorporating new OPA models, making it more accessible for non-expert modellers to implement advanced behavioural inputs. This built-in OPA model approach, exemplified by programs like DeST and ESP-r, offers ease of implementation, flexibility in representing diverse OPA scenarios, and reusability of results [22], [35]. However, the drawback lies in the inability of users to create new types of OPA models or use new algorithms for the built-in models, limiting both reusability and simulation accuracy.

Additionally, the incorporation of built-in OPA models in BPS software is not widespread, with limited scope in terms of action types. While some programs like ESP-r provide built-in schedules and direct data import for occupants, the range of actions covered remains restricted.

- User function or custom code

This approach allows users to write functions or custom code as part of the building energy model input file, offering flexibility in modifying how a BPS program simulates energy models without the need to recompile the source code. Exemplified by features like Energy Management System (EMS) in EnergyPlus and user functions in DOE-2, IDA ICE, and TRNSYS, the user function approach enables the incorporation of both deterministic and stochastic occupant behaviour (OB) models through user-defined mathematical functions. [22], [35], [36].

While providing flexibility, the user function approach faces challenges in terms of usability and reusability. This approach is limited to specific BPS programs and requires advanced user expertise for correct and efficient utilization. The implementation often demands a deep understanding of the BPS program, and the lack of a comprehensive debugging mechanism hinders the process. Users can call new codes only at predefined points within the BPS program, limiting customization options. Despite some attempts within the simulation community to develop and employ user-customized codes, few efforts have been made to rigorously validate this simulation approach, posing questions about its accuracy and reliability.

- **Co-simulation**

Co-simulation, a dynamic simulation methodology, facilitates the simultaneous simulation of distinct components through various tools, enabling the exchange of information within an integrated routine. This approach transforms the landscape of BPS, allowing for an integrated execution of modules developed in diverse programming languages or on separate physical computers. The co-simulation paradigm is gaining prominence as a robust and interoperable method for simulating OPA with increasing adoption by key BPS programs such as EnergyPlus and ESP-r. [22], [35] Implementing occupant models in BPS through co-simulation involves a dynamic exchange of information. The occupancy Simulator is restricted to occupant behaviour from the OPA domain, while two main approaches exist in the literature for co-simulation of further actions: the occupant behaviour Functional Mockup Unit (obFMU) [37] building on data defined in a format of obXML schema [4], [17], [22], [38] and the use of a Building Control Virtual Test Bed (BCVTB) [39]. These approaches are further detailed:

- ***Occupancy Simulator***

The Occupancy Simulator, characterized by its agent-based approach, serves as a sophisticated web-based application designed to simulate the presence and movement of occupants within a building environment. Developed as a tool with broad applicability, this simulator employs stochastic models, particularly a Markov chain model, to capture the spatial and temporal diversity of occupant behaviour. It generates hourly or sub-hourly occupant schedules, presented in CSV and EnergyPlus IDF formats, essential for subsequent building performance simulations. [35] By adopting an agent-based methodology, the simulator models individual occupants, attributing specific movement events and statistical space usage profiles. Notably, users have the flexibility to group occupants with similar behaviour into occupant types and spaces with similar functions into space types. Users interact with the simulator through a hierarchical input structure, defining building, space, and occupant types. The simulator produces three levels of occupancy schedules, catering to diverse application needs: whole building level, individual space level, and individual occupant level. While powerful, the simulator does have limitations, such as using the Markov chain model, which overlooks occupants' walking time between spaces, and the absence of support for personal vacations or leaves. [13]

- **obFMU**

The occupant behaviour Functional Mockup Unit (obFMU) stands as a pivotal innovation in the landscape of occupant behaviour simulation, serving as the key player for co-simulation with Building Energy Modeling (BEM) programs. [22], [35] A core attribute of obFMU is its utilization of the Functional Mockup Interface (FMI), offering users unparalleled flexibility by enabling co-simulation with all building simulation programs implementing the FMI standard. This liberates users from being tethered to a specific tool, fostering an environment of choice and adaptability. Beyond this, obFMU operates as the powerhouse for simulating occupants' behaviours, intricately co-simulating via FMI with various simulation tools such as EnergyPlus. The underlying objective of obFMU is to meticulously replicate occupants' behaviours at each time step, guided by the occupant behaviour description file in XML format and the environmental conditions obtained through the co-simulation interface. The symbiotic relationship with the obXML schema enhances its prowess by standardizing the representation of occupant behaviour, enabling seamless information exchange. This modular software component, represented in the form of Functional Mockup Units (FMUs), supports a myriad of occupant behaviour models, ranging from lighting control to HVAC system adjustments, enhancing the granularity of occupant behaviour modelling. The efficacy of obFMU is underscored by its successful application in conjunction with renowned BEM programs like EnergyPlus and ESP-r, attesting to its capacity to refine the modelling landscape for occupant behaviour.

- **obXML**

This method supports data reading in a standardized XML format through a newly introduced schema, titled 'occupant behaviour XML' (obXML). OB functional mock-up unit (obFMU) is exemplified, showcasing its usability for co-simulation in both EnergyPlus and ESP-r. [35]

The occupant behaviour XML (obXML) schema emerges as a pioneering solution, seamlessly translating the theoretical Drivers, Needs, Actions, and Systems (DNAS) framework into an eXtensible Markup Language (XML) schema named 'occupant behaviour XML.' The elegance of obXML lies in its ability to not only capture the theoretical underpinnings of occupant behaviour but also to provide a standardized conduit for relationships between various drivers and resulting actions. A hallmark feature is its versatility, tailored to encapsulate both current and future occupant behaviour, building energy dynamics, and system models harmoniously and consistently. Utilized extensively in BPS programs, obXML proves to be a pivotal tool for implementing the DNAS framework practically. [22], [35], [40] By fostering interoperability with BPS tools and offering a flexible schema, obXML facilitates end-users in comprehending and applying occupant behaviour models effectively. This interoperability further fuels the development of occupant information modelling by providing a seamless connection between OB models and building energy modelling programs.

- **BVCTB**

The Building Controls Virtual Test Bed (BCVTB) [39] is a software tool, catering to advanced users seeking a sophisticated platform for the coupling of diverse simulation programs. BCVTB operates on a standalone interface (Ptolemy II) to host specific programs. [39] BCVTB serves as a nexus for user-implemented occupant behaviour models, fostering a dynamic connection between MATLAB, Simulink, Modelica, Ptolemy, or user-custom programs and EnergyPlus during runtime. [23], [41] The interconnectivity achieved through BCVTB is instrumental for exchanging data in real-time as the simulation progresses, offering a comprehensive environment for building performance analysis. Its adaptability to various simulation programs positions BCVTB as a versatile tool for users aiming to synthesize diverse models and engage in advanced building performance simulations. The tool developed for co-simulation via BCVTB is specific to EnergyPlus and cannot be reused by other BPS programs.

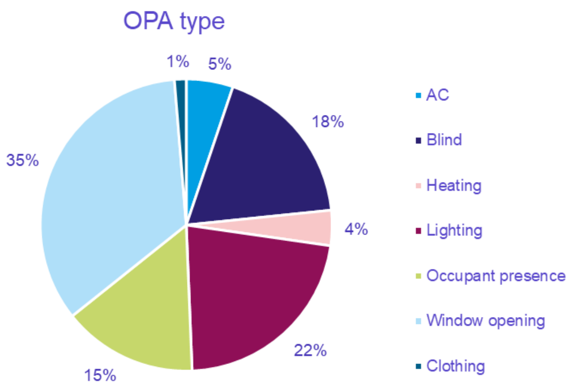
As shown through the review, several options exist for the modellers to shift from a standard steady-state or schedule-based prediction of OPA for energy performance calculations. Table 1 below offers an overview of the occupant modelling capabilities in BPS programs, distinguishing between stochastic and deterministic methods. In this table, the term "user-defined" refers to functionalities or features that allow users to create customized models, as described by [4]. The term "probabilistic control" is used to indicate the management of operation probabilities, which, in some cases, are functions of independent state variables that users can specify. In the context of simulating building occupant behaviour, "operation probabilities" denote the likelihood or probabilities associated with different aspects of occupant actions, behaviours, or events within a building environment. These probabilities help quantify the likelihood of specific occupant-related operations or scenarios occurring during the simulation.

Table 1. Simulation methods available for each OPA action in BPS tools, based on the literature. Cells where advanced OPA modelling techniques are incorporated into the tool are highlighted in pink.

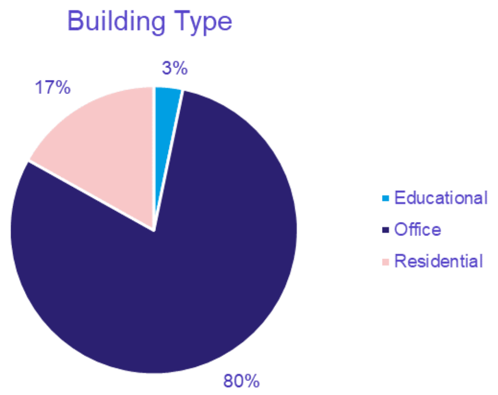
Program	Occupant Presence /Movement	Lighting Operation	Window Operation	HVAC Operation	Equipment	Shading control	Adaptation
DOE-2	User-defined, Prescribed schedules	User-defined, Prescribed schedules	User-defined, Prescribed schedules	User-defined, Prescribed schedules	User-defined, Prescribed schedules for equipment use	Probabilistic User-defined	
EnergyPlus	User-defined, Prescribed schedules	Scheduled probability, User-defined, Prescribed schedules, obFMU	User-defined, obFMU	User-defined, Prescribed schedules, obFMU	User-defined, Prescribed schedules for equipment use.	User-defined,	Dynamic clothing model and adaptive comfort model
DeST	Markov Chain, In built-stochastic OB model Prescribed schedules	Probabilistic Control, Built in-stochastic OB model	Probabilistic Control, Built in-stochastic OB model	Probabilistic Control, Built in-stochastic OB model	Prescribed schedules for equipment use		
ESP-r	Probabilistic arrival and departure, User-defined	Probabilistic Control, User-defined, built-in schedules and direct data import.	Probabilistic Control, User-defined	User-defined	User-defined, User-	User-defined, built-in schedules and direct data import for blind control	Probabilistic fan control,
IDA-ICE	User-defined	User-defined	User-defined	User-defined	User-defined	User-defined	User-defined
TRNSYS	User-defined	User-defined but cannot model daylighting	User-defined	User-defined	User-defined	User-defined	User-defined
IES-VE	User-defined	User-defined	User-defined	User-defined	User-defined	User-defined	User-defined
TRACE	Prescribed schedules		Prescribed schedules				

2.1.3. Review of OPA models available for space cooling demand prediction

In total 150 models have been found and reviewed during the literature review. The full list of the models and their characteristics is found is provided in Annex I. For each model, we have identified the OPA actions it describes, including useful information on what the triggers have been, were relevant; the building types it has been developed for, together with the geographical conditions the model has been based on. Where a model has been developed for multiple locations, these have been considered as separate entries. Also, the availability of the model in BMS tools directly, or through co-simulation has been stated. The oldest model found in the literature is from 1980, for artificial lighting control by Hunt [42]. Figure 4a) and b) and Figure 5 shows the summary of our findings.



a)



b)

Figure 4. Distribution of OPA models based on a) type of OPA actions and b) building type

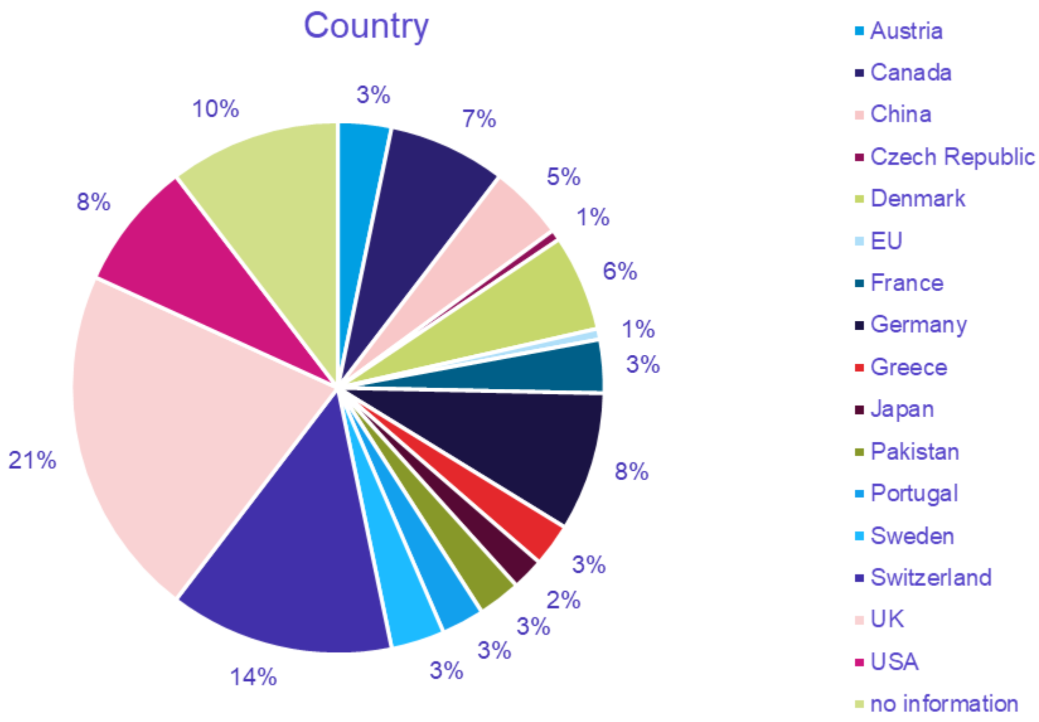


Figure 5. Distribution of OPA models based on the country origin of the data

For the building functions, a similar tendency was seen as stated for empirical studies on OB, that office and residential buildings are in the focus, while a low number of studies are dedicated to commercial and educational buildings. Figure 4b) However, while exhibitions, recreational and healthcare facilities, do have some scarce data on describing behaviour [43], these have not yet been implemented in OPA models.

The models found typically do not address different types of the years, the majority of the models are based on a limited time of the year, not addressing summer conditions particularly. The literature found shows territorial imbalance. Figure 5) While not all papers included data on the location where the data for models had been collected, of the models where this information was disclosed, 73% were based on European data, while 23 were from North America and 14 from Asia (China, Japan, Pakistan). It can be concluded that the majority of the models have been developed for European countries that do not have the highest space cooling loads (e.g. Switzerland, UK, Germany, etc.).

Window opening is the OPA described by the highest number of papers, while for air-conditioning use (AC) only a limited number of models exist, mainly for China. Figure 4a)

As a standard approach, incorporating OPA models that are not based on simple rule-based algorithms needs custom coding to be applied in the simulation environments, however, more than 50% of the models have already been standardized using a so-called, 'occupant behaviour XML' (obXML) language, that can be integrated into the building simulation workflow through the occupant behaviour Functional Mockup Unit (obFMU).

Models typically address only one OPA action. However, some examples where more than one aspect is covered has been found, for example, the Lightswitch-2002 algorithm [44] that incorporates lighting control together with shading control. However. incorporating a sequence of actions or controlling multiple variables on a common logic is not widespread.

Within the domain of urban energy modelling, ready-to-use behavioural models have not been identified through the literature review. The models generated when implementing OPA that are not standard-based are custom generated through data-driven approaches, mainly addressing occupant presence, or occupant presence and activity type, that is then used for prediction of electrical energy use.

2.1.4. Conclusions

As seen in the previous sub-sections, applying conventional models based on fixed schedules coming from standards for occupant behaviour is still the most widespread technique for predicting summer thermal comfort and space cooling energy demand. While these conventional models exhibit consistency and simplicity, they are not without drawbacks, including:

- Limited recognition of two-way interactions between occupants and buildings.
- Deterministic nature, assuming uniform occupant behaviour for given circumstances.
- Separation of occupant-related domains without considering interdependencies.
- Coarseness and abstraction, neglecting the impact of building design on behaviour.

In addressing the recognized limitations of traditional models, which fail to provide a realistic depiction of temporal fluctuations in occupancy-related processes and events, the literature underscores the necessity for innovative approaches. Consequently, more advanced dynamic models employing stochastic algorithms (e.g., Parys et al. [21]) and agent-based representations (e.g., Langevin et al. [45]; Chen et al. [46]) are increasingly employed within the building performance simulation community [17].

Nevertheless, while authors have shown that space cooling energy demand is affected by changing the OB model applied, this cannot be associated with the modelling method alone. One study using personas reported a change in energy use in the range of -12% to +10% compared to the standard assumptions. [34] For another example, Chen et al [47] analysed different window-opening OPA models including fixed schedules and stochastic models and received a wide range of results both negative and positive. However, models were not validated to see which model gives more realistic assumptions. Tahmasebi et al [48] however found that deploying a stochastic occupants' presence model, where input data are solely based on average occupancy profiles coming from standards, does not have a noticeable impact on the annual and peak heating and cooling demand evaluations, compared to using the same standard in a deterministic way.

Hence, while there is an effect of the applied models on the results, it cannot be stated whether applying a certain type of model, without changing the initial assumptions on how occupants behave, would lead to more precise energy predictions. As also William O'Brien et al. conclude, that the prediction of a particular behaviour accurately is difficult. However, the prediction of long-term trends is feasible but is subject to defining generalizable predictors and model coefficients, which still faces challenges due to the diversity of available studies and the fact that many actions are contextually sensitive or differ for personal characteristics. [23]. However, to use these, a lot of work is still to gather specific information and data, especially in the field of space cooling.

Based on the gathered information, in the next chapter, guidelines are developed on how the state-of-the-art OPA modelling approaches can be integrated into the design process, to reduce the performance gap, in the context of sustainable space cooling.

2.2. Guidelines for the integration of the OPA in the design process

As seen in the previous section, occupant behaviour is a complex issue, consisting of a complex, stochastic, diverse, and interdisciplinary nature. The current practices of taking into account OPA in the building life cycle are generally oversimplified, due to the lack of appropriate methodologies. To be able to quantify the impacts of occupant behaviour during the design, new approaches needed to be implemented, or developed. As Hong et al summarize [49], to achieve the goal of low or net-zero-energy buildings, it is crucial to understand occupant behaviour comprehensively, by:

- integrating qualitative approaches and data- and model-driven quantitative approaches,
- employing appropriate tools to guide the design and operation of low-energy residential and commercial buildings that integrate technological and human dimensions.

In the current chapter, we give recommendations on how OPA should be taken into account during the design process, based on the available state-of-the-art modelling techniques, with a focus on summer thermal comfort and sustainable space cooling.

The consideration of behaviour in building energy use during the building lifecycle (design, operation, and retrofit of buildings) has been studied in multiple dimensions, and summarized by Hong et al. [49] Figure 6)

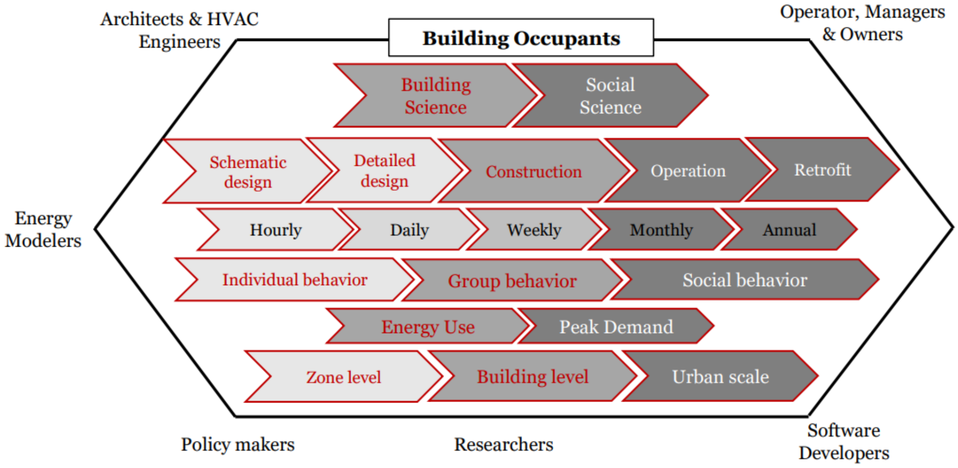


Figure 6. Spatial, temporal, and contextual fields of application of the behaviour research and stakeholders[49]

Souza et al [50] differentiated the building-occupant interactions as i) Effects on occupants within the building, ii) Occupants' interaction with the building, iii) Occupants' interaction with the environment of the wider site, through the building, and provided a list of possible decisions related to construction entities and built spaces and related to construction elements and construction properties. Their generic tables show overarching targets, constraints and requirements, procurement routes, and project management approach, and illustrate how design decisions related to the building, its spaces, and its elements can affect occupants. They highlight that "*the integration of occupant behaviour in design decisions is a non-trivial proposition and can be heavily context-dependent, requiring concerted decisions across different disciplines to address intangible and unquantifiable objectives*."

In the current section, we concentrate on how to incorporate occupant behaviour actions in the design process, to reduce the performance gap. Computational modelling and simulations are state-of-the-art methodologies to compare and predict the energy use of buildings. However, a multitude of studies have evidenced that a performance gap exists between the predicted and actual energy use, partially associated with occupant behaviour and actions [8]. The performance gap is typically attributed to uncertainty in design assumptions, causes rooted in the construction and handover, and predictions that mismatch post-occupancy conditions.[51] Inaccurate prediction of occupants in the building can also lead to poor design decisions and oversizing or under-sizing equipment. [23] Additionally, energy-intensive occupant behaviour can turn a building that is intended to be energy efficient into a building that performs worse than a conventional building [52], also known as the rebound effect. The performance gap tends to be even larger for high-performance buildings, as with stricter requirements the energy flows through the envelope become relatively lower, and occupant's control over the building systems and equipment, including windows and blinds becomes relatively higher.

The Integrated Design Process (IDP) is a holistic approach to high-performance building design and construction. It relies upon every member of the project team sharing a vision of sustainability and working collaboratively to implement sustainability goals at appropriate phases during the project. Effective integrated design leverages synergies among building components, resulting in reduced life cycle costs of the project. For sustainable space cooling, a particular type of IDP can be applied, that is focused on the energy domain, defined as the Integrated Energy Design (IED) method. The IED process was described, tested, and developed with the research Centre for Zero Emission Buildings [53]

In the CoolLIFE project SC is considered both from the perspective of technologies and measures, including interventions on the levels of buildings, neighbourhood, and urban planning. Hence, guidelines have been developed for both the building scale and the neighbourhood/urban planning scale.

2.2.1. Building scale

The performance of a building is influenced by its occupants, while the design, construction, and eventual occupancy of a building also shape occupant behaviour. Building performance during use depends on how well the design accommodates occupants' needs and control, and how accurately the design team anticipates future usage. The extent to which occupants are considered in the decision-making process varies depending on how design decisions align with project targets, are negotiated among team members, and are integrated into the design process flow. [16]

Client goals largely shape the building process, particularly when the client is also the occupant, leading to alignment with occupant needs. Yet, since future occupants are often uncertain, building owners strive for flexibility to accommodate diverse tenants over time. However, if clients and occupants diverge, consulting occupants may be constrained by factors like costs.

Throughout the design process, different types of information about occupants are used, informing bespoke design elements and contractual arrangements. The conventional linear design approach poses issues, as it can result in disparities in design assumptions and, thus, in less-than-ideal or disregarded design resolutions. Normative design processes assume designers have sufficient information about building usage and are general in construction specifics. This underscores the complexity of integrating occupant behaviour into design decisions, which heavily depends on context and requires interdisciplinary collaboration to address intangible objectives.

As design progresses, decisions become more specific and detailed, aligning construction elements with interactions explored during different stages of the design process. Therefore, to integrate consideration of occupants, design teams must systematically record occupant information for easy retrieval. Occupancy-related information can be linked to objects, enabling them to carry information between the design team. As the project advances, the level of detail within these objects grows, allowing for the addition and retrieval of occupant information at various levels. This process is especially beneficial when simultaneous decisions requiring different levels of detail are needed from different team members. [16]

Integrated Design and Delivery (IDP) described in [54], [55], [56], revolutionizes building design by promoting collaboration among diverse stakeholders to achieve excellence in environmental and social aspects within budget and time constraints. It fosters a shared vision from the initial design stages through building operations, adapting to different contexts and integrating people, systems, and practices to optimize outcomes and minimize waste. Trust-based collaboration prioritizes project goals over individual interests, leading to improved decision-making, problem-solving, waste reduction, and conflict resolution. as it is concluded in the literature, continuous learning and improvement are integral to successful IDP. Unlike linear design approaches, IDP incorporates feedback mechanisms to evaluate decisions, ensuring they reflect collective knowledge, consider element interactions, and undergo optimization steps. Design optimization involves iterative processes across pre-design, concept design, and design development phases, transitioning from broad concepts to tangible outcomes through iterative feedback loops.

Based on the seven case studies explored in [57], below is a summary of the key good practices for integrating OPA aspects for sustainable space cooling at different phases of IDP:

- Incorporate occupant assumptions early

Recognize the significance of occupant assumptions in selecting Energy Conservation Measures (ECMs) and Design Parameters (DPs), as well as their impact on design outcomes. Diverse occupant assumptions can result in varied optimal solutions. To enhance design accuracy and attain optimal solutions, prioritize occupants and their assumptions during the design phase, ensuring consistency and accuracy. Employ simulation-based inquiries to analyse the influence of different occupant scenarios on design outcomes and choose optimal solutions accordingly. Additionally, assesses designs using alternative occupant scenarios to forecast building performance and guide design choices [57]. Also, as shown later in Chapter 3 during the simulation of educational buildings, the incorporation of realistic occupancy patterns, including annual occupancy patterns can have notable impacts on the predicted SC demand, which should be considered in due time.

- Establish effective communication mechanisms

Implement clear communication channels within the design team to prevent discrepancies in occupant-related assumptions. This can improve consistency and accuracy throughout the design process[57].

- Identify occupant heterogeneity

Acknowledge the varied demographics and usage behaviours of anticipated occupants, spanning single individuals, elderly residents, people with disabilities, families, students, and social workers. This diversity influences occupancy schedules, especially in shared facilities with unconventional usage patterns. Usage will heavily rely on the simultaneous motivations of diverse occupants, adding complexity to predicting building operations. Discrepancies related to OPA may stem from the increased volatility associated with exploring the correlation between gender, work schedules, and occupancy patterns, distinct from conventional norms [57], [58].

- Conduct participatory Design Process:

Engage occupants in the architectural design process through collaborative problem-solving, fostering mutual learning. This involvement provides access to specific occupancy data and enables the simulation of shared facilities, addressing uncertainties linked to unconventional occupancy patterns, particularly in commercial and co-housing models. By considering diverse occupant motivations simultaneously, participatory design enhances predictions of building operation accuracy. Effective sharing of information among design stakeholders is essential for successful occupant-centric design, which can be facilitated through early involvement to increase awareness [57].

Occupant participation, known as co-design, enhances the representation of occupants' presence and activities, narrowing performance gaps and improving energy efficiency. Raising occupants' awareness of energy-intensive behaviours is crucial for achieving efficiency. Participatory methods, while an ideal, can sometimes be hard to achieve. Towards this end insights from behavioural science can be leveraged to promote further engagement in participatory decision-making. [59]

Collecting post-occupancy data on individual occupant dynamics can enhance spatial design and energy efficiency by optimizing layouts and understanding performance gaps between design predictions and actual outcomes. Various methods, including occupant surveys, sensing infrastructure, and interviews with building stakeholders, are utilized for post-occupancy data collection.

The participatory design offers a promising shift from generic standards to more specific Building Energy Modelling (BEM), serving as a valuable research method to explore occupancy factors and potentially develop more inclusive standards in the field. Integration of participatory design into standard simulation methodologies involves modifying data collection and preprocessing steps to generate detailed, precise occupancy schedules. As tested in case studies conducted by Tareq Abuimara et al. [57], [57], Figure 7 below clearly demonstrates the incorporation of new data collection and preprocessing steps within the framework of the standard BEM pipeline to accommodate participatory design.

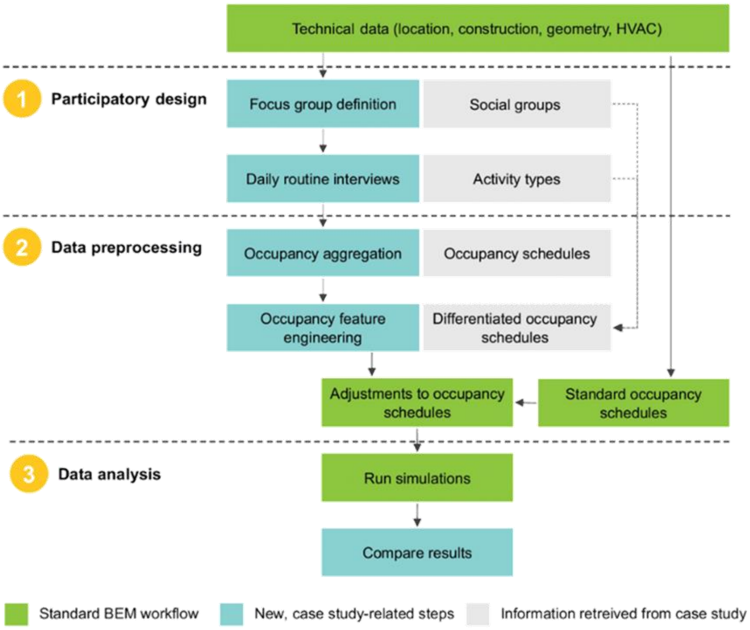


Figure 7. Incorporation of new data collection and preprocessing steps within the framework of the standard BEM pipeline [57]

- Multiple occupant behaviour profiles

Given the profound impact occupants wield on a building's energy usage, the energy performance gap arises when actual consumption diverges from initial projections. Predicting occupant behaviour accurately is challenging, prompting the recommendation for multiple behaviour profiles in energy simulations for building design. This approach aids decision-making by simulating various scenarios, such as different insulation levels or window-to-wall ratios, and observing probability distributions of energy consumption. Designers can thus consider not only average consumption but also extremes based on occupants' usage patterns of building systems [57].

- Enhancing building performance through post-occupancy spatial design optimization

Collecting data on how occupants behave in buildings can help enhance the design of spaces as buildings are used over time. Reassessing the layout of commercial buildings once they're occupied can bring new possibilities for meeting sustainability goals and ensuring buildings perform efficiently over their lifespan. For instance, as illustrated in [16], by installing energy sensors at desks, the study captured individual behaviour patterns. More varied behaviour within lighting zones was linked to increased energy use in those zones. Optimizing methods accurately forecast lighting energy use, leading to reduced consumption compared to the current layout.

In addition to gaining useful insights on the occupant behavioural patterns that can help predict energy use more precisely when conducting a Post Occupancy Evaluation (POE) where satisfaction, health and performance are linked with environmental conditions and with the technical attributes of building systems this has a potential in identifying the technologies and systems that work [60]. By this, robust solutions can be designed, which leads to avoiding the need for alterations due to inefficiently used systems.

- Continuous Improvement and Research

Strive for continuous improvement in integrating occupants and their assumptions throughout the design journey. This involves fine-tuning assumptions, exploring alternate scenarios, and revising design choices in light of fresh insights or data [57].Strive for continuous improvement in integrating occupants and their assumptions throughout the design journey. This involves fine-tuning assumptions, exploring alternate scenarios, and revising design choices in light of fresh insights or data [57].

Building on the gathered information for increasing the OPA modelling precision, Table 2 demonstrates the relevant stakeholder involvement and actions to take to maximize the incorporation of OPA aspects during each phase of the IDP process defined in the literature.

Table 2. Guidelines for OPA aspects for sustainable space cooling during the IDP process, based on [16], [54], [55], [56], [61]

Project phase	Details	OPA aspects for sustainable cooling
1 – Pre-design	At this stage, strategic definitions, vision statements, goals, and targets are formalized, incorporating client-provided lessons learned into the project brief, targets, and POE requirements. Preliminary design is initiated, along with a pre-design report featuring a charrette synopsis, outlines code compliance and environmental frameworks, references standards and articulates vision statements to engage project stakeholders. Business-oriented information, lessons learned, and consultations are emphasized, alongside a preliminary budget covering IDP activities such as energy modelling, and communication pathways are established.	Gather a varied and experienced group, including additional members and stakeholders such as a representative advocating for occupants, building operators, and specialized professionals like energy engineers, who could all offer valuable contributions to the team.
2 - Schematic design	Goals and targets matrix confirmation, concept design and Facility Management (FM) plan review incorporating lessons learned, and preliminary energy analysis with simulations, alongside Schematic Design reports issuance, are undertaken. Additionally, fundamental project components are established, including preliminary systems and analysis through modelling when feasible, with design considerations for typical operation and space flexibility, while promoting occupants' involvement through community consultations.	Involve the core team from the previous stage along with additional members such as energy specialists, and cost consultants. Schedule important meetings like design charrettes and workshops to generate ideas, develop concepts, assess strategies, and refine options. Ensure that all disciplines grasp the functional program requirements and their implications. Lay a solid groundwork by understanding the challenges and opportunities of the site, that can help achieve or hinder sustainable space cooling solutions. Assumptions regarding occupants play a significant role in design parametric analysis. Varied assumptions about

Project phase	Details	OPA aspects for sustainable cooling
		occupants can result in different estimated savings potential for Energy Conservation Measures (ECM) or Design Parameters (DP). Moreover, these assumptions can impact the outcomes of design optimization processes. It's important to verify whether the existing comfort metrics are suitable for the building's function and occupant type, or if there's a need to develop/implement new occupant-centric output metrics. While not mandatory, designers should consider implementation if necessary. Evaluate the feasibility and energy impact of various technologies and measures. Incorporate occupant-related factors as primary design inputs, going beyond codes and standards. This involves considering diverse occupant profiles and preferences. Determine the model complexity of influential OB aspects.
3 - Design development	Spatial coordination involves testing performance requirements through consultations with the design team, Facility Management (FM) personnel, occupants, and contractors, coordinating spatial information, accordingly, establishing a plan of use protocol, and developing a Post-Occupancy Evaluation (POE) for procurement. Technical knowledge and information are integrated to refine the design, involving consultants and specialists through simulations. The Design Development report encompasses Integrated Design Process (IDP) issues, including energy simulation results, while the outline specification incorporates embedded performance criteria. Additionally, updated roles and responsibilities matrix and goals matrix are provided.	In this phase, additional specialists like commissioning agents and external experts, will confirm that sustainable space cooling solutions are designed to achieve the intended performance. Lay a groundwork to evaluate the feasibility and effectiveness of sustainable cooling strategies or technologies. Utilize simulation tools, such as energy models, to assess building performance across various factors like daylighting, and other aspects that contribute to or compromise the focus of summer thermal comfort and space cooling. Incorporate occupant behaviour modelling into the design process, allowing for visualization of performance variations due to different behaviours. Implement a "fit-for-purpose" approach, tailoring the complexity of models to the specific simulation goals. Integrate dynamic building simulation models and feedback loops to account for context-dependent human behaviour, including fluctuations in occupancy. Optimize design through iterative loops that enhance collaboration between disciplines. Hold smaller, focused meetings to address specific issues.
4 - Construction documentation	Creating project specifications with embedded technical details and performance criteria, refining the energy model to reflect final design decisions and ensuring controls for the immediate environment, while developing Post-Occupancy Evaluation (POE) plans to verify targets and gather lessons learned. Additionally, forming tender documents and providing an updated roles and responsibilities matrix along with an updated goals matrix.	Ensure that the detailed design incorporates design elements and controls that have been taken into account during the building energy modelling. Revise models if necessary. Involve the occupant representatives in design reviews and gather their feedback.

Project phase	Details	OPA aspects for sustainable cooling
5 - Bidding, construction, and Commission	The project culminates with the compilation of record drawings, providing detailed visual documentation of the completed construction. Commissioning reports are submitted to ensure that all systems and components are functioning correctly and meeting performance standards. Operation and maintenance manuals are also provided, equipped with instructions and guidelines for ongoing upkeep, including any necessary commissioning activities to maintain optimal performance over time.	To ensure effective building management, maintenance, and operations, staff and occupants are oriented and trained accordingly. Establishing a solid foundation involves updating the design intent and incorporating specific performance criteria into contract documents to guide the implementation and evaluation of the project. Allow occupants or focus groups to test the implemented SC measures on a functional mock-up, and update the design if issues that hinder usability arise. Involve the occupant representatives in the handover process, and educate them on the use of windows, shading, and air-conditioning equipment. Develop a building user guide to be readily available for occupants to use the building as intended.
6 - Building operation	The final stages of the project involve the provision of training and education materials to ensure the effective operation and maintenance of the completed systems. Additionally, measurement and verification data are gathered to assess the performance of the installed systems against predetermined targets. Finally, the commissioning documentation is completed, providing a comprehensive record of all commissioning activities undertaken throughout the project lifecycle.	Involve additional team members such as building operators and occupants. Coordinate efforts to facilitate the exchange of knowledge among the design team, commissioning agent, building operators, and occupants. Create tools for continuous monitoring to maintain performance standards. Organize a debriefing session to disseminate lessons learned and educate staff and occupants about the building's performance and sustainable features.
7 - Post-occupancy	Following project completion, updated building documentation is provided to reflect any changes made during construction or occupancy. Building performance evaluation results are analysed to assess the effectiveness of the implemented systems and strategies. Continuous monitoring ensures ongoing performance optimization and identifies areas for improvement. A re-commissioning plan is developed to address any deviations from expected performance and to maintain optimal building operation. Additionally, an environmental management program is established to support sustainable practices and minimize environmental impact throughout the building's lifecycle.	Collaborate with building operators, occupants, and additional team members such as an acoustician and thermal comfort specialist. Establish a Building Performance Evaluation (BPE) team and allocate a budget for the evaluation process. Plan essential meetings for setting up and coordinating the BPE activities. Ensure that monitoring equipment is installed to track building performance effectively. Potentially moving towards a transition where occupant behaviour models are gradually replaced by real operational data, update the simulations to verify building performance and identify potential performance gaps. In specific cases, convert the building performance simulation model into a digital twin, reflecting the building's momentary, actual performance. During the occupancy and operation phases, comprehensive team meetings are held to facilitate the smooth transition, educate users, and conduct periodic evaluations of building performance through post-occupancy assessments.

2.2.2. Neighbourhood scale

While the guidance on building scale in the previous section contains general notions that are also applicable to any development project, a particular application of the IPD and IED process framework has been developed in the syn.ikia project [62], which has extended the scope to integrated energy design process at neighbourhood scale (IED^N) by taking the building level process as a baseline, to support achieving sustainable plus energy neighbourhoods. As authors conclude: *"When working at a neighbourhood scale, the integrated energy design processes will consider not only quantitative parameters related to the environmental and energy performance of buildings in the neighbourhood but also qualitative variables related to social environment or economic framework".* Thus, on the neighbourhood scale, the incorporation of further, socially or economically influenced OPA aspects and patterns might need to be incorporated in the design process. Taking the 7-step framework of the IED^N as a baseline, the integration of OPA in this process can be suggested as detailed in Table 3.

Table 3. OPA guidelines for the IED^N process. The IED^N process steps and details are based on the syn.ika project [62]

Step	Details	OPA aspect for sustainable cooling
Step 1. IED^N design team	Involve a multi-disciplinary team that is skilled in energy/environmental issues	Include also social or behavioural scientists in the team who help in identifying the project-specific OPA patterns and aspects and set-up data-collection or surveying if needed
Step 2. Boundary conditions and ambitions	Define stakeholders and their needs	Involve occupants of existing buildings or future users if known. Identify occupant needs and barriers that might hinder the implementation of preferred occupant behaviour.
Step 3. Quality assurance.	Make a quality assurance program and a quality control plan for follow-ups throughout the project phases	Incorporate metrics that help achieve or showcase the preferred occupant behaviour (e.g. number or operable windows per m^2)
Step 4. IED^N kick-off workshop.	Arrange a kick-off workshop to make sure that all stakeholders and team members have a common understanding of the project and its goals	Identify occupant needs and barriers that might hinder the implementation of preferred OPA, and identify possible solutions to overcome these
Step 5. Design team workshops, methods and tools used.	Facilitate close cooperation between stakeholders and members of the design team	Include the social and behavioural scientists and occupant representatives during this. Incorporate occupant behaviour assumptions in the energy quantification

Step	Details	OPA aspect for sustainable cooling
	Apply appropriate methods and tools for continuous performance prediction and evaluation of design options.	
Step 6. Document QA	Update the Quality Control Plan and document the energy and environmental performance at critical points (milestones) during the design.	Check whether occupant needs can be met during the process
Step 7. Contracting	Make contracts that encourage integrated design and construction.	Prioritize solutions where the occupant's perspective is included

In detail, the OPA should be taken into account with high emphasis in the following phases, compared to the building scale:

- Step 2. Boundary conditions and ambitions

Identify occupant needs: with the help of social and behavioural scientists, data should be collected on the actual or possible users of the neighbourhood. As outlined in *D3.1 Knowledgebase of occupant-centric space cooling* [2], different sociocultural groups will have different background knowledge, thermal expectations, and beliefs, thus will react differently when thermal comfort needs to be restored. A helpful resource in defining these characteristics for a statistically representative sample on a national level is the CoolLIFE Questionnaire for surveying household behaviours, published in the Annex I. of the same deliverable. The following aspects can affect the occupant behaviour and affect design goals, and should be considered throughout the development process:

- occupancy:
    - number of occupants
    - occupied periods, based on e.g. employment status, working schedule, etc.
- thermal expectations:
    - demographics: age, sex
    - cultural background
    - health conditions
- social-cultural background, habits, attitudes and beliefs
    - attitude towards using sustainable cooling solutions, based on traditional methods of passive space cooling, e.g. night ventilation, or energy awareness of the users
    - cognitive: ease of using new technologies or controls
- lifestyle:
    - types and usage of household equipment
    - their daily routine, activity schedules
- socioeconomics:
    - ownership
    - income

Identification of boundary conditions that enhance the implementation of a certain behavioural pattern should be taken into stock (e.g. vicinity of natural areas which provide better microclimate), and also barriers that might hinder the implementation of occupant behavioural actions to implement sustainable space cooling solutions. These for example are noise, pollution, and heat island effects that will hinder window opening as a passive measure. Evaluation of these inherent to the project also should be considered.

- Step 5. Design team workshops, methods and tools used

During energy performance analysis taking into account the climatic context and regulatory framework of the given project is inevitable. These have a high effect on energy use and also influence the possibilities regarding the implementation of passive measures and the maximum operative temperatures needed to be achieved. However, to implement the aspect of the occupant the following is suggested:

- Scenario analysis:
  - in addition to using standard values for energy prediction, implement also different scenarios using more realistic occupancy and occupant behaviour profiles or models,
  - if occupants are known use the data collected, however, where not known different personas can be used, e.g. active or passive, or based on different household compositions,
  - The diversity in the occupants of the different functional units is suggested to be considered by using stochastic user behaviour profiles where available,
  - identify factors that influence space cooling through sensitivity analysis,
  - take into account the specific needs for the temperature setpoints and other design variables, e.g. thermal comfort expectations of occupants with special needs (Children, elderly, etc.),
  - implement different future scenarios and quantify the robustness of the solutions.
- Evaluation of results:
  - analyse passive and active strategies with corresponding thermal comfort model,
  - identify synergies between the buildings with different usage patterns.

2.3. Conclusions

In the current chapter state-of-the-art methodologies and tools for OPA modelling, such as presence and movement in the buildings, and actions covering practices for thermal adaptation, interactions with windows, shading and air-conditioning devices, and other equipment, including lighting are collected. The main model types, data collection methodologies for data-driven models, and applied mathematical models to develop stochastic or rule-based OPA models, and their applicability in the energy modelling toolset were summarized. Existing OPA model where categorized based on the action they cover, the building they relate to and the country where it had been developed. While more than 150 models have been found, the use of these alone do not guarantee more specific results in energy modelling, and models are not usable instead of standardized input data. To provide realistic data usable on a large scale, data collection needs to be extended. In the final part of this section, suggestions are made to guide the participants in a design process in incorporating OPA actions to the IDP workflow.

3. Quantification of the effect of OPA on space cooling demand

The goal of this chapter is to identify how different OPA undertaken by building occupants can affect the space cooling demand of the building stock.

3.1. Methodology

The overall methodological approach has been defined as the following:

- defining typical occupant behavioural measures in residential and commercial buildings (resulting from the findings outlined in *D3.2. Analysis of behavioural interventions across Europe [3]*)
- simulation and quantification of energy performance in selected scenarios using parametric analysis in Grasshopper and EnergyPlus, and
- analysing their individual and integrated impact on energy use in buildings.

The scenarios cover different climatic conditions, building archetypes and constructions to address the heterogenous characteristics of the existing building stock throughout Europe.

Also, where the literature review contains several approaches for the formulation of a single behavioural measures, a sensitivity analysis was done for a limited number of cases considering only one climate and location, to determine the effect of the parameter selection on the results. The whole set of simulations considering different archetypes

The results are evaluated by the annual space cooling demand of the building/building space, and also through the number of discomfort hours in case of free-running non-residential buildings.

The effectiveness of a certain measure is identified by comparing the range, the mean, maximum and minimum values of the results within the domain of a certain input parameter/scenario. Also, the percentage reduction that can be achieved by a certain measure compared to the baseline is calculated and presented.

Altogether 2592 simulations were run for residential buildings and 2304 for the tertiary sector.

3.1.1. Definition of typical occupant behavioural measures in residential and non-residential buildings

In D3.2, typical occupant behavioural measures have been identified in residential and commercial buildings that can influence summer thermal comfort and space cooling energy use in buildings.Table 4) These behavioural measures are commonly applied in residential and non-residential buildings, as described in Chapter 2.1 of D3.2. During the literature review of D3.2, theoretical and realistic input data had been collected on occupant presence in both the residential sector and the non-residential sector. Regional differences in occupancy patterns were identified and compared to the profiles implemented in standards and legislations.

Table 4. Occupant-dependent factors influencing SC demand

Factor	Significance of SC demand	
	What?	**How?**
Occupant presence	Internal load	Direct effect: person dissipates heat increasing SC demand Indirect effect: equipment use is higher when occupants are present
	Cooling setpoints	Higher comfort expectations when occupants are present
Equipment use	Internal load	Contributing to internal heat gains which increases SC demand
Perceived thermal comfort and adaptation	SC setpoints	Occupant actions, clothing and the possibility to control the thermal environment by passive measures affect the temperature expectations in a space leading to SC demand
	Internal load	Higher metabolic rates mean higher internal loads
Space cooling set-point preferences and schedules	SC setpoints	Lower setpoints increase SC demand Setbacks in unoccupied periods can decrease SC demand
Window opening and ventilation strategies and schedules	Cooling loads	Ventilation has a complex effect on SC demand. It can either increase or decrease SC demand, depending on the internal and external conditions
Shading types and operation schedules	Solar loads	Solar heat loads through transparent façade elements are a major contributing factor in SC demand Shading can however also increase lighting, heating energy demand

Table 5. Occupant behavioural measures to be quantified

Factor	Standard building use	Occupant behaviour measures applied
Occupant presence	Standard	Realistic
Equipment use	Standard	Reduced
Perceived thermal comfort and adaptation	Mechanically-cooled	Adaptive comfort model Fans
Space cooling set-point preferences and schedules	26°C with setback	Various, building-specific setpoints
Window opening and ventilation strategies and schedules	Mechanical ventilation	Function-specific daytime window opening Nighttime ventilation
Shading types and operation schedules	No shading	Conscious shading operation, using shading devices appropriate to the archetype definition

Based on these results, the framework for the occupant presence and action types serving as a basis for the quantification is summarized. (Table 5) The definition of each measure has been determined based on the building's functional requirements and typical patterns, and local factors, where identified, and presented separately for residential and non-residential buildings in section 3.1.4..

3.1.2. Definition of scenarios for the simulation and quantification of OPA in building energy performance

3.1.2.1. REPRESENTATIVE COUNTRIES AND CITIES SELECTION

The methodological approach was to select locations that are not only representative of different climatic conditions but also to take into account environmental and social aspects that represent the exposure of residents in the given countries to the expected rise in space cooling demand due to climate change. During the selection process, a scoring methodology was developed, and for each criterion, a weighted factor was assigned. Based on a discussion with project partners we assessed a weighting factor for each indicator. Priority was given to climate change and space cooling indicators.

According to the European Environment Agency, in 2050 Europe [63] will be characterized by five climatic regions:

- Atlantic region
- Boreal region
- Mountain region
- Continental region (central and south-east)
- Mediterranean region

For each of those areas, a representative country and city has been selected based on several criteria affecting the present and future cooling demand. The criteria selected to define climatic areas are:

1. Climate change criteria
    a. Number of heat wave days per year [64].
    b. Increase in temperature during the warm season [65].
2. Vulnerability
    a. Vulnerability index [66].
    b. Population density [67].
    c. People age
3. Energy poverty
    a. People living in dwellings equipped with air conditioning
    b. People living in dwellings comfortably cool in summer time
    c. Arrears on utility bills
4. Space cooling
    a. Household space cooling demand

For each criterion, indicators were identified as well as reference data sources to retrieve the value of each indicator for all EU countries. The countries are then ranked based on each indicator to identify:

Using this method, it was possible to determine the ranking of European countries. Due to climate change, climatic areas are changing, moving progressively northwards. The ranking (Figure 8) shows that the most affected European countries are in the Mediterranean and Continental areas. By combining the ranking and the areas identified by agency European Environment Agency, it was possible to identify the country for each most critical climate area.

Table 6. Indicators applied to countries' ranking definition, weighting factors applied to each indicator and reference data sources for the assessment of selected indicators in EU countries

Category	Indicator	EU	Weighting factor	Reference
Climate change	Number of heat waves days per year	[-]	1	2050 projections, RCP4.5 https://cds.climate.copernicus.eu/cdsapp#!/software/app-health-heat-waves-projections?tab=app
	Increase in temperature (warm season)	[°C]	1	2050 projections https://doi.org/10.1371/journal.pone.0224120 ; https://hooge104.shinyapps.io/future_cities_app/
Vulnerability	Vulnerability index	[-]	0.5	2023 projections https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk/Risk-Facts-Figures
	Population density	[pers/km2]	0.5	Data from 2021 https://ec.europa.eu/eurostat/cache/digpub/demography/bloc-1a.html?lang=en
	People age	[year]	0.5	data from 2021 https://www.istat.it/demografiadelleuropa/bloc-1c.html?lang=en
Energy poverty	Pop. Liv. dwelling equipped with air conditioning	[%]	0.3	data from 2007 - reporting highest % https://energy-poverty.ec.europa.eu/observing-energy-poverty/national-indicators_en
	Pop. Liv. dwellings comfortably cool in summer time	[%]	0.3	data from 2012 - reporting lowest % https://energy-poverty.ec.europa.eu/observing-energy-poverty/national-indicators_en
	Arrears on utility bills		0.3	data from 2021 https://energy-poverty.ec.europa.eu/observing-energy-poverty/national-indicators_en
Space Cooling	Household space cooling demand	[GWh]	0.8	data from 2018 https://energyatlas.eurac.edu/

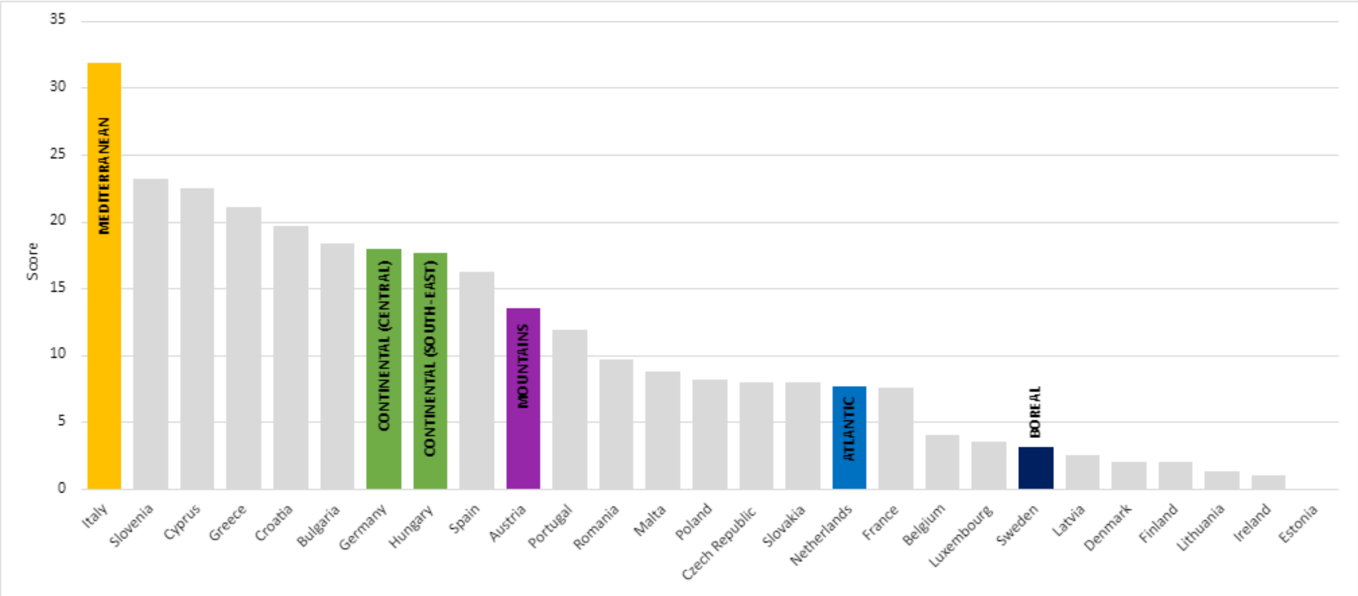


Figure 8. Country ranking from most affected to less affected countries to increase of cooling demand risk.

The identified representative countries and cities are listed in Table 7.

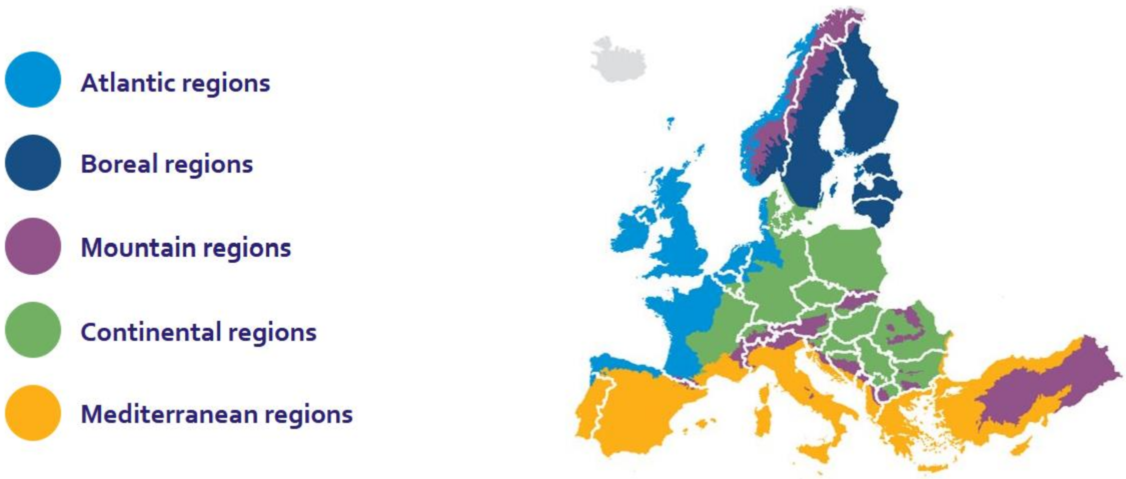


Figure 9. Map of climatic areas considered

Table 7. The identified representative countries and cities in residential buildings

Climatic area	Country	City
Atlantic region	Netherlands	Amsterdam
Boreal region	Sweden	Stockholm
Mountain region	Austria	Innsbruck
Continental region (central)	Germany	Berlin
Continental region (south-east)	Hungary	Budapest
Mediterranean region	Italy	Milan

Meteonorm 8 was used to generate future weather datasets for each representative country. A medium emission scenario is considered (RCP4.5). The time scenarios considered in the simulations are 2020, 2050 and 2080.

For non-residential buildings, the analysis has been limited to three cities that represent different climatic zones from the six identified countries for residential building archetypes. Table 8) Regarding the weather scenarios, the same methodology was applied for selecting the current and future years of 2020, 2050 and 2080.

Table 8. The identified representative countries and cities in non-residential building

Climatic area	Country	City
Boreal region	Sweden	Stockholm
Continental region (south-east)	Hungary	Budapest
Mediterranean region	Italy	Milan

3.1.3. Building archetypes definition

3.1.3.1. RESIDENTIAL BUILDINGS

To cover the residential sector, energy simulations were carried out considering Single Family Houses (SFH), Multi Family Houses (MFH) and Apartment Blocks (AB).

- Residential building archetypes (both MFH and SFH) were defined according to the paper of Dipasquale et al [68]. Shape is the same but building plan dimensions were adapted according to project requirements ($100m^2$ area).

The geometry remains fixed for all the simulated countries.

- ***Multi Family House:***
  - *Three story building*
  - *Building archetype dimensions: 13.5 x 7 x 8.10 m*
  - *Three thermal zones (one per each floor)*
  - *Shading system changes according to the country's specificities*
- ***Single Family House:***
  - *Two story building*
  - *Building archetype dimensions: 8 x 6.5 x 5.4 m*
  - *Three thermal zones (two floors + non-heated volume below the tilted roof)*
- ***Apartment building:***
  - *5 story building*
  - *Building archetype dimensions: 17 x 7 x 8.10 m*
  - *5 thermal zones (one per each floor)*
  - *Shading system changes according to the country's specificities.*

Occupant density is assumed to be 24 m^2/pers.

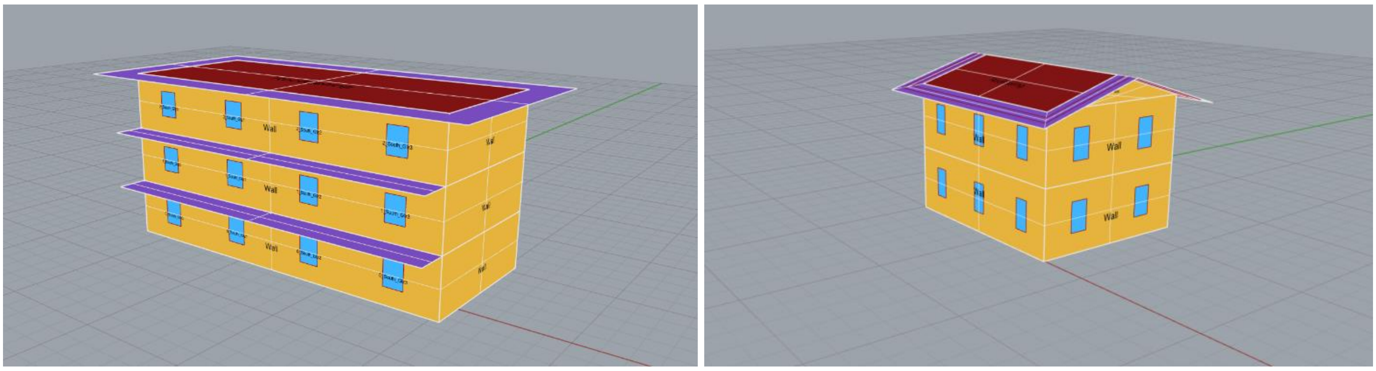


Figure 10. Archetype definition of MFH and SFH in EnergyPlus

Two building orientations are considered to evaluate the impact of building orientation on solar gain control:

- *North-south orientation (longer building axis oriented east-west)*
- *East-west orientation (longer building axis oriented south-north)*

Table 9. WWR in different orientations in different archetypes

	Window to wall ratio (WWR)			
Archetype	**North-faced**	**East-faced**	**North-faced**	**West-faced**
SFH	10%	10%	10%	10%
MFH	10%	-	10%	-
OB	10%	-	10%	-

Three opaque and transparent construction systems for each country were defined representing three renovation levels (Table 11):

- *Existing state*
- *Usual refurbishment*
- *Advanced refurbishment*

Table 10. Residential building envelope

		Opaque envelope U-value [W/m²K]		
	Envelope component	**Existing state**	**Usual refurbishment**	**Advanced refurbishment**
Austria	Roof	0.52	0.12	0.10
	External wall	1.39	0.21	0.14
	Floor	0.93	0.17	0.17
Germany	Roof	0.68	0.26	0.2
	External wall	0.85	0.21	0.12
	Floor	0.47	0.18	0.08
Hungry	Roof	0.73	0.24	0.12
	External wall	1.11	0.46	0.2
	Floor	0.62	0.27	0.17
Italy	Roof	0.93	0.25	0.2
	External wall	0.96	0.29	0.23
	Floor	0.81	0.24	0.20
Netherlands	Roof	0.77	0.21	0.13
	External wall	1.17	0.23	0.17
	Floor	1.68	0.24	0.17
Sweden	Roof	0.19	0.09	0.04
	External wall	0.72	0.23	0.08
	Floor	0.66	0.19	0.19

The thermal transmittance data of the opaque envelope were taken from Tabula Webtool [69]. Considering only thermal transmittance, the effect of thermal mass on the thermal loads is not considered, then it was necessary to model building stratigraphy.

The layers of the construction systems were coupled to reach Tabula U-values'.

Windows were modelled according to ASHRAE Handbook [70]. Thermal transmittance includes both glazing part and window's frame.

Table 11. Thermal transmittance includes both the glazing part and the window's frame

		Transparent envelope properties		
		Existing state	**Usual refurbishment**	**Advanced refurbishment**
Austria	Glazing system	Double glazing, wood frame	Low-e double glazing, vinyl frame	Low-e triple glazing, vinyl frame
	U-value [W/m² K]	2.74	1.69	1.36
	g-value [-]	0.62	0.34	0.49
	τ_{vis} [-]	0.65	0.58	0.54
Germany	Glazing system	Double glazing, vinyl frame	Low-e double glazing, vinyl frame	Low-e triple glazing, vinyl frame
	U-value [W/m² K]	3.14	1.69	1.24
	g-value [-]	0.62	0.34	0.34
	τ_{vis} [-]	0.65	0.58	0.50
Hungry	Glazing system	Low-e double glazing, wood frame	Low-e double glazing, vinyl frame	Low-e triple glazing, vinyl frame
	U-value [W/m² K]	2.74	1.69	1.24
	g-value [-]	0.62	0.34	0.34
	τ_{vis} [-]	0.65	0.58	0.50
Italy	Glazing system	Single glazing, wood frame	Low-e double glazing, wood frame	Low-e triple glazing, wood frame
	U-value [W/m² K]	4.86	2.02	1.73
	g-value [-]	0.70	0.53	0.34
	τ_{vis} [-]	0.72	0.61	0.50
Netherlands	Glazing system	Single glazing, wood frame	Low-e double glazing, vinyl frame	Low-e triple glazing, vinyl frame
	U-value [W/m² K]	5.20	1.76	1.24
	g-value [-]	0.70	0.53	0.34
	τ_{vis} [-]	0.72	0.61	0.50
Sweden	Glazing system	Low-e double glazing, vinyl frame	Low-e triple glazing, vinyl frame	Low-e quadruple glazing, vinyl frame
	U-value [W/m² K]	2.27	1.24	1.16
	g-value [-]	0.53	0.34	0.34
	τ_{vis} [-]	0.61	0.50	0.50

Each of the three refurbishment levels also corresponds to a different airtightness level. Advanced refurbishment airtightness corresponds to Passivhaus standard requirements [71]. Usual refurbishment airtightness corresponds to AECB retrofit standard [72]. We assumed the existing state airtightness as 3 ach @ 50Pa.

Table 12. Airtightness level

	Infiltration rate [ach@dP]		
	Existing state	**Usual refurbishment**	**Advanced refurbishment**
Airtightness level at 50Pa	3.0	1.5	0.6
Airtightness level at 4Pa	0.6	0.3	0.1

3.1.3.2. NON-RESIDENTIAL BUILDINGS

While national building typologies of the residential building stock exist for several European countries, e.g. the TABULA project [73] that also served as the basis of the archetype development in the current work, comprehensive information and official data for the non-residential (NR) building stock is rather limited, as diversity in terms of typology within the non-residential sector is vast. These buildings can come in many forms and can be categorized such as offices, shops, hospitals, hotels, restaurants, supermarkets, schools, universities and sports centres, and other buildings, also, typically, multiple functions exist in the same building. Some attempts have been made to develop country-specific NR building archetypes for different purposes, e.g. archetypes for German office and administration buildings for life cycle inventory analysis [74], and extensive survey of the commercial buildings stock in the Republic of Ireland [19]. The BPIE report on a country-by-country review of the energy performance of buildings [75] concludes that the distribution of building size within non-residential buildings is heterogeneous in the surveyed European countries. In the literature, it is also confirmed that the lack of data in this sector provides a challenge that all EU member states will need to overcome [19].

To overcome this challenge, for the quantification of the behavioural aspect of the space cooling demand of non-residential buildings, a synthetic building model covering the typical space uses and behaviours has been developed based on the characteristics of the specific buildings found in the literature. The input data for the model buildings created in the current evaluation is derived from the following sources:

- building stock data:
  - BPIE Europe's buildings under the microscope (2011) [75]
  - Extensive survey of the commercial buildings stock in the Republic of Ireland [76]
  - Building-Stock Aggregation through Archetype Buildings: France, Germany, Spain and the UK [77]
- case studies defining building specific geometric of functional aspects ([73], [78],[79])
- involvement in previous research projects (e.g. FP7 FASUDIR),
- energy evaluation of case studies in the framework of consulting activities.

The synthetic models consist of one floor/wing of a specific building type that is constructed of two spaces divided by a corridor. Based on the Hotmaps [80] archetype definition the following buildings were simulated:

- *offices*
- *hotels and restaurants*
- *healthcare buildings*
- *educational buildings.*

The reason for selecting the given types can be justified: occupants have the highest effect on the space cooling demand in the given functions as they can freely move around and interact with the building systems. Commercial buildings in the trade sector and other buildings have been excluded from this analysis as the internal environmental parameters are not defined by human comfort, and the occupants lack the control over their thermal environment.

The generalized synthetic model represents a section of a particular non-residential building with spaces that provide the highest freedom for occupants to adjust their environment. Geometrical and space usage data have been defined for each space separately, based on the suggested values of EN16798-1 [81] and empirical data [82], as shown in The model consists of two thermal zones oriented in two distinct directions, connected by an adiabatic zone representing a corridor. (Figure 11) Simulations have been run both facing S-N and E-W orientations.

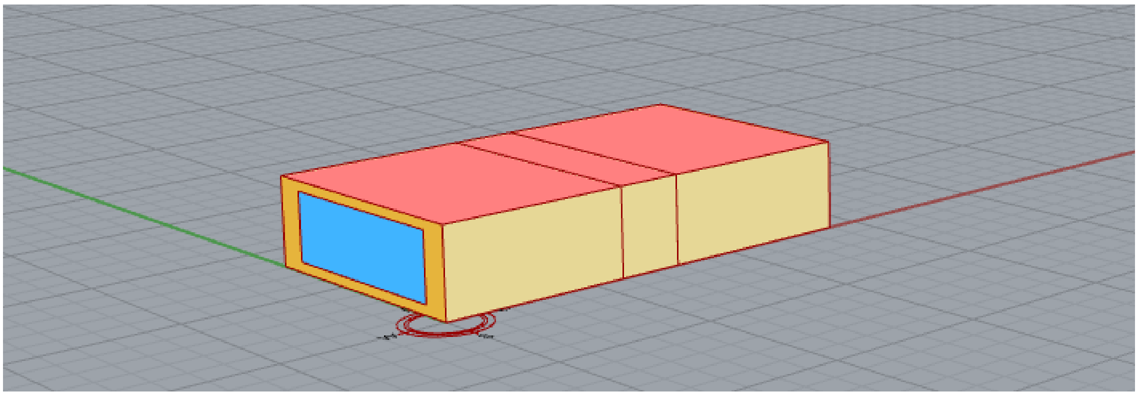


Figure 11. Visualization of a building model for non-residential buildings in EnergyPlus

Table 13. Geometrical properties of the archetype buildings

	Office	Hotel and restaurant	Healthcare	Education
Geometry (width, depth, height)	6m*8.1m*2.7m	4m*8.1m*2.7m	6m*8.1m*3m	6.8m*8.1m*3.3m
Space usage	landscaped office	hotel room	maternity hospital ward	classroom
Window-to-wall ratio	60%	30%	30%	30%
Shading type	external Venetian blind with country-specific slat angles	interior blind allowing daylight transmission	interior blind allowing daylight transmission	interior blind allowing daylight transmission

Table 14. Internal loads of the modelled archetypes

	Office	Hotel and restaurant	Healthcare	Education
Occupant density [m2/occupant]	0.0588 [81]	0.0476 [82]	0.0909 [82]	0.1852 [81]
Lighting power density [W/m2]	12 [82]	8 [82]	9 [82]	15 [82]
Equipment power density [W/m2]	12 [81]	1 [82]	4 [82]4 [82]	8 [81]

The air-tightness and building envelope U-values of the non-residential building stock according to [75] are similar to the residential stock of the same construction period. However, the retrofit level of the non-residential buildings is expected to be higher, sources confirm that the office building stock is considered to be relatively new and constant growth is seen in the renovation activities within this sector, 78% of offices and 90% of hotels have double- or triple-glazed windows [75], [76], [83]. For the non-residential buildings the opaque and transparent constructions of the external walls, and windows are modelled are aligned with the constructions used for residential buildings, but considering the information on the building stock, they are limited to the two retrofit scenarios:

- *Usual refurbishment*
- *Advanced refurbishment*

The roofs, floors and internal walls have been considered adiabatic.

Table 15. Envelope propertied of the modelled archetypes

		Italy	Sweden	Hungary
Wall construction, U-values (W/m^{2}K)	Usual refurbishment	0.32	0.1	0.29
	Advanced refurbishment	0.24	0.24	0.18
Window construction, U-values (W/m^{2}K)	Usual refurbishment	2.0	1.6	0.9
	Advanced refurbishment	1.7	1.0	0.76
Infiltration rate	Tight building m3/s/façade m^2	0.0001	0.0001	0.0001

3.1.4. Definition of OPA actions

3.1.4.1. RESIDENTIAL BUILDINGS

User lifestyles are simulated by setting different occupant behaviour profiles and indoor thermal comfort expectations, reflecting also different user attitudes towards energy-saving habits and different adaptations to heatwave events. Different occupancy profiles have been defined per each climate context reflecting realistic occupancy presence in residential buildings. These are compared with a fictive occupancy profile where building occupants are assumed to stay always at home. See par. “user lifestyles”

User lifestyles

Two daily profiles of occupancy reflecting different user lifestyles were modelled:

- ***O1 – At home:*** *it was assumed that a person spends more time at home.*
- ***O2 – Realistic:*** *it was a more realistic profiles (Figure 12)*

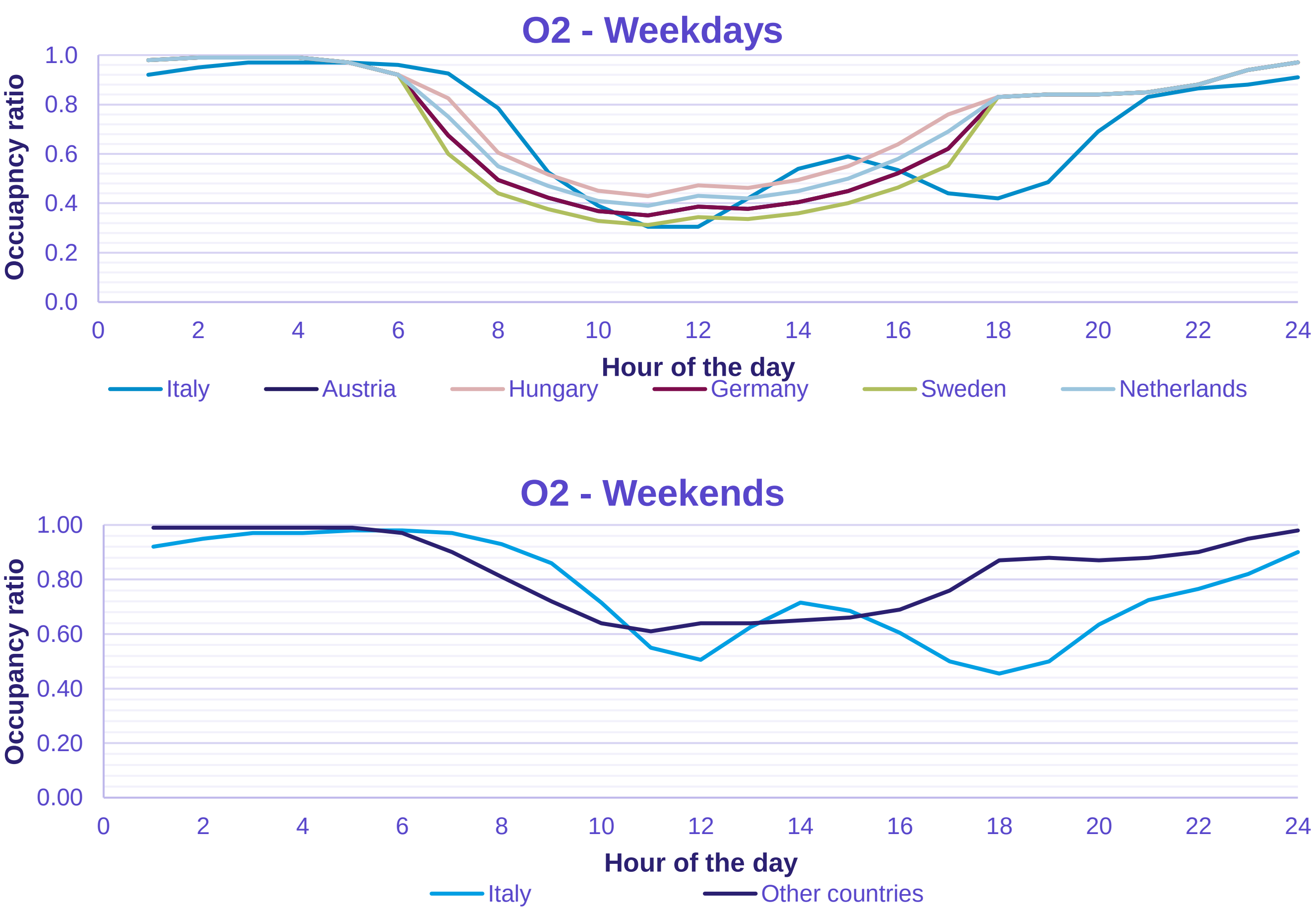


Figure 12. Realistic occupancy patterns simulated

Occupancy schedules were adapted according to people's habits in the various countries and were differentiated between weekdays and weekends/holidays. Country specific profiles were developed from the occupancy profiles published based on statistical data collected in Time use surveys (TUS) [30], [84]. In lack of data for each country, the country specific occupancy profiles had been adjusted using daily average occupancy hour data [85] for weekdays, assuming the differences are due to mainly working habits. Where no data for the exact country was found, data was based on neighbouring countries.

User behaviour scenario

Three main scenarios of user behaviour have been defined representing:

- *Baseline: unconscious behaviour scenario where users are passive and take no mitigation or adaptation measures*
- *Mitigation scenario: users are supposed to react to a discomfort condition and take action as a direct consequence of that aiming at improving indoor environment conditions*
- *Adaptation scenario: users adopt behaviour to prevent a discomfort condition or adapt to that condition.*

Table 16. Behavioural scenarios for residential buildings

User behaviour scenario	BASELINE - UNCONSCIOUS	MITIGATION	ADAPTATION
Rationale behind each scenario	unconscious behaviour	occupants react to a discomfort condition	occupants adopt behaviours to prevent a discomfort condition
Indoor temperature expectations	Indoor temperature below reference cooling setpoint (category 2 EN 16798-1)	An indoor temperature within the upper comfort temperature level of the adaptive thermal model	An indoor temperature within the upper comfort temperature level of the adaptive thermal model, night setback (h22-7) and use of smart air movement
Ventilation	Constant ventilation rate with no heat exchange or free cooling options	Daytime natural ventilation (7 am - 10 pm) when indoor temperature is above comfort level and outdoor temperature conditions are comfortable.	Daytime natural ventilation and night ventilation to prevent building overheating over the next day
Shading control	no shading system or control - just overhangs depending on the building archetype	Shading is activated if the building zone is overheated and if the solar radiation on the window is significant (higher than 400 W/m2)	Shading is activated every time the solar radiation on the window is higher than 150 W/m2 to prevent building overheating
Internal loads	lighting and appliances standard use profile from EN 16798.	lighting and appliances reduced profile assuming a lower use during the cooling season	lighting and appliances reduced profile assuming a lower use during the cooling season

For each of the three main scenarios of user behaviour, we defined mitigation and adaptation behaviours related to indoor temperature expectations, ventilation, shading control and internal loads and compared them against a baseline, presented in the following subsections.

Indoor temperature expectations

Different indoor temperature expectations are implemented in the model by using different cooling setpoints for each scenario.

Table 17. Different cooling setpoints for each scenario

BASELINE -UNCONSCIOUS	MITIGATION	ADAPTATION
Constant temperature setpoint of 26°C as reported in EN 16798-1 for comfort category 2.	Adaptive temperature setpoint according to the upper comfort temperature level of adaptive comfort model reported in EN 16798-1 for comfort category 2. in this case the upper comfort temperature level depends on the outdoor temperatures and has been calculated for each weather scenario	Adaptive temperature setpoint according to the upper comfort temperature level of adaptive comfort model reported in EN 16798-1 for comfort category 2. This setpoint is increased by 1.8 K assuming an increased air velocity within the building due to the use of fans and personal comfort systems.[86] Night temperature setback within h22:00 and h7:00.

Ventilation

Natural ventilation is modelled using the wind and stack open area model of EnergyPlus and by setting different control inputs depending on the user behaviour scenario.

Table 18. Ventilation assumptions for each scenario

BASELINE -UNCONSCIOUS	MITIGATION	ADAPTATION
Constant infiltration rate with no natural ventilation	windows are partially opened (opening factor = 0.25) during daytime (7 am - 10 pm) when: - indoor temperature is greater than 24°C, - outdoor temperature between 18°C and 30°C and the temperature difference between the zone and outdoor is at least 2K	Windows are partially opened (opening factor = 0.5): - during daytime (7 am - 10 pm) when indoor temperature is greater than 24°C, outdoor temperature between 18°C and 30°C and the temperature difference between zone and outdoor is at least 2K - during nighttime when the temperature difference is at least 4K and the outdoor temperature is between 22 and 30 °C)[87]

Shading control

Shading type and material depend on the building archetype (see par. 3.1.2)

Table 19. Shading control strategies in each scenario

BASELINE -UNCONSCIOUS	MITIGATION	ADAPTATION
no shading control, shading is assumed to be always off - just overhangs depending on the building archetype	Shading is activated if the zone temperature exceeds 24°C and if the solar radiation on the window is higher than 400 W/m^2	Shading is activated if the solar radiation on the window is higher than 150 W/m^2

Internal loads

Two daily profiles of lighting were considered:

- ***L1 (EN 16798):*** *daily profile taken by standard EN 16798.*
- ***L2 (reduced EN 16798):*** *daily profile taken by standard EN 16798 and manipulated. Fractions are reduced by 20% because, during the summer period, lighting loads are lower due to the higher amount of natural light and lower number of people indoor (vacations?)*

Lighting and electric power density are defined for each scenario based on SIA2024: 2015 Swiss standard [88], current and target value for MFH and SFH lighting power density and electric equipment power density.

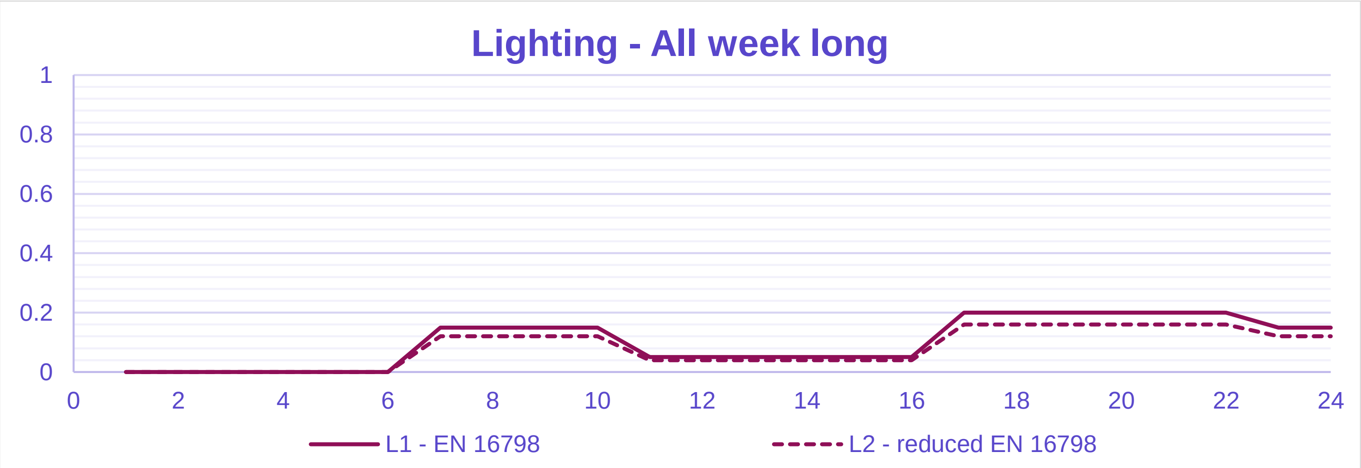


Figure 13. Lighting schedules

Two daily profiles of appliances were modelled:

- ***A1 (EN 16798):*** *daily profile taken by standard EN 16798.*
- ***A2 (reduced EN 16798):*** *daily profile taken by standard EN 16798 and manipulated. Fractions are reduced by 20% because, during the summer period, electric equipment tends to be used less (vacations?)*

- *Appliances power (expressed in W/m²) was taken by a reference standard (SWISS SIA 2024-2015) [88].*

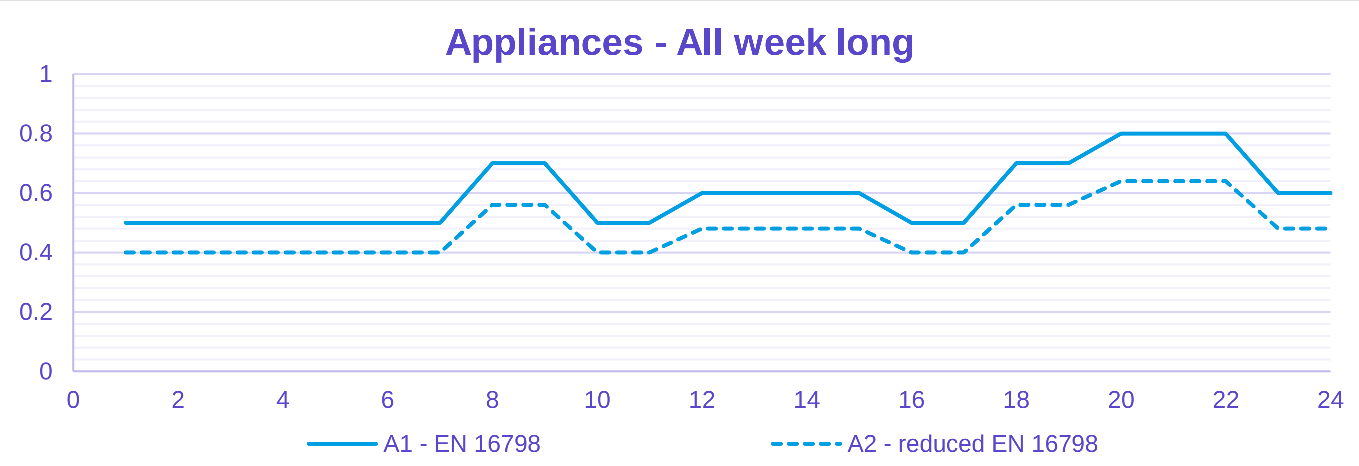


Figure 14. Appliance schedules

Table 20. Internal load in each scenario

Internal loads	BASELINE - UNCONSCIOUS	MITIGATION	ADAPTATION
Lighting use profile	L1 (EN 16798)	L2 (reduced EN 16798):	L2 (reduced EN 16798)
Lighting power density	2.7 W/m² (SWISS SIA 2024-2015 standard value for MFH and SFH)	1.7 W/m² (SWISS SIA 2024-2015 current value for MFH and SFH)	1.7 W/m² (SWISS SIA 2024-2015 target value for MFH and SFH)
Appliances use profile	A1 (EN 16798)	A2 (reduced EN 16798)	A2 (reduced EN 16798)
Electric equipment power density	10 W/m² (SWISS SIA 2024-2015 standard value for MFH and SFH)	8 W/m² (SWISS SIA 2024-2015 current value for MFH and SFH)	4 W/m² (SWISS SIA 2024-2015 target value for MFH and SFH)

3.1.4.2. NON-RESIDENTIAL BUILDINGS

The modelled occupant behaviour measures are similar to the residential building stock but are customized to the building's functional aspects and aligned with the review made in D3.2. The scenarios marked with an * have been subject to the selection process based on a sensitivity analysis.

Occupant presence

The baseline for occupant presence has been drawn from standards [81] [88], empirical data [82] and for the educational buildings, country-specific spring, autumn and summer holidays based on the literature [89] for primary schools have been implemented for each country analysed. Alternative occupancy measures based on scientific papers of case studies and empirical data were defined. For Hotels and restaurants and Healthcare, the occupant presence is hard to change, hence this was not considered as measure.

In offices, two types of alternatives were defined, the first one that implements summer holidays and a behaviour where working hours are shifted to the earlier, cooler periods of the day, and a model where employees have Friday afternoons off during the summer periods.

For educational buildings, a similar shift to the earlier hours is applied. Additionally, altering the start and end dates of the summer holidays by 1 week is explored.

Table 21. Simulation inputs for non-residential buildings for occupant presence

Occupancy	Office	Hotel and restaurant	Healthcare	Education
Baseline	OFF_O1_Baseline Landscaped office [81]	HOT_O1_Baseline Hotel room [82]	HOS_O1_Baseline Hospital [82]	EDU_O1_Baseline Classroom [81] with annual holidays implemented [89]
Occupant behavioural measures applied	OFF_O2_Reduced* 20% reduction in office presence and starting 1 hour earlier	n/a	n/a	EDU_O2_Reduced Implement 1-hour shift to an earlier start
	O3_Summer Fridays* In June, July and August occupants can leave earlier on Fridays			EDU_O3_Summer holiday shift Shifting the summer holiday 1 week later

Equipment use

Equipment use has been aligned with the occupancy profiles of the buildings. Please see Table 21 for the simulated alternatives.

Space cooling setpoints

The effect of increasing the space cooling operative temperature limit has been explored. The maximum operative temperature value of 26°C in the IEQ_{II} category, considered as the medium level of comfort expectation in the EN 16798 standard has been taken as a baseline, which is also aligned with the legislative values indicated as a minimum value of space cooling temperature setpoints for energy performance calculations in most countries where such a limit exists, outlined in D3.1. [2] In this work, we analysed the potential SC demand reduction through the implementation of different setpoints, and also, the adverse effect if higher setpoints are implemented. In the unoccupied hours, a setback is applied for office and educational buildings.

Table 22. Simulated setpoints in non-residential building archetypes

Occupancy	Office	Hotel and restaurant	Healthcare	Education
Baseline	26 °C	23 °C	25.5 °C	26 °C
Occupant behavioural measures applied	24 °C	24 °C	n/a*	24 °C
	25 °C	25 °C		25 °C
	27 °C	26 °C		
	28 °C			

For office buildings, the preferred setpoints implemented in reality are lower than the high limit of the standard. Aghniaey and Lawrence [90] found that in many cases setpoint temperatures are even lower than 24°C in the office environment, however, 24°C is deemed to be acceptable, while on the other end of the range setpoints up to 28 °C have been also applied, e.g. in the CoolBiz campaign [91]. Spain adopted in August 2022 a decree to temporarily (until November 2023) set the minimum temperature setpoint for space cooling systems in public buildings to 27°C, with the assumption that this might reduce cooling consumption by about 7% (compared to 26°C). [92]

In healthcare buildings, the setpoint adjustment is not assessed as the indoor environment needs to be maintained within a strict range. The temperature setpoint selected for the baseline even corresponds to the upper limit of the IEQ_{I} category of the EN 16798 standard, which corresponds to a higher thermal expectation level, due to the presence of occupants with special needs.

In hotel buildings, it is evidenced that occupants tend to behave differently than at home, as guests tend to prioritize convenience over energy savings. Nica et al [93] showed that the customers have different demands than at home - they want it warmer/colder than the temperature they are familiar with. The setpoints implemented in reality are lower than the higher limits suggested by the EN16798-1 standard. Torres et al suggested 21-23 °C as typical values for setpoints in the cooling season [94], while some other studies suggest values as low as 20-22 °C for guest rooms [73]. Behavioural models regarding the efficient energy-use reduction interventions in hotel buildings have also shown that the overwhelming majority of the guests (85%) have *Resistant to Change and Indifferent to Change* energy use profiles and only 15% of the hotel guests have *Prone to Change* energy-use profile, thus behaviour could only be changed through aggressive strategies/interventions and expensive incentives to hotel guests [95].

For educational buildings, the standard setpoint of 26 °C is considered as a baseline. Studies however suggest that reducing moderately high indoor temperatures from around 25°C improves the performance of tasks and also in test results [96], [97], hence lower setpoints are also evaluated.

Perceived thermal comfort and adaptation

In contradiction to residential buildings, non-residential buildings are subject to having higher requirements regarding indoor environmental conditions. Buildings are generally mechanically cooled and also ventilated, where the EN 16798 standard defines the acceptable operative temperature ranges. When spaces are not mechanically cooled and ventilated, the adaptive comfort model acknowledges adaptation to average daily temperatures by allowing higher indoor setpoints. 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). Thus this method does not apply to healthcare buildings where the occupant is limited in the freedom to use operable windows and also faces limitations in adapting their clothing to the indoor and/or outdoor thermal conditions. Also, the application of this to hotel rooms is neglected due to the different metabolic rates of sleeping. However as educational buildings are generally not mechanically cooled, the adaptive model is considered.

To allow the users to apply adaptive measures, the adaptive comfort model was modelled together with the corresponding natural ventilation behavioural measure and models evaluated in free-running mode, separately from the buildings with space cooling.

The use of fans can reduce the perceived temperatures, thus increasing the comfortable temperature range. When fans or personal systems providing occupants with personal control over airspeed at occupant level are provided, an indoor operative temperature correction is applied. These strategies can be applied to offices and educational buildings.

Table 23. Simulated Perceived thermal comfort and adaptation measures in non-residential building archetypes

Perceived thermal comfort and adaptation	Office	Hotel and restaurant	Healthcare	Education
Baseline	Adaptation through window opening	No adaptation	No adaptation	Adaptation through window opening
Occupant behavioural measures applied	Use of fans 0.6 m/s	n/a	n/a	Use of fans 0.6m/s
	Use of fans 1.2 m/s			Use of fans 1.2 m/s

Window opening and ventilation

For offices, hotels and restaurants, and healthcare buildings the simulation baseline case consists of mechanically ventilated spaces with an air change rate based on the relevant standards, applied in the occupied periods. For educational buildings natural ventilation is considered to be dominant in most countries. Natural ventilation can offer free cooling both daytime and nighttime, even in spaces with mechanical cooling. Additionally, when the space relies on natural ventilation and cooling, higher temperatures can be perceived as comfortable.

In the literature, more than 20 factors have been identified to influence window-opening behaviour. [98] Window operation behaviour shows strong correlations and environmental variables and also time-dependent events. In the simulations, the indoor temperature has been set as the trigger for acting. The literature confirmed that the probability of opening windows rises significantly above 20 °C indoor temperature, although different researchers found different correlations. [98] To quantify the sensitivity of the behaviour to this value, two thresholds have been tested for opening windows in naturally ventilated buildings.

Table 24. Simulated window opening behaviour in non-residential building archetypes

Window opening	Office	Hotel and restaurant	Healthcare	Education
Baseline	Natural ventilation, if the indoor temperature is higher than 20 °C, and the outdoor temperature is at least 2 °C lower than the indoor temperature.	Mechanical ventilation	Mechanical ventilation	Daytime natural ventilation, opening ratio: 0.125, corresponding to the limited time the windows are opened.
Occupant behavioural measures applied	Natural ventilation, if the indoor temperature is higher than 18 °C. *	Natural ventilation, if the indoor temperature is higher than 20 °C, and the outdoor temperature is at least 2 °C lower than the indoor temperature.	Natural ventilation, if the indoor temperature is higher than 20 °C, and the outdoor temperature is at least 2 °C lower than the indoor temperature. The opening ratio is 0.25	Conscious natural ventilation, if the indoor temperature is higher than 20 °C, and the outdoor temperature is at least 2 °C lower than the indoor temperature. The opening ratio is 0.25
	Night-time ventilation if the indoor temperature is higher than 20 °C.		Night-time ventilation in addition to daytime ventilation. Cooling setpoint adjusted to 28°C at night.	Night-time ventilation if the indoor temperature is higher than 20 °C.

Additionally, nighttime ventilation has also been considered as an option. In this case, 20 °C has been implemented, which is lower than the value for residential buildings. The reason for this is that in office and educational buildings there is no requirement regarding the thermal comfort at night, which allows a higher pre-cooling potential compared to residential buildings.

In hospitals, window opening proportion is lower than other commercial buildings, due to safety and security reasons, which has been taken into account in the models.[99]

For educational buildings window opening is regularly applied to maintain the indoor air quality. The literature review showed that in schools, teachers are the main actors in manipulating windows [100], and comparative studies show that there are differences in the habits of window opening [101], [102], dependent on the teacher. In the case studies, it was found that windows are more often opened during breaks than during lessons. As simulations are run with hourly timesteps only, in the baseline case, a limited opening ratio has been applied to express the temporal limitation of windows opening. As an alternative, an opening ratio is applied that represents also window opening during the lectures. As detailed above, the potential of daytime ventilation was considered separately for buildings without space cooling in offices and educational buildings, while the night-time ventilation was considered in cases with mechanical cooling as well.

Shading control

In the literature, shading was also found to be triggered by different discomfort sensations, In the baseline cases, shading had not been considered for the alternatives, different shading control patterns were defined based on the literature review done in D3.2, triggered by visual discomfort and thermal discomfort.

Table 25. Simulated shading control behaviour in non-residential building archetypes

Shading control	Office	Hotel and restaurant	Healthcare	Education
Baseline	No shading	No shading	No shading	No shading
Occupant behavioural measures applied	Shading behaviour triggered by thermal discomfort Ti>23 °C.	Shading behaviour triggered by thermal discomfort Ti>23 °C.	Shading behaviour triggered by thermal discomfort Ti>23 °C.	Shading behaviour triggered by thermal discomfort Ti>23 °C.
	Shading behaviour triggered by visual discomfort Gi>150 W/m^2 on the facade			

Shading types were defined specifically to the archetypes, as shown above in Section 3.1.3.2.

3.1.5. Methodological limitation

In the service sector, the calculations have been made for single spaces with typical space usage where occupants can control their thermal environment. Depending on the building type this accounts for approximately 65-70% for schools [103], 60-85% for hotels [104], [105], 60% of the treated area for offices [106] and even lower of hospitals [107](48%). and even lower for hospitals [107](48%).

In educational buildings thermal sensation has been evidenced to vary from what is anticipated in the standards, and studies anticipate that the current models for adults in non-residential buildings would not be suitable for estimating the thermal comfort of children [108]. Results in the literature are heterogeneous and seem to be dependent on the thermal background as well. The review by Romero et al covering studies from four Köppen-Geiger Climate zones concluded that while the neutral temperature of the students was found to be 2 °C lower than that corresponding to the adaptive comfort limits of the EN15251 and ASHRAE 55 standards, the comfort band was wider, especially when concerning the upper band. [109] Another study showed that during summer, in kindergartens in Korea, children's comfort temperature is 0.5°C lower than adults' [110], while a study for a Spanish school however showed a widening in the thermal comfort range for children compared with EN 16798–1 and the ASHRAE-55 Standard, where many higher temperatures were also perceived as comfortable [108]. However, in lack of robust methodology, the standard values are used for the sake of evaluation.

3.2. Results

3.2.1. Residential buildings

3.2.1.1. INDIVIDUAL EFFECTS OF OPA ACTIONS

The individual actions defined within the Baseline, Mitigation and Adaptation scenarios were simulated for the Italian MFH building archetype, using the climate of Milan with the scenario of 2020, and considering an active space cooling with a setpoint of 26°C. The results are presented in the current subsection individually for each OPA action.

User lifestyles - Occupant presence

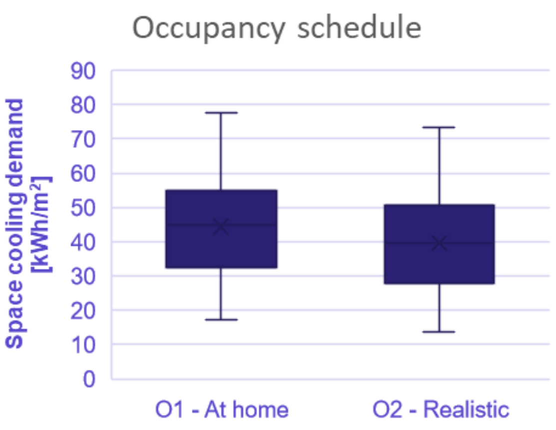


Figure 15. Effect of the change in occupancy schedule

Applying occupancy schedule based on statistical data from the Italian TUS reduced the space cooling demand of the simulated cases from an average 44.35 kWh/m^2 to 39.59 kWh/m^2.

Window opening and ventilation

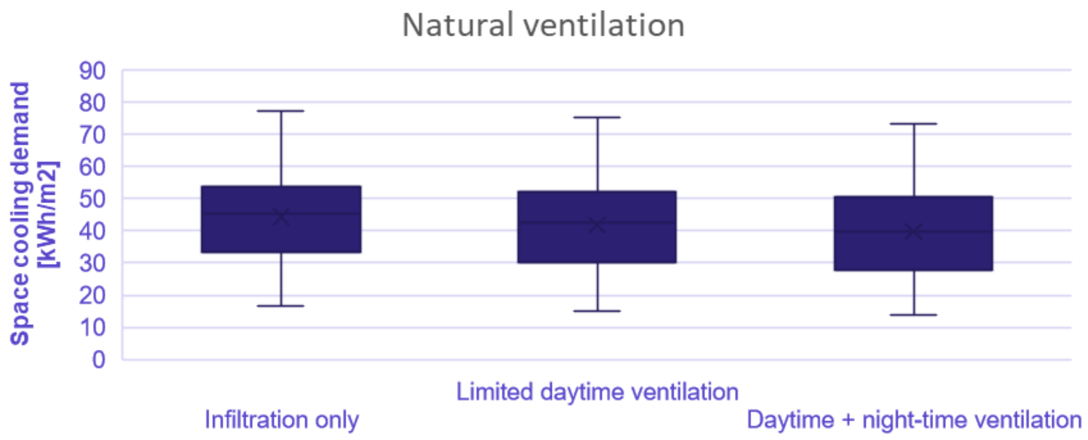


Figure 16. Effect of natural ventilation scenarios

Natural ventilation practices can reduce the space cooling demand from an average 44.4 kWh/m^2 to 41.76 kWh/m^2 and 39.75 kWh/m^2, when a daytime ventilation with limited opening fraction, and a more efficient daytime ventilation combined with night-time ventilation is modelled.

Shading control

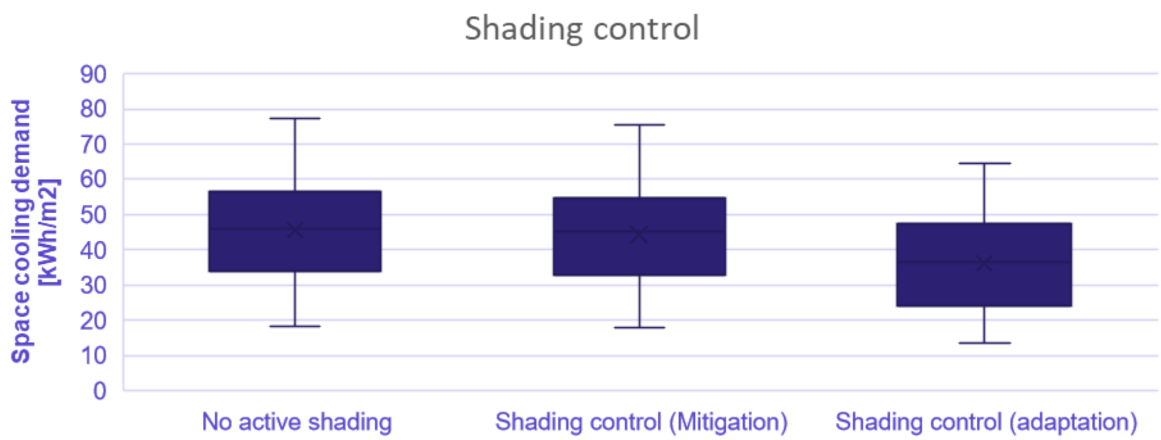


Figure 17. Effect of shading control behaviour

Compared to the baseline case, when only passive shading is considered, an implementation of shading control strategies can reduce the space cooling demand from an average 45.7 kWh/m^2 to 44.29 kWh/m^2 when shading is activated at an internal temperature of 24 °C and the solar radiation falling on the window is higher than 400W/m^2.

When a more conscious behaviour is applied, when windows are already activated at 150W/m², the average SC demand was reduced to 36.04 kWh/m².

Internal loads

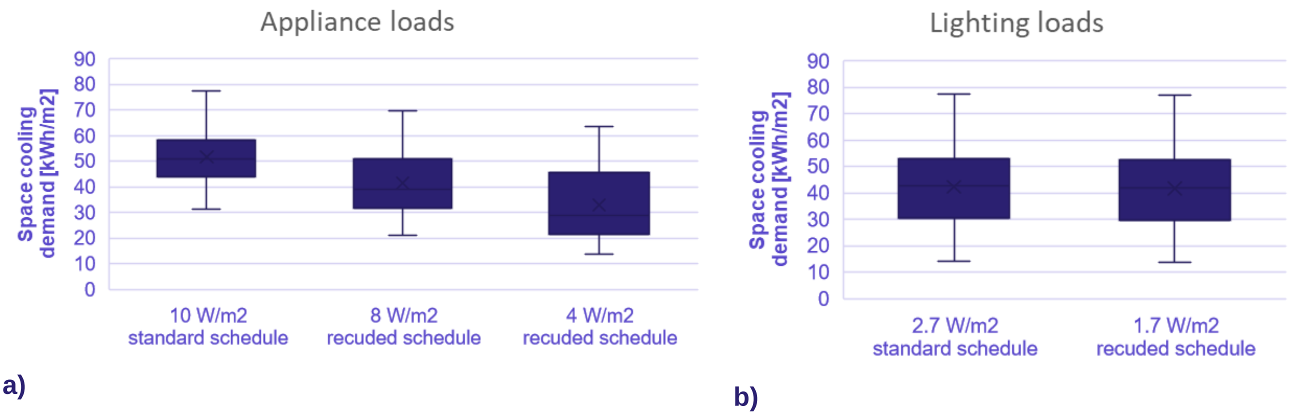


Figure 18. Effect of inputs to electrical equipment use: a) Appliance power density and schedules b) Lighting power density schedule

Electrical equipment use reduce the space cooling demand from an average 51.72 kWh/m² to 41.35 kWh/m² and 32.83 kW/m² when power density is reduced from 10 W/m² to 8 W/m² and 4 W/m² and reduced operational schedule is applied, respectively. Applying the reduced lighting schedules and power density, space cooling loads were reduced from an average of 42.2 kWh/m² to 41.69 kWh/m².

3.2.1.2. COMBINED ACTIONS

Figure 19 shows the effect of user lifestyles and user behaviour scenarios in all cases simulated, while 0 shows the mean percentage reduction of annual space cooling demand in the Mitigation and Adaptation occupant behaviour scenarios, compared to the baseline case, for all residential building archetypes.

The space cooling demand in the Milan(IT) cases is the highest, reaching up to 86,35 kWh/m2,year, followed by Budapest (HU), Innsbruck (AT), Berlin (DE), Amsterdam (NL) and Stockholm (SE), (69.32 kWh/m²,year, 86.35 kWh/m²,year, 60.18 kWh/m²,year, 54.4 kWh/m²,year, 50.62 kWh/m²,year and 51.42 kWh/m²,year respectively)

With the mitigation behaviour, the space cooling demand in the cases of Italy, Hungary, Austria, Germany could be reduced to maximum 30 kWh/m²,year, and for cases in the Netherlands and Sweden, the maximum value was below 15 and 20 kWh/m²,year, respectively.

In the adaptation scenario, the space cooling demand in all countries, climates, and cases is below 5 kWh/m², year.

When expressed as a percentage reduction (Figure 20), it is seen that in comparison to the Unconscious behavioural scenario, the Mitigation scenario can reduce space cooling demands by an average of 69-84%, while the percentage reduction of the Adaptation scenario is between 97%-100%. Also, the range of the space cooling demand covering by the different behaviours and scenarios reduced by adapting more conscious behaviours, spreading from 31-48 kWh/m² to 1-5 kW/m².

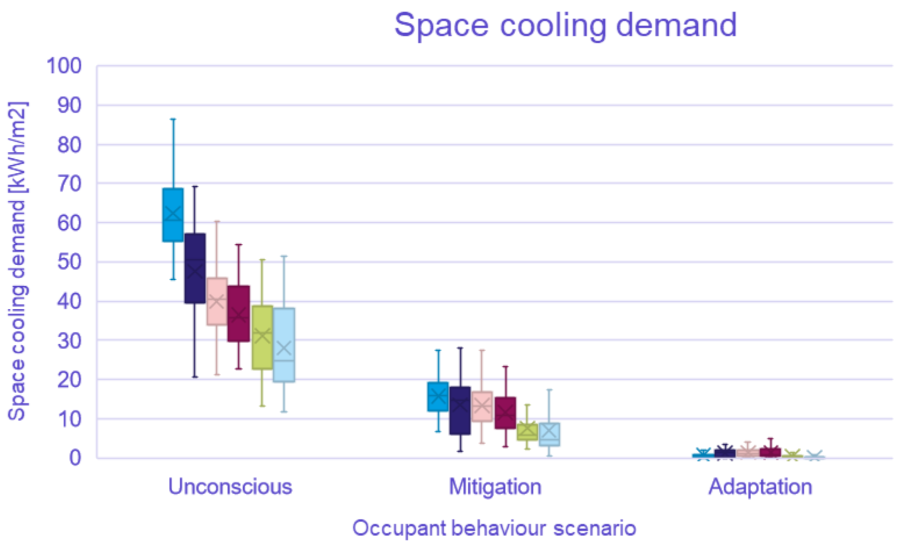


Figure 19. Effect of occupant behaviour scenarios on SC demand, considering all residential building types, for all simulated scenarios - annual SC demand of each scenario

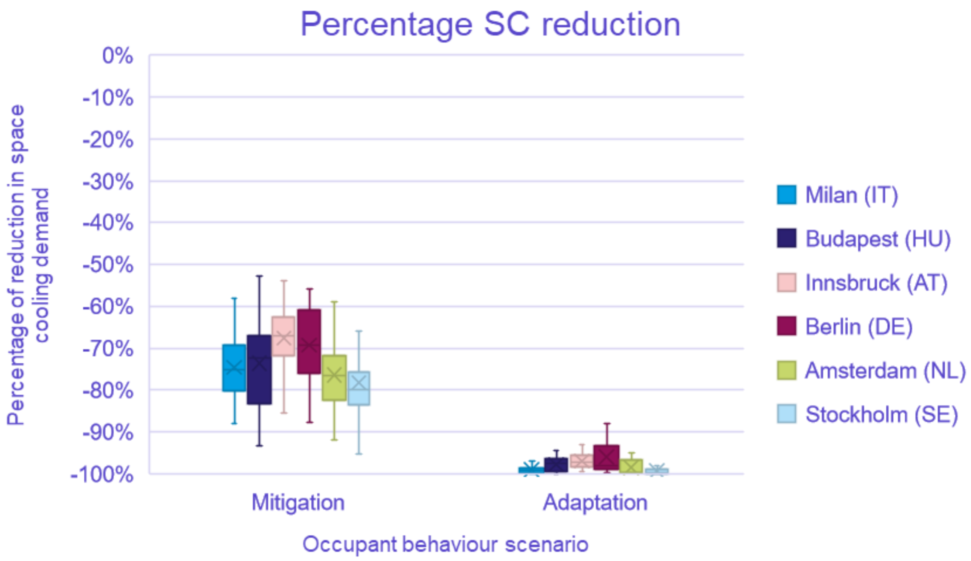


Figure 20. Effect of occupant behaviour scenarios on SC demand, considering all residential building types, for all simulated scenarios - Percentage reduction of each scenario

Table 26. Mean percentage reduction of annual space cooling demand in Mitigation and Adaptation occupant behaviour scenarios for all residential building archetypes

		Milan (IT)	Budapest (HU)	Innsbruck (AT)	Berlin (DE)	Amsterdam (NL)	Stockholm (SE)
Mitigation	Mean	-77.4%	-83.6%	-71.4%	-69.3%	-75.6%	-77.3%
	Min	-58.1%	-52.9%	-53.9%	-55.8%	-59.1%	-56.4%
	Max	-88.0%	-93.5%	-85.5%	-87.8%	-92.1%	-96.2%
Adaptation	Mean	-99.6%	-99.7%	-98.8%	-96.7%	-98.6%	-99.5%
	Min	-97.1%	-94.4%	-93.2%	-88.1%	-95.0%	-98.0%
	Max	-100.0%	-100.0%	-99.6%	-99.8%	-99.9%	-100.0%

The application of realistic occupant presence (O2) inputs was considered as a separate input from the occupant behaviour scenario (O1). The application of a realistic presence schedule resulted in 0.12-5.99 kWh/m^2,year reduction in annual space cooling demand, compared to the standard schedule when all occupants are considered to be at home. (Table 27)

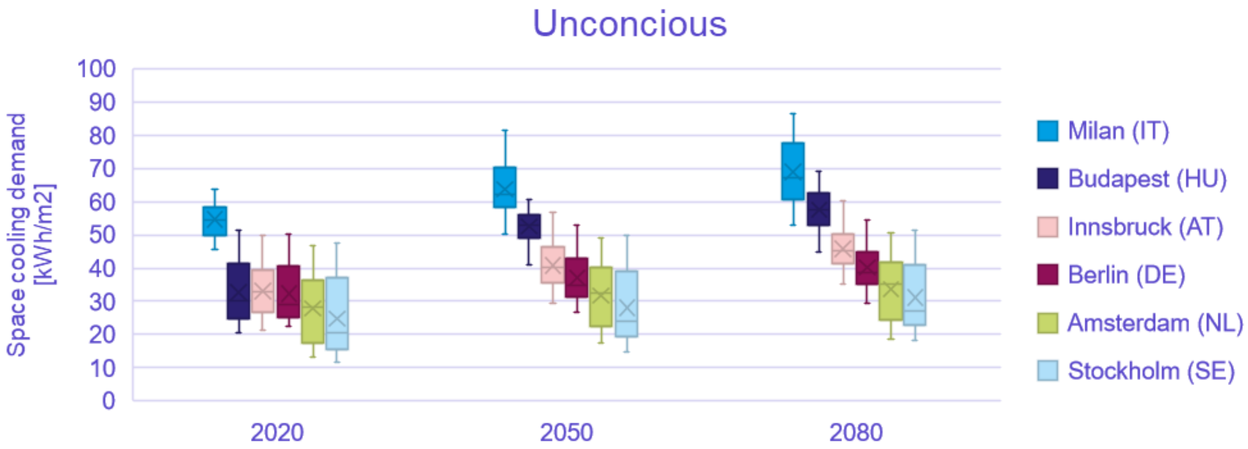
Table 27. Average difference of the annual space cooling demand between the O1 – At home and O2 – Realistic occupancy scenarios [kWh/m2,year]

	Milan (IT)	**Budapest (HU)**	**Innsbruck (AT)**	**Berlin (DE)**	**Amsterdam (NL)**	**Stockholm (SE)**
Unconscious	-5.99	-3.94	-4.55	-4.30	-3.83	-4.09
Mitigation	-2.81	-1.76	-2.21	-1.99	-1.66	-1.76
Adaptation	-0.21	-0.23	-0.35	-0.31	-0.06	-0.12

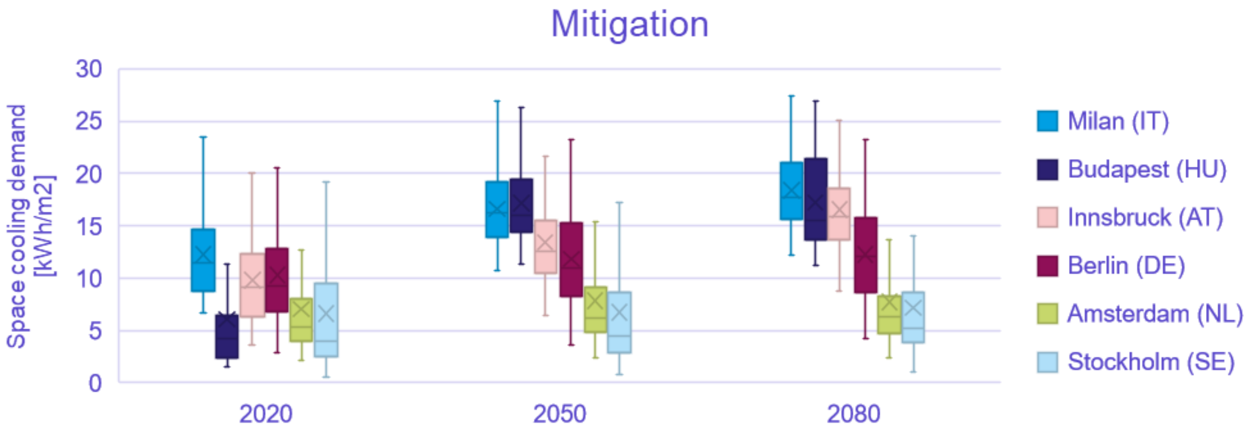
3.2.1.3. EFFECT OF BOUNDARY CONDITIONS

The effects of the change of the boundary conditions (climate change scenario, archetypes and refurbishment levels) are detailed on the next pages, Figure 21 to Figure 23.

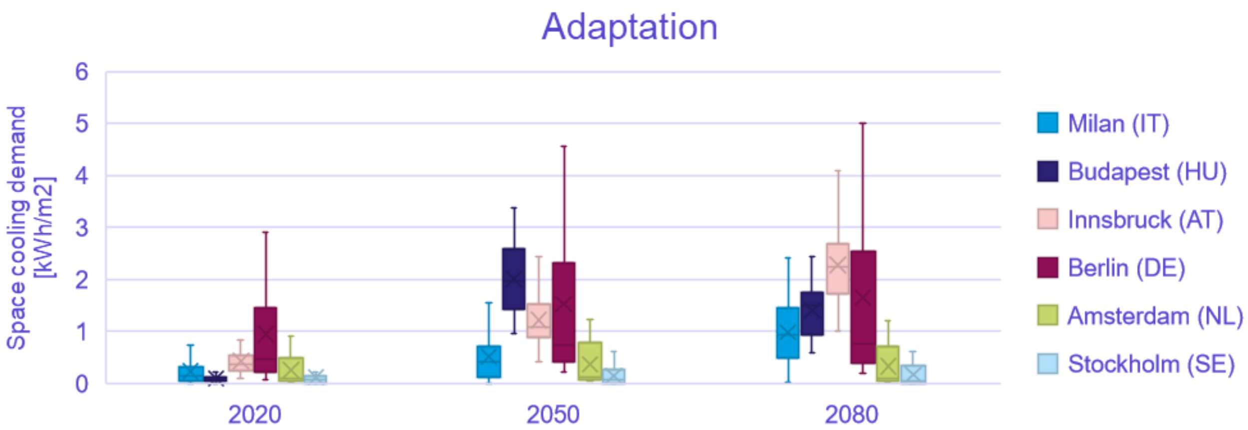
Figure 21 shows the effect of climate change on the space cooling demand of each country and behavioural scenario. With climate change, each country shows rising space cooling demand. In the Unconscious behaviour, space cooling demand rises by 4.10 kWh/m^2,year on average from 2020 to 2050, and by 1.71 kWh/m^2,year from 2050 to 2080, the same values for the adaptive behaviour are only 0.62, 0.16 respectively.



a)

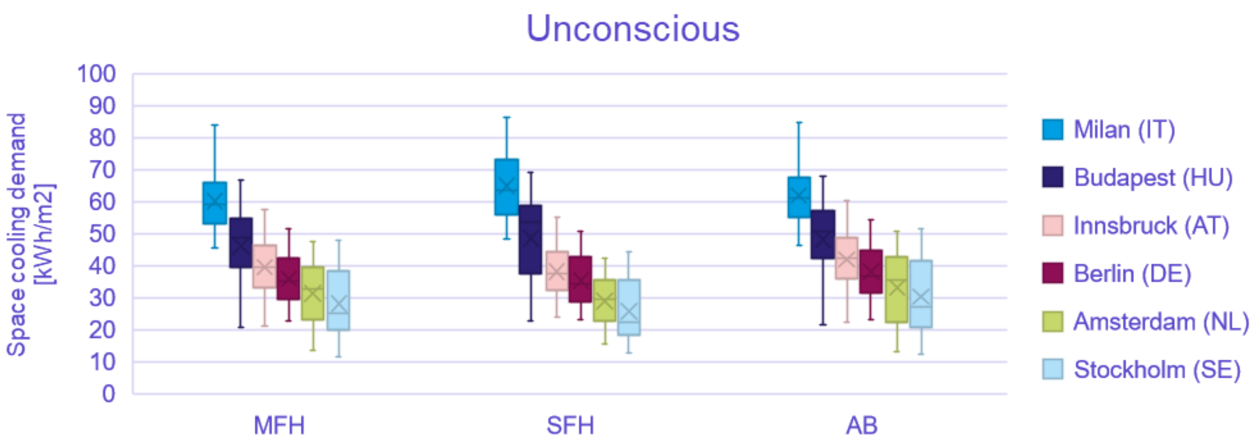


b)

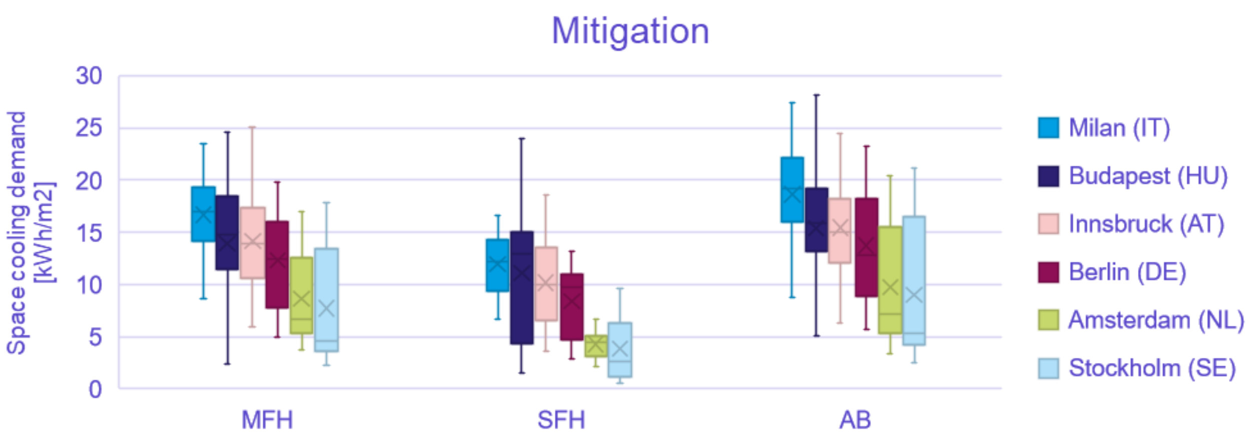


c)

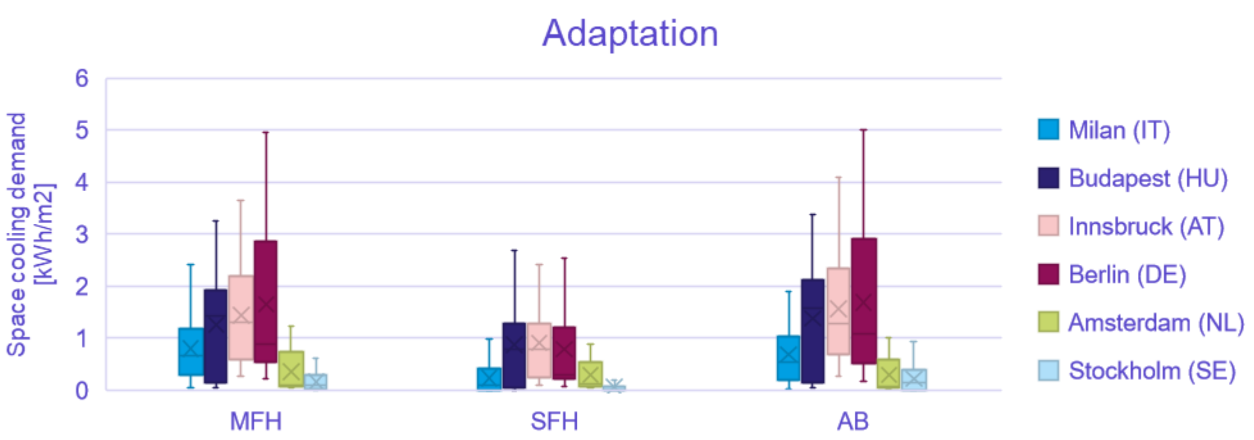
Figure 21. Effect of Climate Change scenarios (RCP4.5) on SC demand, considering all residential building types for the a) Unconscious b) Mitigation c) Adaptation behaviour scenario



a)

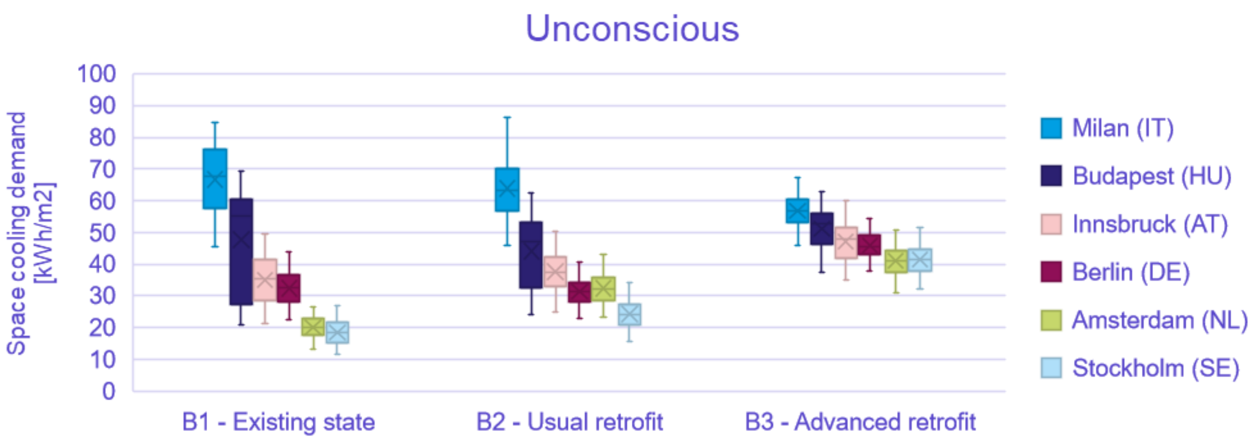


b)

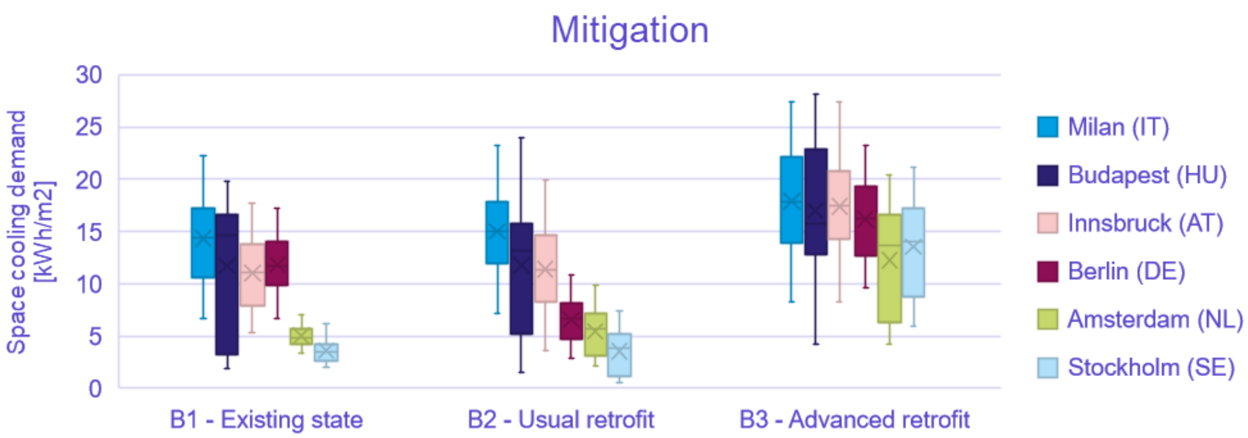


c)

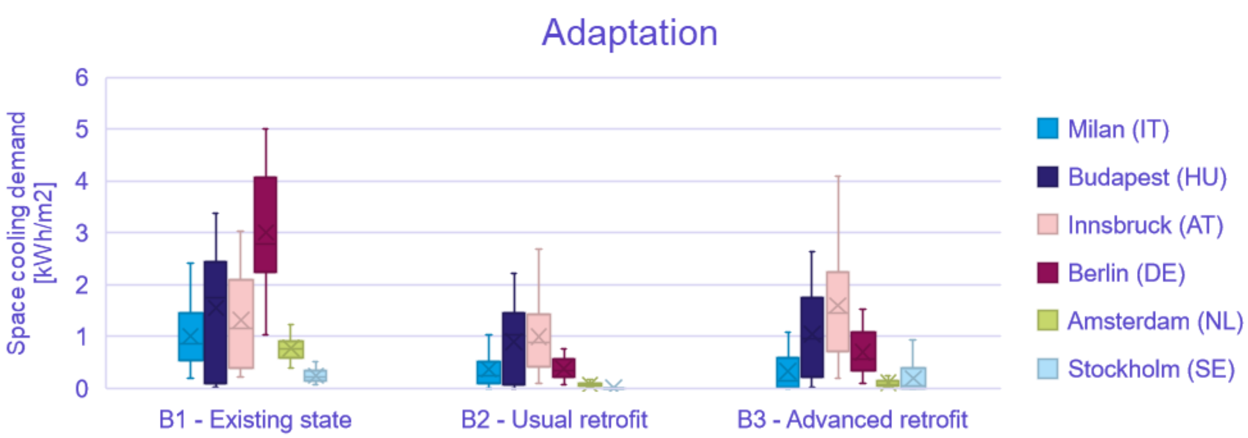
Figure 22. Effect of building archetype on SC demand, considering all scenarios for the a) Unconscious b) Mitigation c) Adaptation behaviour scenario



a)



b)



c)

Figure 23. Effect of building refurbishment level on SC demand, considering all scenarios for the a) Unconscious b) Mitigation c) Adaptation behaviour scenario

On Figure 22, results are presented based on the behavioural scenario and the building archetype. In the Unconscious behaviour, space cooling demand is similar in all three evaluated building types. However, when adapting more conscious behaviour, the lowest values can be seen for the SFH archetype.

Figure 23 shows how SC demand changes with the behavioural patterns adapted. When unconscious behaviour is simulated (Figure 23 a)), the cases with the existing envelope properties and the usual retrofit levels show similar mean values for Milan, Budapest and Innsbruck. For Berlin, the usual retrofit shows a small decrease, however, for Amsterdam, Stockholm, the SC demand increases further when applying a Usual retrofit level. When the envelope performance is are further improved, to the Advanced retrofit level, SC demand decreases only for Milan, while for all other countries, an increase is seen.

Similarly, with the in the Mitigation behavioural scenario (Figure 23 b)), SC demand is similar in the B1 – Existing state and B2 – Usual retrofit cases, while the highest values are seen for the B3 – Advanced retrofit levels. However, in case of Adaptive behaviour scenario (Figure 23 c)), the B1 - Existing state has the highest, while the B2 - Usual retrofit level has the lowest SC demand values, with B3- Advanced retrofit being in-between for most cases.

3.2.2. Non-Residential buildings

3.2.2.1. SENSITIVITY TO THE INPUT PARAMETERS

The literature review showed that there are no general, clear threshold values for occupant behaviour. To specify which actions have the highest impact on energy savings and increase thermal comfort, sensitivity analyses have been conducted to specify which adaptive comfort actions are critical in these interventions. A series of analyses were conducted for the specific case of S-N oriented office spaces, for the climate conditions and construction parameters of Italy and for the year 2020, to identify the effect of the inputs on the results. The following were analysed:

- *occupancy schedule*
- *window opening setpoints*
- *shading control strategies*
- *ceiling fans*

For the occupancy, two types of strategies for reduction of occupancy were tested: “Reduced occupancy” representing the increased application of home office policies and a more conscious behaviour in avoiding work in hot hours, and “Summer Fridays”, representing a policy where Friday afternoons are free for the workers in the summer months. The results show that the two profiles result in up to 9% difference in the indicators, a similar order of magnitude in the free-running and the cooled buildings.

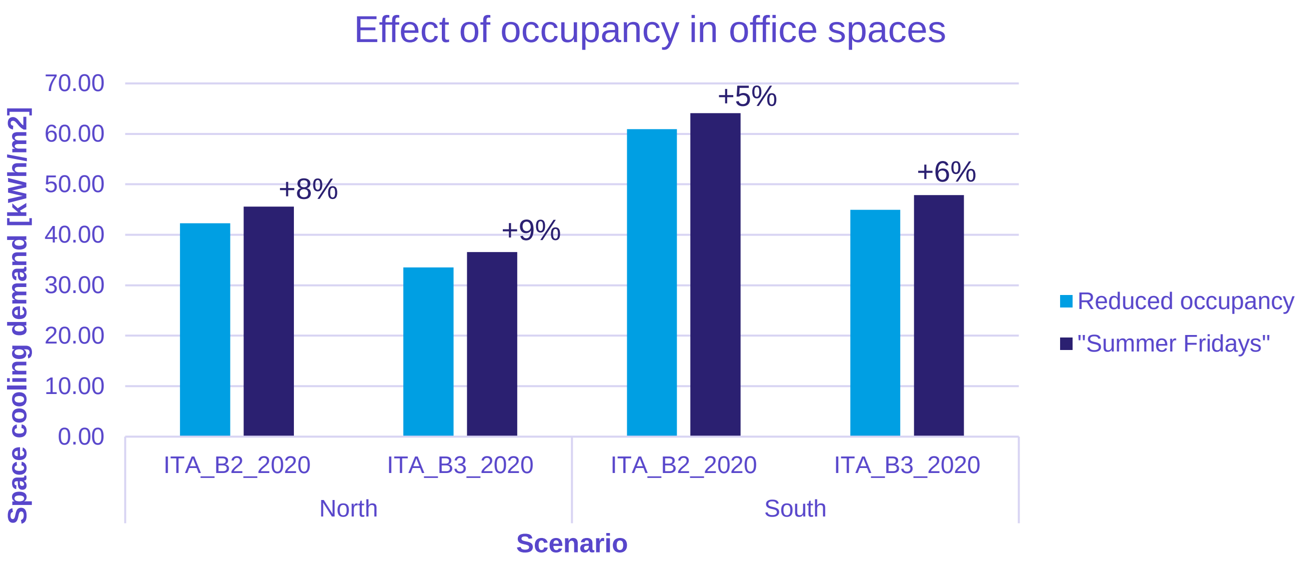


Figure 24. Effect of occupancy schedule on the number of occupied hours exceeding the adaptive thermal comfort limit in naturally ventilated and cooled office spaces

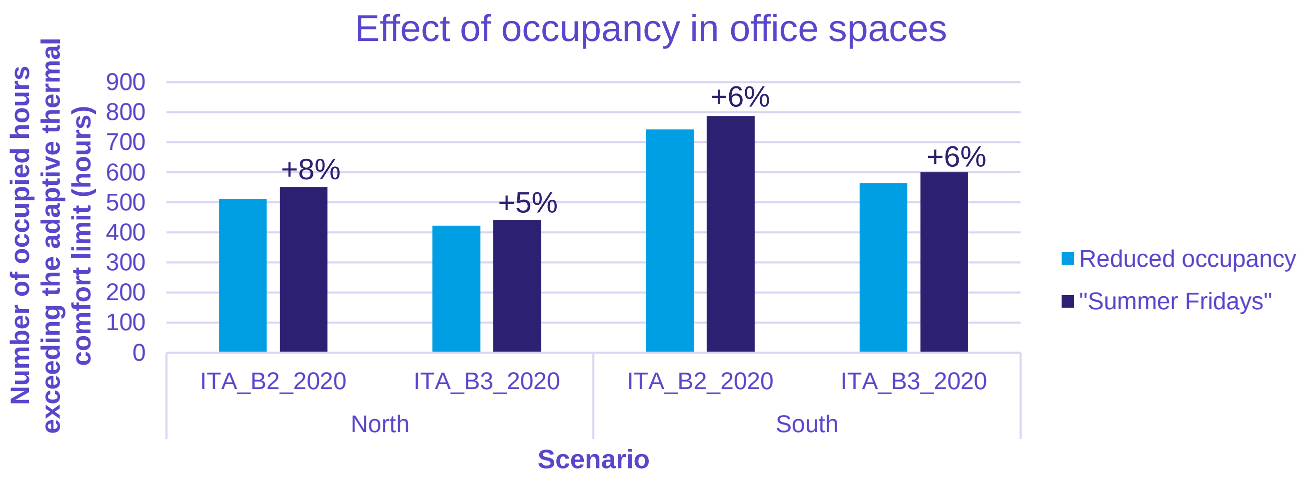


Figure 25. Effect of occupancy schedule on the annual space cooling demand in mechanically cooled office spaces

For the window temperature setpoint, 20 °C indoor air temperature was adopted in the baseline case. The sensitivity of the results to this threshold has been tested if reduced to 18 °C. However, as seen in Figure 26, the results are not sensitive to this input parameter.

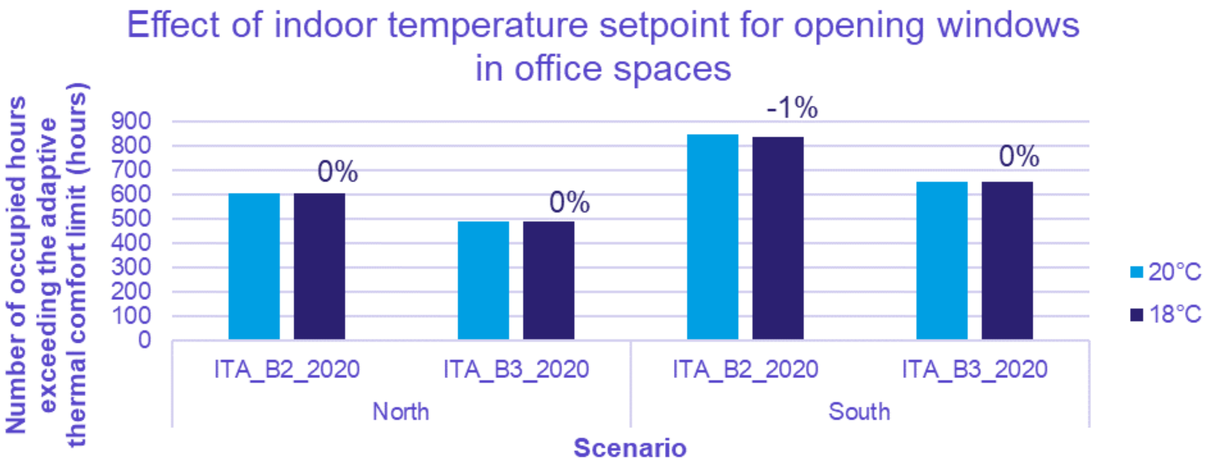


Figure 26. Effect of indoor temperature setpoint of opening windows on the number of occupied hours exceeding the adaptive thermal comfort limit

For the control setpoint for activation of shading devices two controls were tested, one based on the indoor temperature as a baseline, anticipating a trigger of thermal discomfort and one based on the global radiation hitting the external façade, anticipating a trigger of visual discomfort. As seen inFigure 27 and Figure 28 the effect is within 5% of the overheating hours in free-running buildings, and in a similar range of the space cooling demand in mechanically ventilated and cooled buildings as well. Only one shading control is modelled, based on the indoor temperature control.

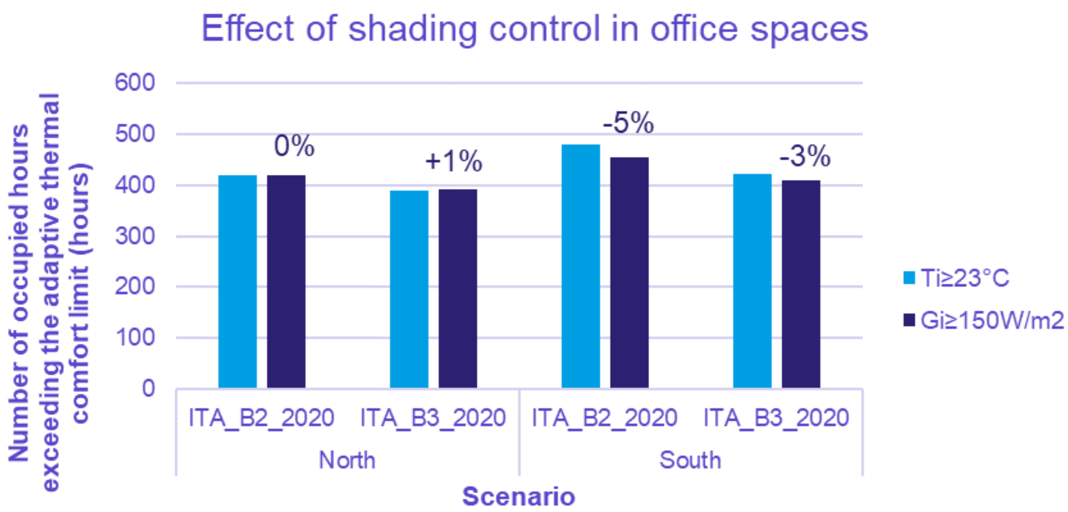


Figure 27. Effect of shading control strategy on the number of occupied hours exceeding the adaptive thermal comfort limit in naturally ventilated and cooled office spaces

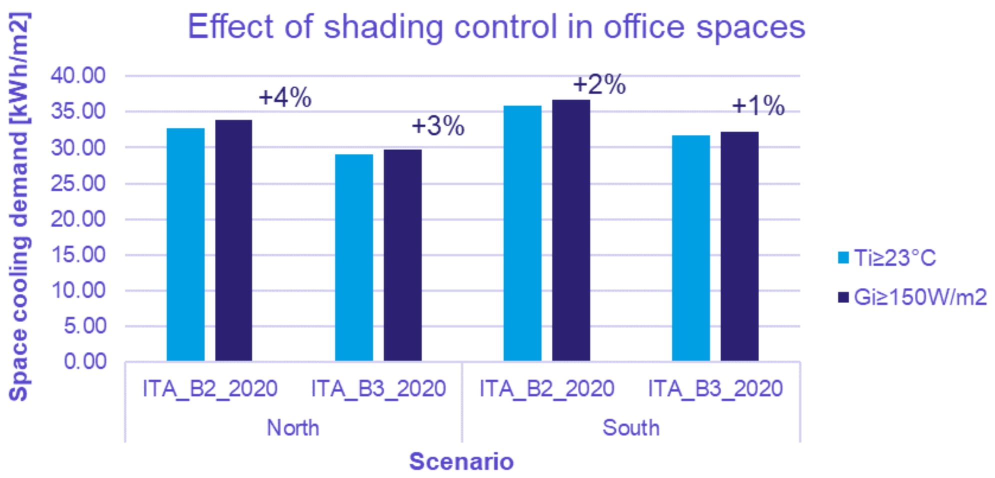


Figure 28. Effect of shading control strategy on the annual space cooling demand in mechanically cooled office spaces

In the baseline scenario, no personal fans have been considered. In the free-running building, the effect of providing personal fans with two different speeds is shown in Figure 29. The results are sensitive to the modelled fan speed, thus both fan speeds are modelled for the quantification of OPA actions.

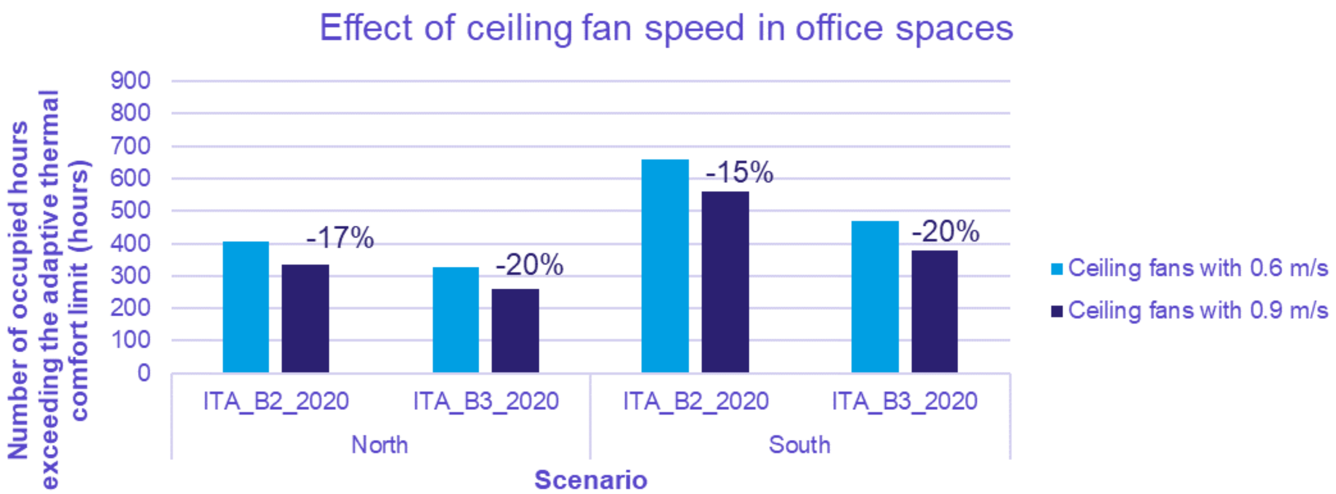


Figure 29. Effect of fans on the annual space cooling demand in mechanically cooled office spaces

From the above actions, the ceiling fan speed is considered to have the highest significance in the simulations, and the two airspeeds are implemented as separate input scenarios. Occupant presence is of moderate significance. The scenario with the highest reduction potential ("reduced occupancy") is implemented further on.

3.2.2.2. INDIVIDUAL EFFECT OF OPA ACTIONS

The effect of each OPA action is shown in the following section for spaces with mechanical space cooling and for free-running buildings separately, for each modelled space usage type in the following order:

- *occupancy presence*
- *setpoints*
- *adaptative comfort through ventilation and fan use*
- *night-time ventilation*
- *shading control*

Occupant presence

For offices a reduced occupant presence compared to the standards has been taken into account incorporating an overall 20% reduction in presence together with a shift to start work 1 hour earlier to reduce working hours in the hottest afternoon hours. Together with the reduced occupancy, the equipment loads have also been reduced. The effect of this change resulted in an average 12% to 15% reduction of SC demand, the lowest percentage reduction for Milan and the highest for Sweden. (Figure 30)

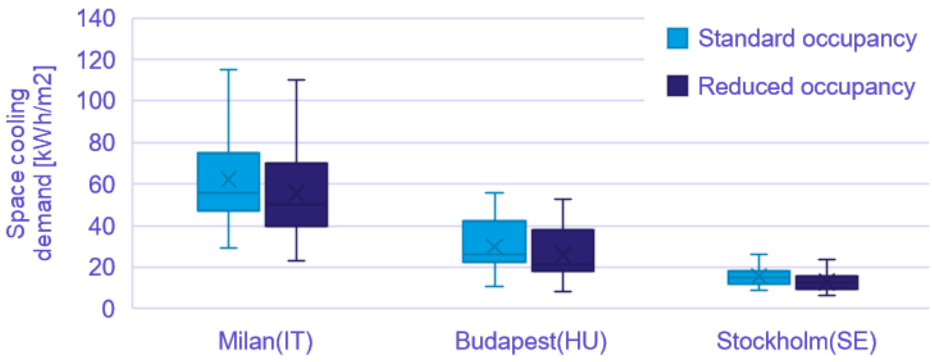


Figure 30. Effect of reduced occupancy on the space cooling demand in modelled office spaces

For educational spaces summer holidays have been implemented in the base model according to the country specific summer holidays from the literature. The alternative occupant presence was on one hand defined as shifting the start of the lectures 1 hour earlier; on the other hand, the effect of shifting the summer holiday 1 week later in the calendar year was also modelled. Together with the reduced occupancy, the equipment loads have also been shifted. The change in occupancy hours reduced space cooling load by 8% to 15% on average, the lowest percentage reduction for Budapest and the highest for Sweden. (Figure 31). Shifting the holiday period by one year had different trends. In Budapest, this shift resulted in an average of only 1% saving, while in Stockholm the average saving was up to 46%. Also, the range of the space cooling demand in the simulated cases reduced significantly.

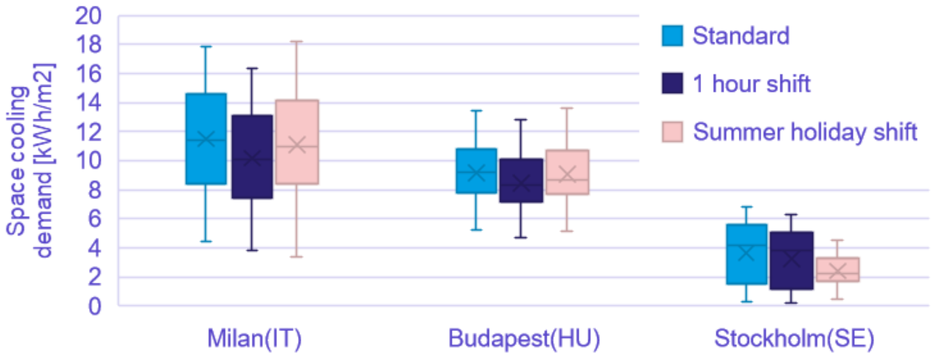


Figure 31. Effect of reduced occupancy on the space cooling demand in modelled educational spaces

Setpoints

The effect of changing setpoints is shown as the total space cooling demand that has resulted from the simulations of all relevant cases for the given building type, Figure 32, Figure 34, Figure 36a) and also, the change of each incremental 1 °C setpoint reduction is calculated Figure 33, Figure 35, Figure 36b). A consistent reduction is seen when the setpoints are increased, however, the effect of changing from one setpoint to another is not the same. For example, Figure 33 for offices shows that the effect of changing the setpoint from 27 °C to 28 °C is lower, than changing from 24 °C to 25 °C. This indicates that already the first steps in order to relax expectations towards indoor temperature conditions are worth taking. This effect however is lower for Italy, than for Hungary and Sweden. Also, there is some difference how the building types are affected.

Changing the setpoints by 1°C can have a reduction in space cooling demand in the range of 1.5-12.2 kWh/m^2 for offices, 1.2-17.6 kWh/m^2 for hotels, and 0.51-3.17 kWh/m^2 for classrooms, depending on the building construction, location, climate change scenarios, and other occupant behaviours adopted by the users. This equals up to 25% savings of the annual space cooling demand of offices, 34% for Hotels and up to 68% for educational buildings.

The mean reduction of 1 °C for the hotel and office models in Italy is around 7-8kWh/m^2,year, equalling 11-14% of the annual space cooling demand. For Hungary, this is around 16-18%, while for Sweden 17-24%. The percentage savings are the highest in the educational buildings, the mean saving is 20% for Italy, 22% for Hungary, and 29% for Sweden. The overall range of savings considering all building types and cases studied is 4-68%.

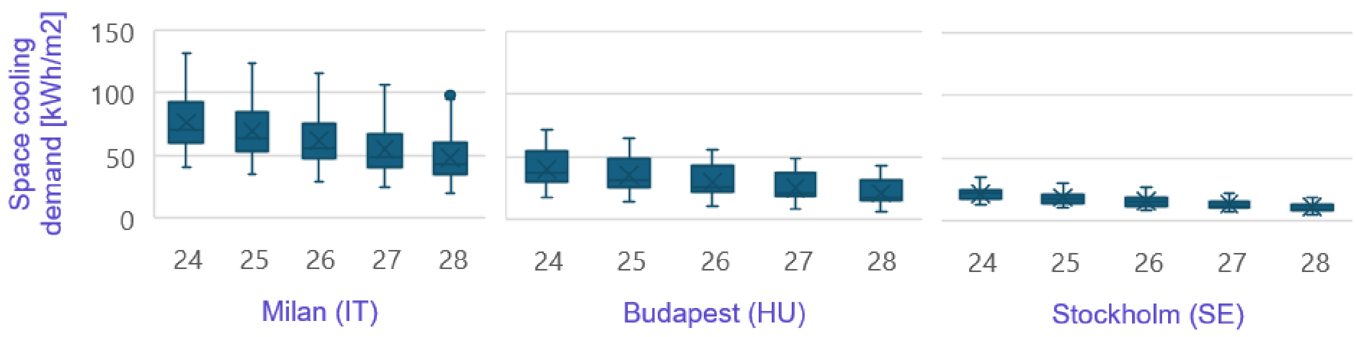


Figure 32. Effect of setpoint selection on the space cooling demand in modelled office spaces

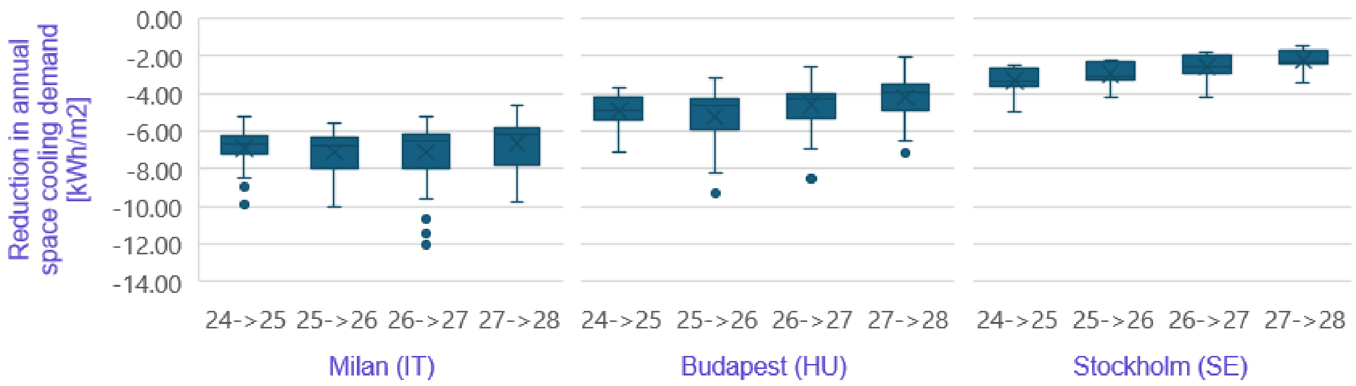


Figure 33. Reduction in annual space cooling demand by each additional 1°C setpoint change on the space cooling demand in modelled office spaces

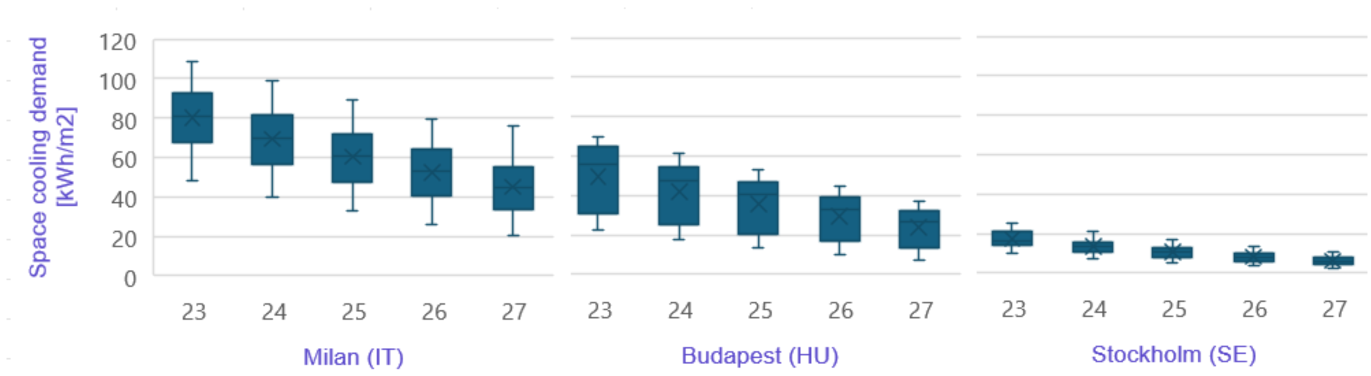


Figure 34. Effect of setpoint selection on the space cooling demand in modelled hotel rooms

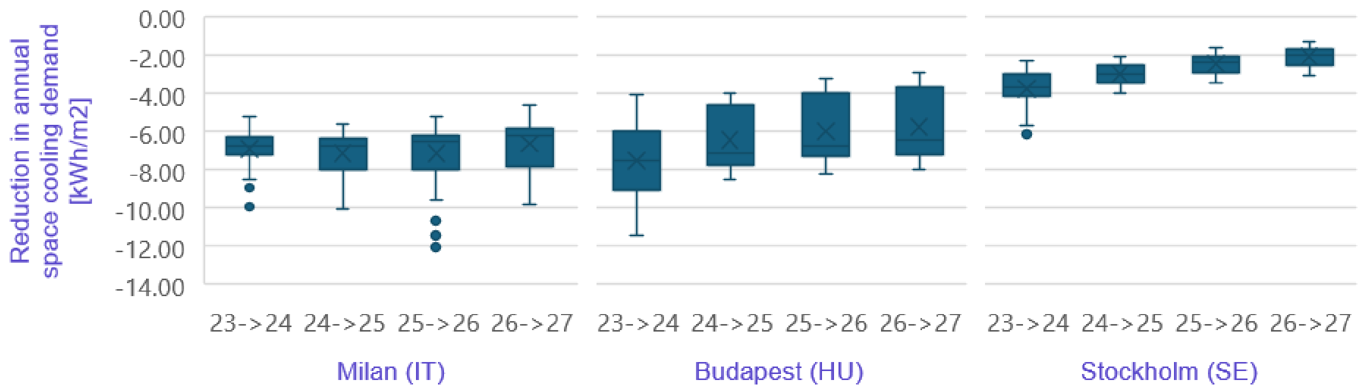


Figure 35. Reduction in annual space cooling demand by each additional 1°C setpoint change on the space cooling demand in modelled hotel spaces

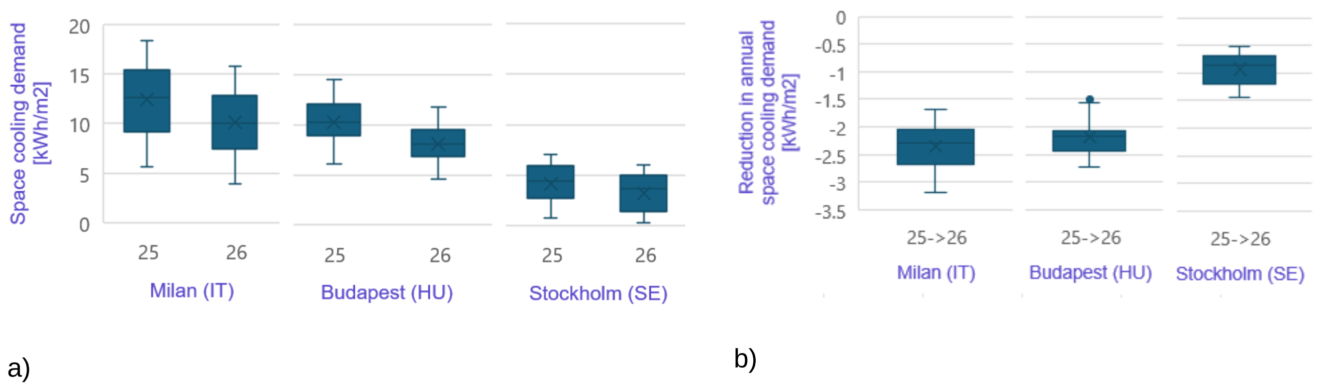


Figure 36. a) Effect of setpoint selection on the space cooling demand in modelled classrooms b) Reduction in annual space cooling demand by each additional 1°C setpoint change on the space cooling demand in modelled classrooms

Window opening, ventilation and fans

For educational buildings window opening is simulated with two opening ratios, one that represents that windows are only opened in the breaks, and an alternative, where a higher opening ratio is applied that represents also window opening during the lectures. For schools increasing the ventilation rate can be effective in up to 200 hours of the occupied periods, and can reduce the percentage of occupied hours too hot, i.e. above the adaptive comfort limit by up to 12%.

Fans alone have a similar effect, they can reduce the percentage of occupied hours above the discomfort limit by up to 8%. However, combining these two measures is even more effective, an improvement of up to 18% of the occupied hours can be shifted to the thermally comfortable temperature range.

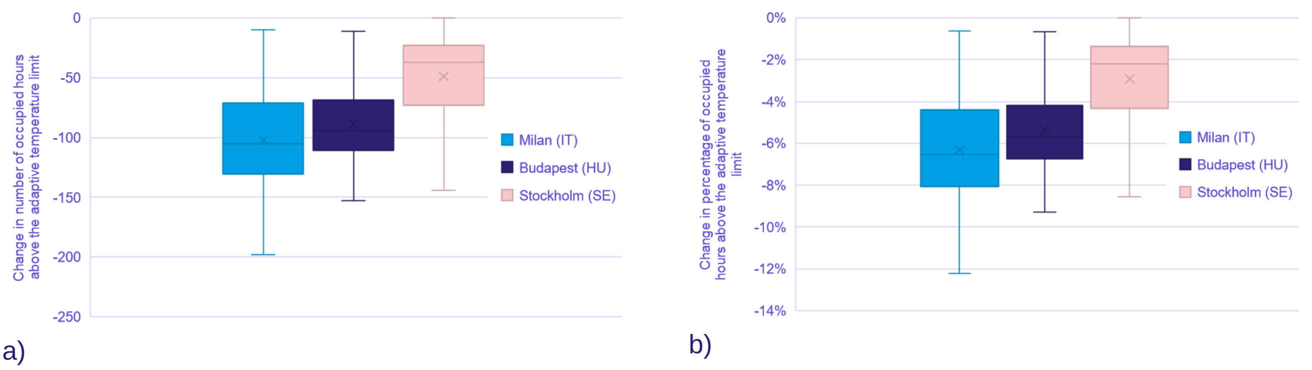


Figure 37. Effect of increasing natural ventilation rates in modelled classrooms a) number of hours b) percentage of occupied hours

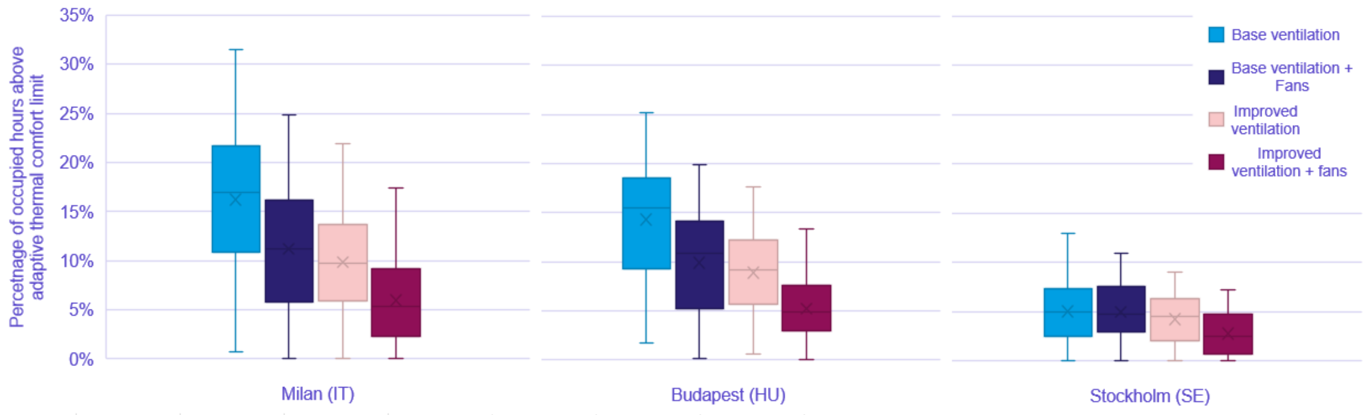


Figure 38. Effect of increased natural ventilation rates and application of fans

Night-time ventilation

In offices, night-time ventilation can reduce the mean space cooling demand of mechanically cooled buildings by 20.83 kWh/m^2,year for Milan, 9.47 kWh/m^2,year and 9.42 kWh/m^2,year for Budapest and Stockholm respectively. (Figure 39) In the educational function the mean reduction of the space cooling demand was between 1.67-4.62 kWh/m^2,year for the simulated cities. (Figure 40)Figure 40 For hospital wards simulating night ventilation together with a relaxation of cooling setpoint resulted in 15.47 kWh/m^2,year, 9.98 kWh/m^2,year, 5.41 kWh/m^2,year reduction in mean space cooling demand for Milan, Budapest and Stockholm respectively. (Figure 41).

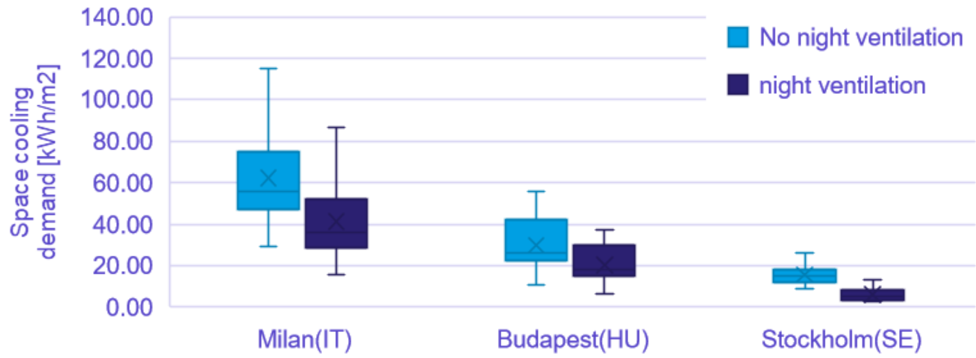


Figure 39. Effect of night ventilation on the annual space cooling demand in mechanically cooled office spaces

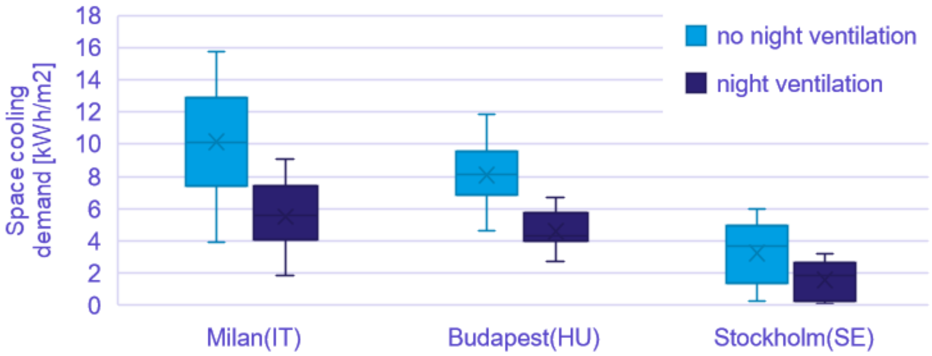


Figure 40. Effect of night ventilation on the annual space cooling demand in mechanically cooled classrooms

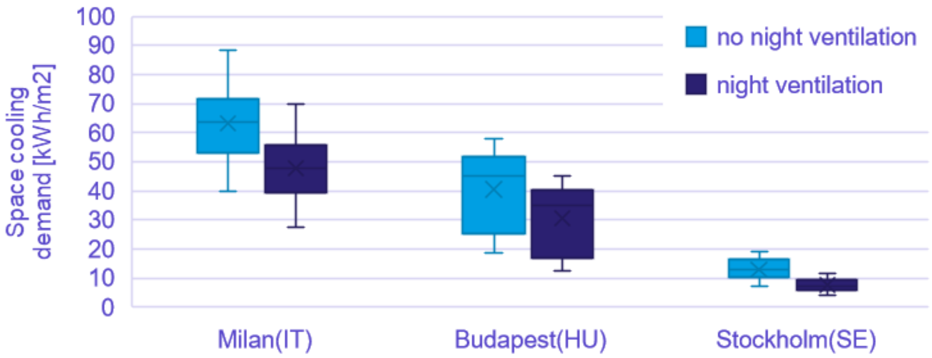


Figure 41. Effect of night ventilation on the annual space cooling demand in mechanically cooled hospital wards

Shading

First, the effect of shading on the spaces with mechanical space cooling are shown for each building function.

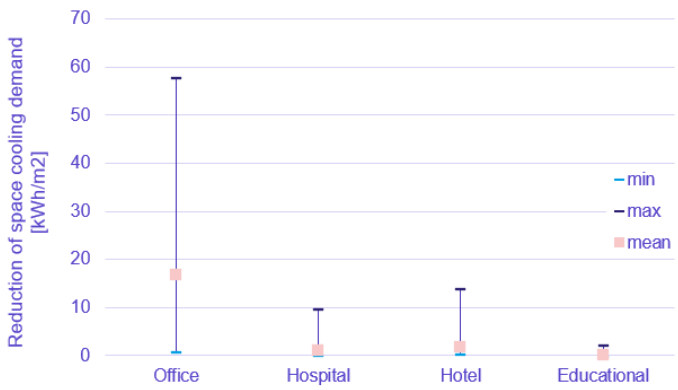


Figure 42. Summary of space cooling demand reduction for all simulated cases of each building type

Figure 42 summarizes the effect of shading for all cases, grouped only by building functions. Table 28 shows the minimum, mean and max percentage reduction of space cooling demand for the office models, hospital models, the hotel rooms and classrooms, for Milan, Budapest and Stockholm. All spaces with different orientations are considered, which resulted in the high range of percentage savings.

Table 28. Percentage space cooling demand reduction for simulated cases

	Milan (IT)			**Budapest (HU)**			**Stockholm (SE)**		
	min	max	mean	min	max	mean	min	max	mean
Office	19%	56%	37%	27%	65%	49%	6%	64%	32%
Hospital	2%	12%	6%	1%	9%	4%	-2%	12%	5%
Hotel	1	18	7%	1	19	6%	1	28	10%
Educational	-7%	13%	4%,	-2%	5%	3%	-23%*	11%	3%

*The high negative values were seen in cases where the space cooling demand was particularly low and night ventilation was implemented.

Further on, the effect of shading for the different climatic scenarios is shown.

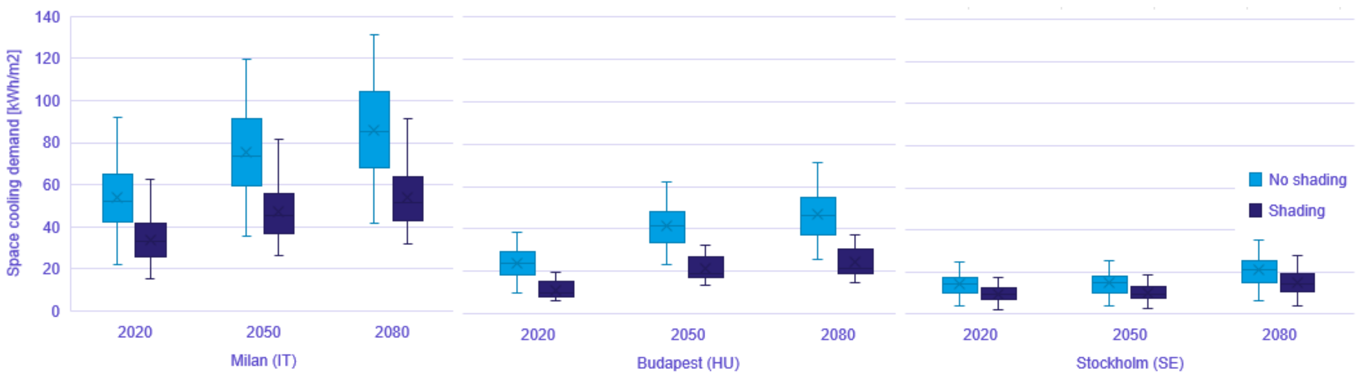


Figure 43. Effect of shading use on the space cooling demand of modelled office spaces

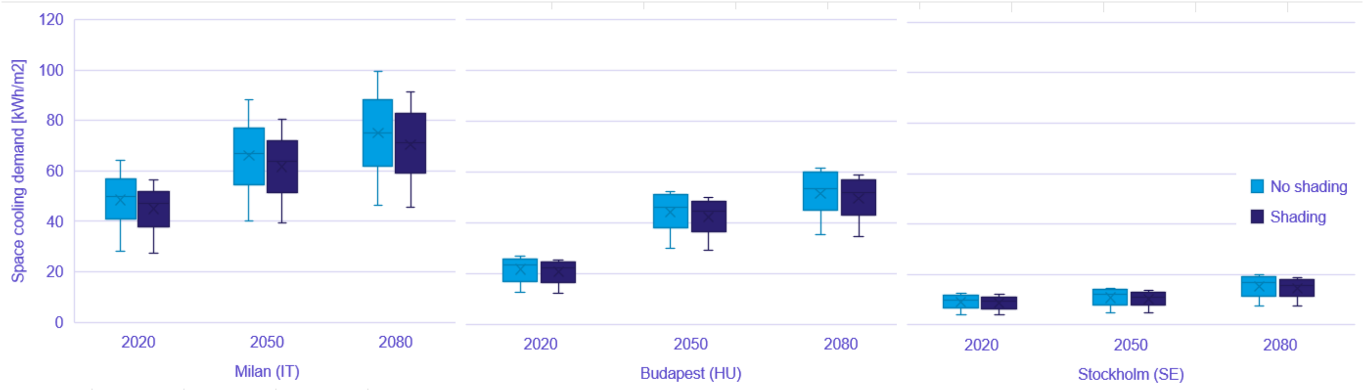


Figure 44. Effect of shading use on the space cooling demand of modelled hospital rooms

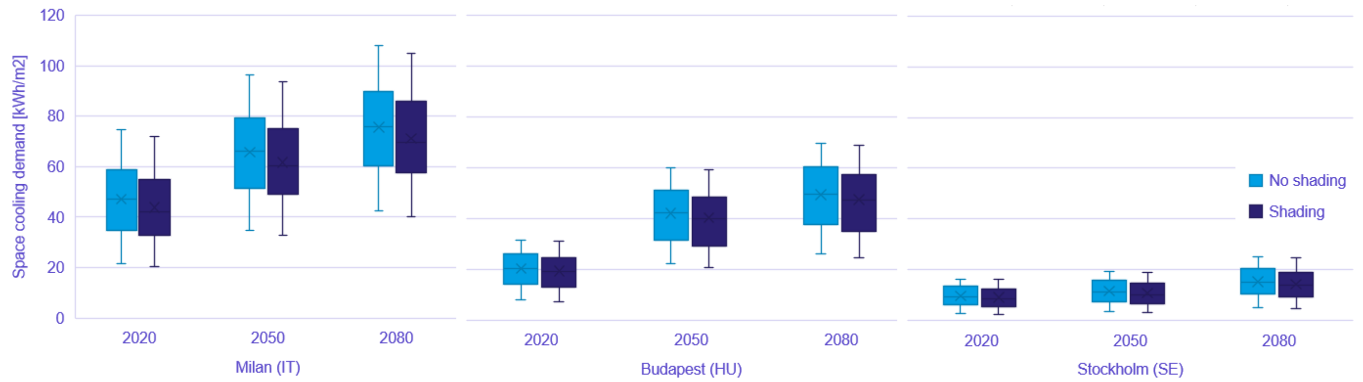


Figure 45. Effect of shading use on the space cooling demand of modelled hotel rooms

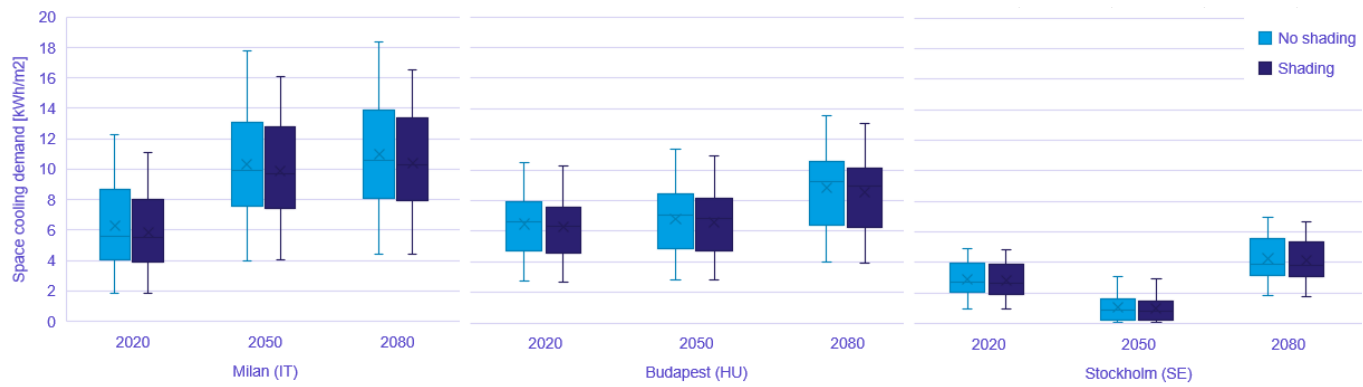


Figure 46. Effect of shading use on the space cooling demand of modelled classrooms

Effect of shading on the discomfort hours of free-running buildings are shown on the following figures. The mean percentage reduction of discomfort hours compared to the adaptive comfort limit for the office models with and without shading was 33%, 46%, and 43% for Milan, Budapest and Stockholm respectively.

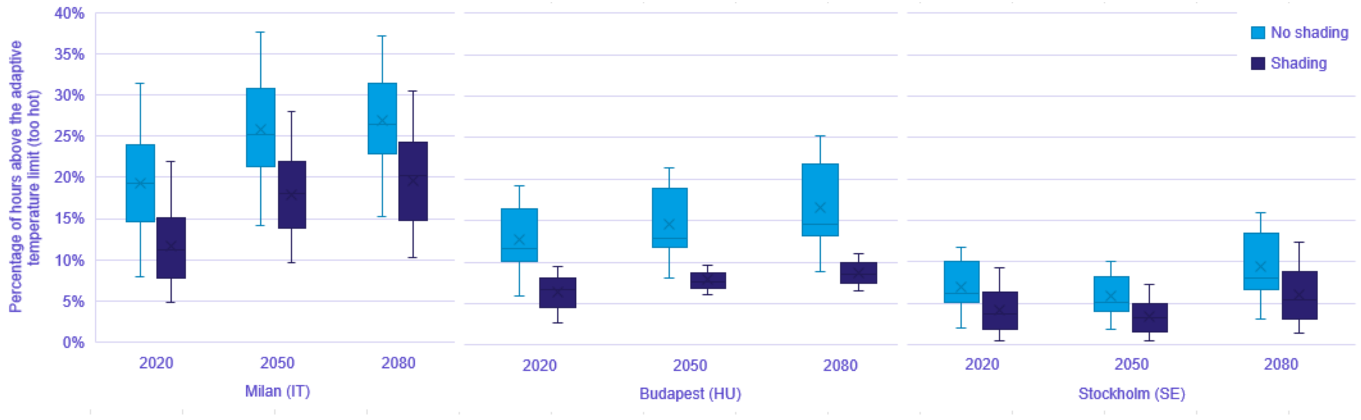


Figure 47. Effect of shading use on the discomfort hours (too hot) in modelled free-running offices

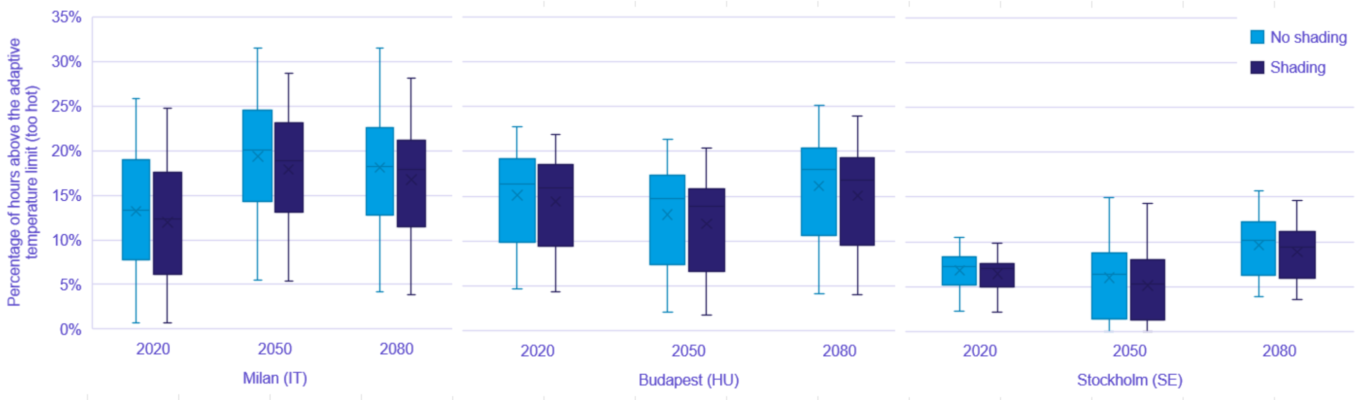


Figure 48. Effect of shading use on the discomfort hours (too hot) in modelled free-running classrooms

The mean percentage reduction of discomfort hours compared to the adaptive comfort limit for the office models with and without shading was 9%, 7%, and 9% for Milan, Budapest and Stockholm respectively.

Summarizing the above, the highest potential in reducing SC demand / or increasing thermal comfort by the effective use of shading lies in office buildings, where external shading is more widespread than in other building functions. The mean reduction of the SC demand is 39% for all office cases considered, ranging from 6-65% depending on the country, orientation, building construction, and other occupant behavioural settings.

In the other building functions, the archetypes contained internal, high-transparency blinds, which limited the efficiency of implementing this behavioural measure. Nevertheless, the space cooling demand could be reduced up to 14 kWh/m^2 even with internal, high transparent blinds.

3.2.2.3. COMBINED EFFECT OF OPA ACTIONS

All cases combined are shown on the following figures. Table 29 shows the percentage reduction of the worst and best performing behavioural combination. The space cooling demand for the individual cases with different orientation has been averaged to receive a single value per scenario, function, and occupant behavioural scenario.

Table 29. Average reduction of space cooling demand from the worst to the best performing behavioural combination, for all non-residential cases simulated

	Office	Education	Hotel	Hospital
Milan (IT)	67%	58%	48%	38%
Budapest (HU)	76%	56%	56%	34%
Stockholm (SE)	84%	69%	69%	48%
Average	**76%**	**61%**	**58%**	**40%**

Offices

For mechanically cooled offices, implementing shading and nighttime ventilation was shown to be behavioural measures with the highest yield, regardless of building construction, climate change or building orientation. This combination outperforms even the case when the setpoints are changed to 28 °C.

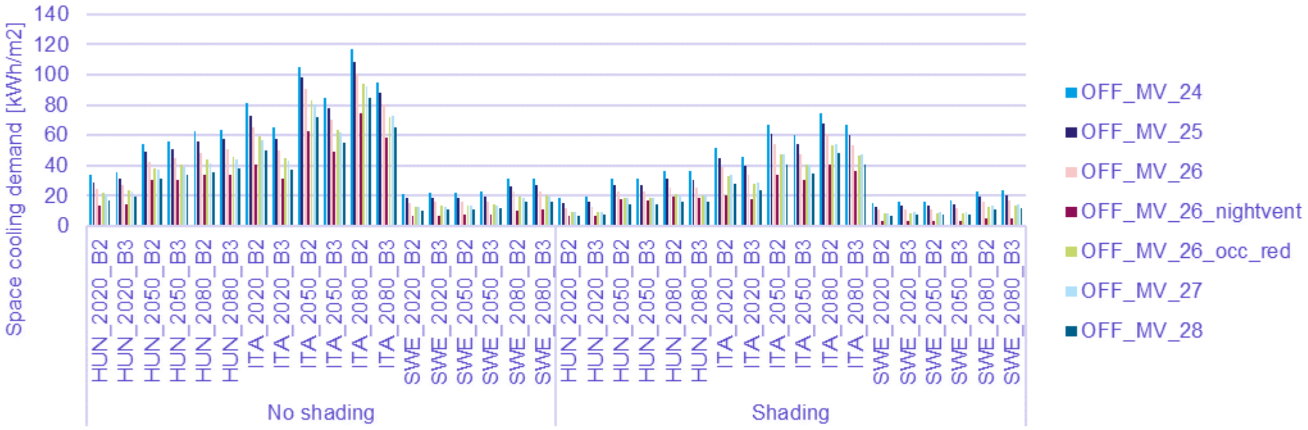


Figure 49. SC demand of all mechanically cooled office cases

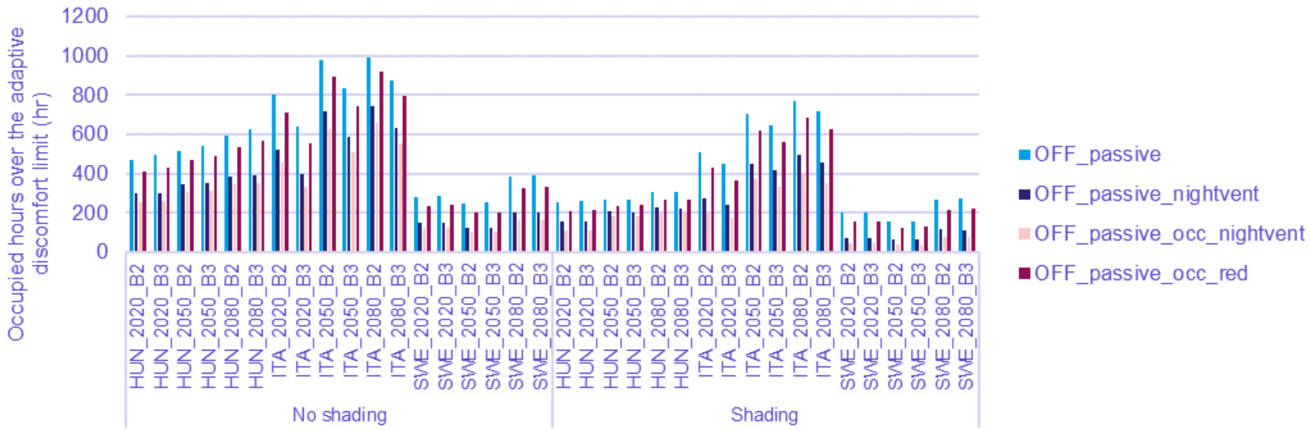


Figure 50. Number of occupied hours over the discomfort limit of all free-running office cases

Hospitals

For the hospital spaces simulated the most effective combination of behavioural measures was applying night time ventilation together with the relaxation of night time space cooling setpoints to 28°C, combined with shading. Natural ventilation alone only resulted in notable savings for the future, 2080 weather scenarios.

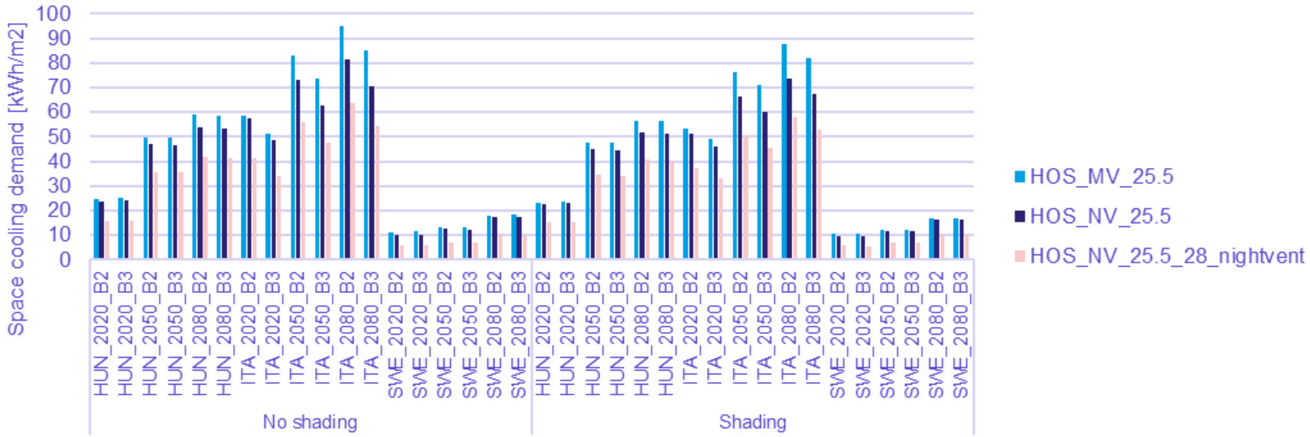


Figure 51. SC demand of all mechanically cooled hospital cases

Hotels

Similarly to the hospitals, the palette of occupant behavioural measures was limited. The change in setpoints together with the implementation of shading was explored. Relaxing the thermal comfort requirements are suggested together with shading.

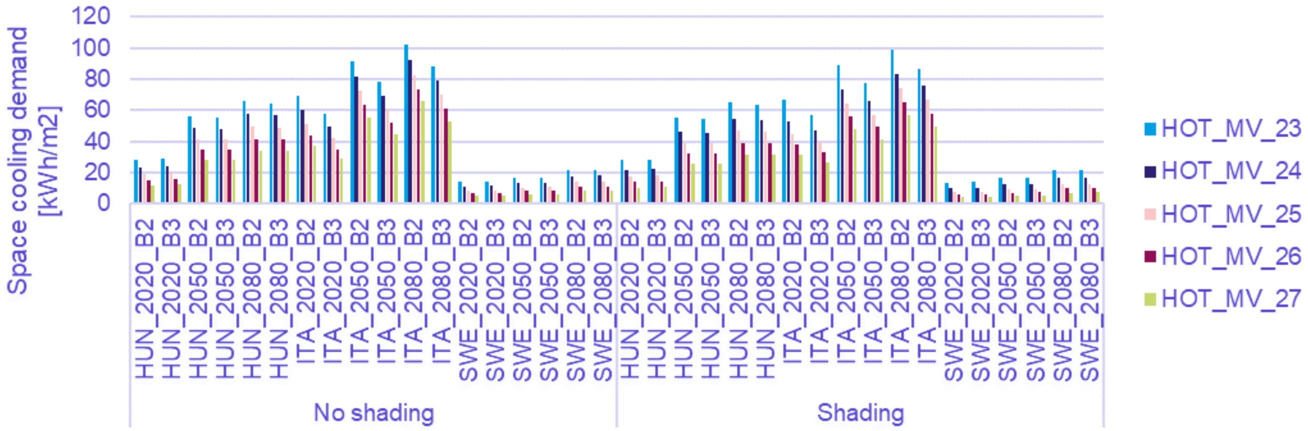


Figure 52. SC demand of all mechanically cooled hotel cases

Education

For the educational buildings, first the mechanically cooled (Figure 53), then the adaptive comfort scenarios that incorporate modified ventilation rates and the operation of fans are presented Figure 54 a-c)). Implementing shading and night ventilation, and relaxing the setpoint to 26 °C also provide the lowest space cooling demands. Nevertheless, as stated above, the shading in this instance is less effective.

When no space cooling is provided, the lowest discomfort hours can be achieved when night ventilation and increased daytime ventilation is provided, together with fans. Figure 54 c). Also, the date of the summer holiday has notable effect on the number of discomfort hours.

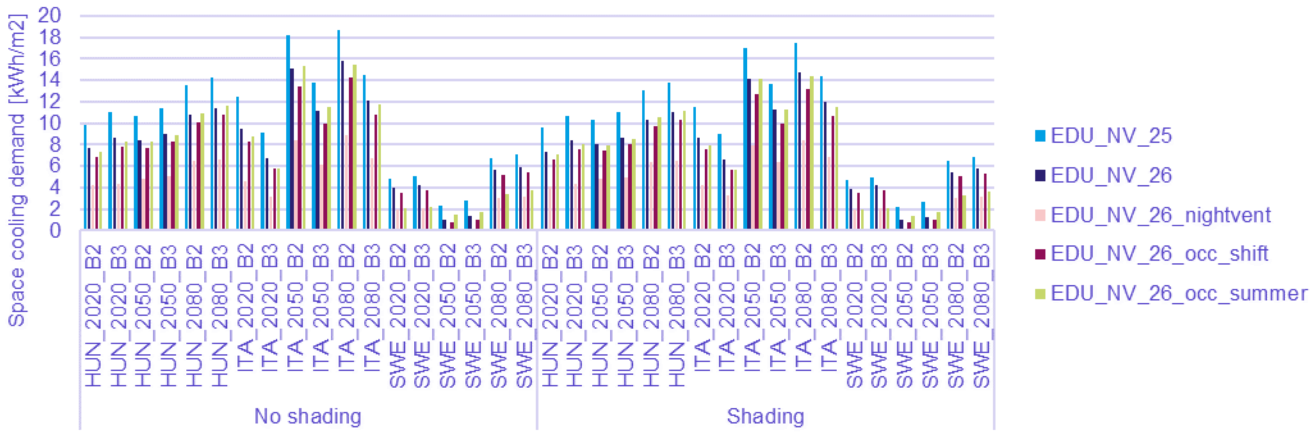
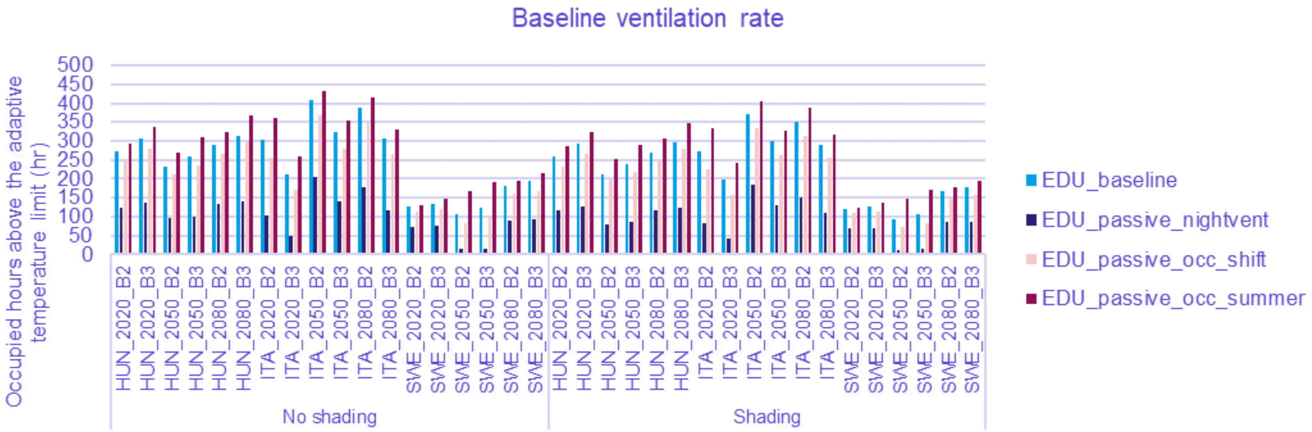
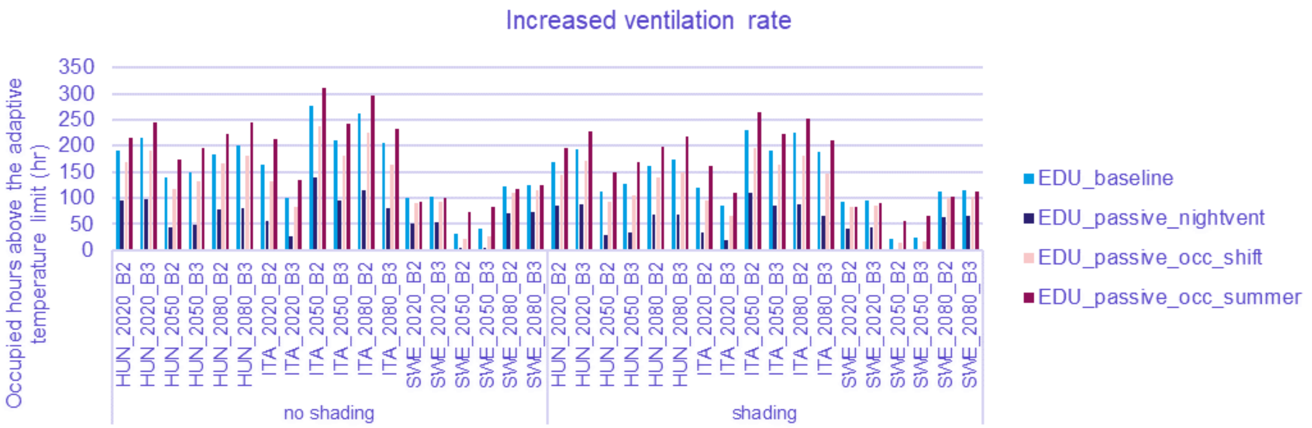


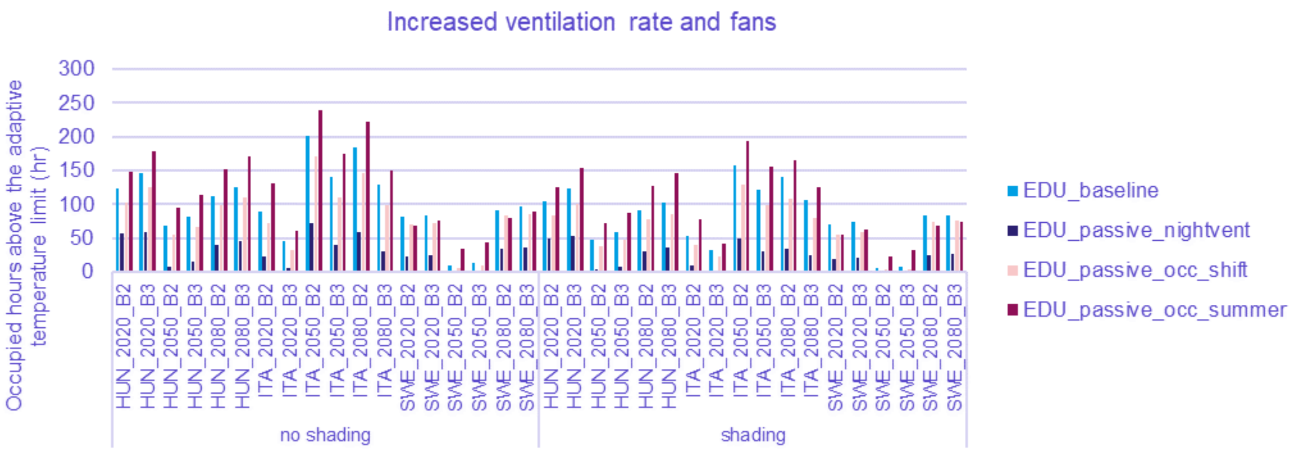
Figure 53. SC demand of all mechanically cooled education cases



a)



b)



c)

Figure 54. Number of occupied hours over the discomfort limit of all free-running education cases

3.3. Conclusion and discussion

The individual and combined effects of behavioural interventions on space cooling and summer temperatures were evaluated for a set of OPA actions defined on standard and empirical data.

Regarding occupancy presence, when schedules based on the available TUS data was used instead of always at home schedules, space cooling demand was reduced by up to 6 kWh/m^2.

From the individual effects of OPA measures, the reduction of internal loads through lower appliance power density and limited usage hours has the highest effect on the results. When power density is reduced from 10 W/m^2 to 4 W/m^2 and reduced operational schedule is applied, the average space cooling demand was reduced by nearly 20 kWh/m^2,year. This result confirms the significance of behavioural interventions targeting the reduction of energy used in electrical and heat generating appliances, to reduce space cooling demand. Motivating the residents to reduce electricity costs by monetary incentives, information campaigns or nudging has also been found to be a popular behavioural intervention that has well documented positive impacts in the literature. [3] It is advisable to implement such programs in the future as well to limit the space cooling loads.

The second most effective measure was applying conscious shading behaviour, that showed nearly 10 kWh/m^2 reduction in the annual SC demand for the Italian MFH case study. Reaching SC savings though shading requires more active involvement of the occupant, which might need different motivations. To utilize the potential lying in the use of shading, instead of conscious behaviour, building automation systems can relieve the occupant of this responsibility. It is however the responsibility of the policymakers to facilitate the adaptation of these behaviours by incorporating the installation of movable shadings into the building regulations.

As an individual effect, natural ventilation combined with night cooling could result in an average of nearly 5 kWh/m^2 reduction for the Italian MFH case study. However, this effect considers space cooling with constant setpoints, while when relaxing the thermal comfort requirements to the adaptive comfort limits, an additional effect can be seen, evidence during the simulation of the combined actions.

The simulations quantifying the combined effects of Mitigation and Adaptation behaviours showed that a huge potential lies in the occupant behaviour change to reduce space cooling demand. It is seen, that in comparison to the Unconscious behavioural scenario, the Mitigation scenario can reduce space cooling demands by an average of 69-84%, while the percentage reduction of the Adaptation scenario is between 97%-100%. Also, the range of the space cooling demand covering by the different behaviours and scenarios reduced by adapting more conscious behaviours, spreading from 31-48kWh/m^2 to 1-5kW/m^2.

The analysis of the boundary conditions showed that with climate change – as expected - SC demand will increase. The results however confirm that the increase is the highest in case of the Unconscious behaviour (4.10 kWh/m^2,year on average), while marginal if the Adaptation behavioural patterns are followed. However, the effect of an improved the refurbishment level did not show a reduction on the SC demand when the envelope performance increased. The behavioural scenario and the country influenced which refurbishment level resulted in the lowest SC demand. This can be due to the different assumptions on envelope performance of the individual elements, different U-values defined based on Tabula, and the presence and types of shading elements. The results show that with the B2 - Usual and B3 Advanced retrofit levels, it is not definite that space cooling demand will also decrease. Thus, when defining requirements on envelope properties, the effects on space cooling demand should also be assessed, in addition to space heating.

For non-residential buildings, there is high potential in increasing setpoints as the buildings typically operate under thermal conditions that are at the lower end of the comfort range, lower than the legislative values considered in energy calculations. The effect of changing the setpoint to 1°C is higher when applied at the lower ranges of the comfort range. Changing the setpoints by 1°C can have a reduction in space cooling demand in the range of 1.5-12.2 kWh/m^2 for offices, 1.2-17.6 kWh/m^2 for hotels, and 0.51-3.17 kWh/m^2 for classrooms, depending on the building construction, location, climate change scenarios, and other occupant behaviours adopted by the users. This equals up to 25% savings of the annual space cooling demand of offices, 34% for Hotels, and up to 68% for educational buildings.

The potential of energy savings through shading is also high, especially in offices where the building function supports the installation and control of external shading devices. Up to 65% reduction in SC demand could be reached with this measure.

Also, free-running buildings were analysed. However, a limitation in the methodology exists for the evaluation of thermal comfort in schools, there is a lack of robust adaptive thermal comfort model for children in schools, leaving the results to be presented using the EN16798 methodology.

Nevertheless, the results show that for schools increasing the ventilation rate can be effective in all climates. However, the practical application of ventilation through the lectures is in many cases hindered by external noise. To enhance positive occupant behaviour and utilize the sustainable space cooling potential of ventilation, the environmental conditions should be assessed and improved.

Educational buildings are closed for several weeks during the cooling season, which results in lower specific space cooling demands. Aligning the holidays with the periods with peak cooling demand can be beneficial. Shifting the holiday 1 week later did not result in a reduction in cooling demand, which indicates that the current practices (while different in each country) seem to be aligned with the local climatic conditions. However, the holiday periods are not by default considered in the energy modelling standards, it is important to include this as customized input data during the design parameter collections.

In hospitals both the use of shading and natural ventilation through window opening is limited, which is reflected in the SC demand reduction possibilities of OPA. Nevertheless, implementing night ventilation and increasing the corresponding night setpoint can reduce SC demand.

4. Impact assessment

As seen in the previous sections how user comfort expectations, user behaviour and user lifestyle habits can impact SC demand in buildings. Key behaviours that impact SC demand in the residential sector are (i) usage of electricity-powered SC appliances (i.e.: indoor fans, air conditioning systems, etc.), (ii) interaction with a thermostat or A/C SC set-points, (iii) uptake of natural ventilation measures (i.e.: window opening, night-time ventilation), (iv) shading practices, and (v) occupant presence and heat-generating equipment use in the building. These behaviours impact the technical parameters of SC, namely: thermal comfort, set-point preferences, window-opening factor, shading typology, and schedules of occupancy.

Behavioural intervention programmes that have been collected are initiatives specifically designed to influence or change behaviours and shift attitudes towards environmental sustainability. The ultimate goal of these types of interventions is to create long-term shifts in behaviour and the permanent adoption of environmentally responsible habits.

As seen in D3.1 and D2.1 to maintain the physiological balance of the human organism, the behaviour reactions of the users are induced. Generally, it has been recognized that occupants' adaptive behaviour on passive measures, which are mainly provoked by various environmental conditions, are stochastic but with some predictability through identifying triggering factors. Comfort lifestyle and user behaviour measures have been categorized into environmental adjustments, personal adjustments, physiological adaptation and behavioural adaptation. Within Chapter 4 in Deliverable 3.2 *Analysis of Behavioural Interventions across Europe* [3] a collection of successful behaviour-change interventions, aimed at promoting more sustainable SC behaviours was provided, where the most important tools had been identified for the reduction of energy use for SC from an individual behaviour-change perspective and key considerations were highlighted. While the studies scarcely focus on space cooling-related behaviour directly, as previously discussed in D3.2, it can be reasonably assumed that any intervention with a marked impact on reducing electricity consumption in the presence of SC appliances can contribute to lowering SC demand. Reduction in energy used for household appliances and lighting, which generate heat loads, directly contributes to lowering the need for SC in buildings.

The previous Chapter in this document has adopted a systematic methodology to reduce space cooling demand for residential and non-residential buildings through adaptational and behavioural measures. It is seen that by conscious, adaptive behaviour the space cooling demand can drastically be reduced in residential buildings, and also around 50% reduction potential is available in the evaluated non-residential spaces, compared to an unconscious behavioural baseline. Shading and nighttime ventilation have particularly been found as effective measures, but also reduction of electrical appliance loads and adjusting the setpoints are advisable. However, the application of certain behavioural measures can only be effective in an appropriate built environment: for example, for nighttime ventilation, windows or openings are prerequisites, but as detailed in D3.2, the lack of a quiet, safe external environment can hinder the usage of these. To target behavioural changes, hence the ability of the built environment to support sustainable space cooling habits has to be evaluated as a complex topic.

Energy savings in the building sector directly benefit the building owner or user in the form of lower energy bills. The quantification of the direct energy savings and the cost-benefit analysis (CBA) of the installation of different space cooling technologies has been explored in *D2.1 Taxonomy of space cooling technologies and measures* [1] However, energy savings have benefits on a wider scale, not directly associated with the building itself. Energy savings may help reduce Greenhouse Gases (GHG) – in particular, CO_2 emissions directly, and help to reach the climate goals.

Additionally, investments made in sustainable cooling solutions have an impact on the economy and society on a wider scale.

Within CoolLIFE, D2.3 *Impact assessment* currently under publication, concentrates on the impacts of the installation of different technologies and measures, while the current document focuses on the multiple impacts of behavioural changes. The theoretical background of defining the impacts and quantifying these are however included in this document, highlighting the aspects of multiple impacts of SC arising from changing technologies, and passive and behavioural measures as well.

4.1. Methodology for defining and quantifying multiple impacts

In recent years research projects have been launched to define and quantify the multiple impacts that energy efficiency improvements (EEI) can have apart from the reduction of GHG emissions. The concept of "impact pathway" was first proposed in the ExternE project and has been demonstrated in the context of Multiple Impacts (MI) [111]. In the ExternE Project, impact pathways were defined as the sequence of events connecting a burden to an impact and its subsequent valuation [112]. It is a bottom-up approach where benefits and costs are estimated by following the pathways considering the causality chain. The pathway map starts from implementing an energy efficiency action and ends at the 'endpoint'. Here, the endpoint can be defined as the last impact which is not transferring to another impact and also it is a policy target. Impact maps can help identify causal relationships and interactions among co-impacts and distinguish between co-impact end points and intermediate co-impacts that influence other outcomes, which is crucial to evaluating co-impacts comprehensively.

The impact pathway approach decomposes the chain of effects linking a root cause or causes starting from the implementation of an EEI action to the impact receptor or welfare endpoint, i.e. the impact that directly leads towards utility. This approach aims to better identify and characterize the interaction among impacts. An impact pathway map enables the representation of the multiple impacts in a way that facilitates a more consistent and comprehensive accounting of impacts and also, catalyses their integration in a way that minimizes double counting and the under- and overestimation problems.

The most recent project to map and quantify multiple impacts is the MICAT project (Multiple Impacts Calculation Tool) [6] [7]. MICAT builds upon the work of previous projects with comparable scope of Multiple Impacts [11] and COMBI (Calculating and Operationalizing the Multiple Benefits of Energy Efficiency) and ODYSSEE-MURE's (MB:EE or Multiple benefits of energy efficiency) [115] [116]. The MICAT methodology not only allows the consideration of individual EEI actions separately but by combines the findings of COMBI and MB:EE projects.

The COMBI project (Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe) [10], [117] had been the first complex approach towards the quantification of the numerous non-energy benefits of energy efficiency in the EU-28, by incorporating these multiple impacts into decision-support frameworks for policy development.

Both COMBI and MICAT follow a framework of assessing the impacts of reduced pollution on health, eco-systems, crops, resource impacts, social welfare impacts, impacts on productivity in commercial and public buildings and macroeconomic impacts: employment, GDP, public budgets, arising from a wide range of EEIs, including the residential and non-residential building sector.

The multiple impact pathway mapping approach introduced by COMBI identifies the interactions among the impacts through the following framework: i.) identification of impacts and root causes starting from energy efficiency measures, ii.) identification of overlaps between the impacts, iii.) selection of significant end-points (receptor of the impact), iv.) scenario analysis (based on a comparison of a reference scenario and an efficient scenario) v.) quantification in physical units (where possible), and vi.) incorporation in the decision-making analysis. 31 individual impact indicators were quantified in the project using state-of-the-art models.

Both MICAT and COMBI methodologies rely on existing models: GAINS model for air quality, material flow accounting for resource efficiency, general equilibrium models and input-output analyses for economic impacts, IPCC-based LCA for carbon footprinting, dedicated models for specific health and welfare outcomes relying on national statistical and EU-SILC data. COMBI developed its energy balance model for energy security. [118] While COMBI provides a complex approach to quantifying multiple benefits from EEI actions the behavioural and structural changes are only incorporated into the baseline scenarios, and energy saving from space cooling is addressed as part of the general EEI action scenarios. [118] MICAT, on the other hand, provides possibilities for custom inputs to override the default values.

The applicability of MICAT has also been extended to custom scenarios, covering a wider range of MI, providing impact quantification based on factors or functional relationships linked to energy savings, and allowing both ex-ante and ex-post calculations on EU level, or national level, and also per a smaller territory within a country.

Building upon the COMBI and MICAT methodologies, the following methodology has been followed in the current work:

1. Development of an Impact Pathway Map relevant to summer thermal comfort and space cooling

   a) identification of impacts and root causes starting from space cooling-related behavioural and energy efficiency measures
   b) identification of overlaps between the impacts,
   c) selection of significant endpoints (receptor of the impact)

As the scope of existing impact maps has been developed to apply to a wider range of EEI scenarios, combining EEI in space heating and cooling as a single root cause, a scale change is needed to identify relevant causes and amend the list of endpoints.

Space cooling and summer thermal comfort can be addressed through EEI (e.g. installing shading or active systems with better performance), behavioural measures (e.g. increasing setpoints), or lifestyle measures (reducing the need for SC demand).

2. Quantification

   d) Scenario analysis (based on a comparison of a reference scenario and an efficient scenario)
   e) Quantification in physical units, based on the framework of COMBI and MICAT, where possible

For the quantification of the multiple impacts, the existing methodologies will be used, where possible. A literature review is done to identify further quantification of the impacts identified during the mapping process, with possible indicators. During the scenario development, energy savings from behavioural measures are defined, with a focus on the member states with the highest space cooling demand.

4.2. Impact mapping

Impact maps from COMBI and MICAT were compared, and a critical review of the pathways was done to identify the relevance of the aspects of space cooling. Building on the impact map within the literature, an impact map highlighting the multiple impacts of the complex topic of the different actions regarding summer thermal comfort is shown.

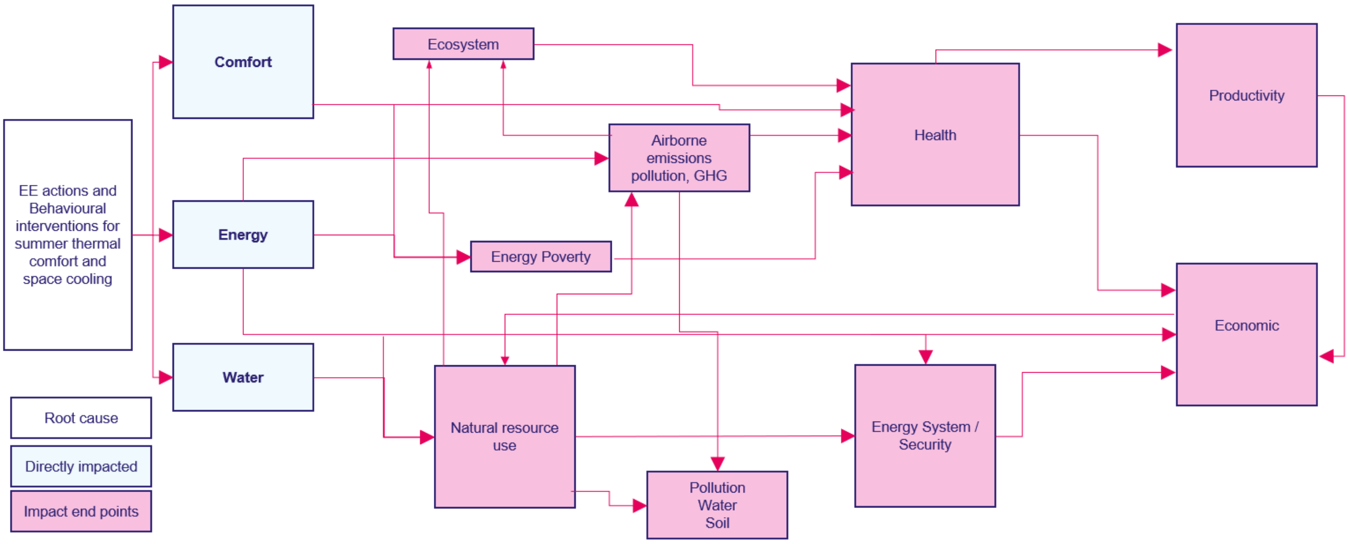


Figure 55. Simplified impact map based on COMBI and MICAT

Space cooling and summer thermal comfort can be addressed through EEI (e.g. installing shading or active systems with better performance), behavioural measures (e.g. increasing setpoints), or lifestyle measures (reducing the need for SC demand). In the following sections, the impacts are described in relationship to the summer conditions.

4.2.1. Social

4.2.1.1. ENERGY POVERTY

Globally, energy poverty reduces the well-being of several million people and causes several hundred thousand excess deaths every year, affecting both developed and developing countries [119]. Recent Energy Efficiency Directive [Article 2(49) of COM (2021) 55 final [120]] defined energy poverty, as '*means a household's lack of access to essential energy services, where such services provide basic levels and decent standards of living and health, including adequate heating, hot water, cooling, lighting, and energy to power appliances."* Others defined energy poverty as a state in which a household uses a disproportionately low level of energy services due to financial hardship (MICAT [121]) or inability to secure socially and materially needed levels of energy services at their home (IEA [122]). Adequate and affordable sources of electricity are not equally distributed worldwide, and energy poverty contributes to malnourishment, unhealthy living conditions and limited access to education and employment [123]. Bigger societal gains can be obtained when energy efficiency improvements target low-income groups [124]. Despite its global relevance and increased attention from governments, academia, and international institutions in recent decades, Guevarra et al. [11] systematic literature reports that the field lacks a clear theoretical basis, particularly an agreed-upon conceptual framework and measurement methodology. This includes ambiguous frameworks on summer energy poverty and space cooling.

In measuring energy poverty, there are two different approaches, namely a consensual approach that utilizes subjective indicators or an expenditure approach using actual or required fuel spend. Consensual approaches include measures energy poverty is measured as a yes/no question in either question on arrears on utility bills, and ability to keep home adequately warm, as gathered by EU-panel databases such as EU statistics on income and living conditions (EU-SILC) [125]. This same indicator was used to gather the percentage of fuel poverty in a study conducted in Hungary [126]. Meanwhile, expenditure-based approaches use an indicator on a threshold of their fuel costs, residual income, and poverty indicators. This notion explains that if a household's domestic energy costs exceed the designated threshold, it is likely that the household is having trouble affording sufficient energy services. For example, in the United Kingdom, their indicator named LIHC (Low Income High Cost) considers households as energy-poor if their fuel costs are above average (national median level) and if they spent all that money, they would still have a residual income below the poverty line [127]. In Hungary, Herrero et al. [126] calculated fuel poverty rates according to 10 to 20% fuel poverty line range (annual energy expenditures vs. income), rather than transferring the 10% fuel poverty line to the UK. In MICAT [121], Energy poverty was defined as either of two states of households based on low energy expenditure (M/2 indicator) or high energy expenditure share (2M Indicator) in comparison with national threshold. M/2 indicator defines households as energy poor when absolute energy expenditure is below half the national median value, while the 2M indicator defines them when the share of energy expenditure in income is more than the national median value. These indicators quantify the impact of policy-induced energy cost savings in the residential building sector, whether to enable financial access to energy services above the M/2 energy poverty threshold or decrease the share of expenditure in income below the 2M energy poverty threshold, thereby escaping energy poverty and its negative consequences [128], [129].

In the context of space cooling, summer energy poverty and indoor cooling is an overlooked issue in Europe [130]. The Cooltorise project [131] remarked that there is a lack of a common definition and specific indicators to measure and characterize summer energy poverty. As a project that aimed at raising summer energy poverty awareness to reduce cooling needs, they also concluded the need to develop new indicators for summer conditions, that can be incorporated into energy and health plans. Part of the difficulty can be shown in indicators that represent and assess energy poverty currently [132].[132]. The Energy Poverty Advisory Hub (EPAH) measures and collects data on indicators related to energy poverty, covering several indicators that are general, or applicable to space heating, the last published dataset for 2022*:*

- Inability to keep hope adequately warm,
- Population living in dwellings comfortably warm in wintertime,
- Low absolute energy expenditure (M/2)
- High share of energy expenditure in income (2M))
- Arrears on utility bills: percentage of households that are unable to pay the utility bills.

One of the mentioned Eurostat indicators, “inability to keep home adequately warm” [125], is frequently used as the key indicator to assess the number of energy-poor households, despite focusing solely on winter. The complementary indicator would be the “share of population living in a dwelling not comfortably cool during summer time” [133], however, this indicator has been only surveyed once last 2012. Up-to-date data on the number of households suffering from summer energy poverty is not available. Indeed, summer energy poverty remains to have significantly less effort compared to other indicators.

Interventions aimed at handling Energy Poverty are generally associated with improvements in health and a reduction in exposure to health risk factors [129]. Tax systems, low energy investments, as well a lack of awareness and knowledge can be considered as a driving force of energy poverty [134]. Various government programs, such as the Warm Front Scheme [135], provide grants of up to UK£2500 to households in or at risk of fuel poverty to improve the energy efficiency of their households. Gilbertson et al. [136] analysed data from households before and after receiving the Warm Front Scheme to gauge the relative impact of improved living conditions compared with the alleviation of fuel poverty. Results show that higher temperatures, satisfaction with the heating system, greater thermal comfort, reductions in fuel poverty and lower stress were significantly correlated with improved health.

Apart from providing cleaner technologies and financial aid, behavioural change can be a significant driver for the alleviation of energy poverty. Everyday decisions made by individuals with instability homes and other financial struggles have limited cognitive resources to make rational decisions [137]. Understanding such scarcity in decision-making can aid us in identifying behavioural factors that affect energy poverty, such as those that relate to budgeting ability, energy consumption and energy efficiency adoption [138]. A pilot study, by Caballero & Della Valle [139], conducted in an Italian social housing context examined the effectiveness of norm-based interventions in energy-vulnerable groups. Despite providing a useful methodology insight on designing behavioural-informed interventions, complications from the study arose, including data limitations, narrow research, and application of a uniformly applied norm-based intervention. However, they advise further research on the pilot/study’s household composition and energy consumption to design behaviour change interventions.

In MICAT [121], [140] Energy poverty was defined as either of two states of households based on low energy expenditure (M/2 indicator) or high energy expenditure share (2M Indicator) in comparison with national threshold. M/2 indicator defines households as energy poor when absolute energy expenditure is below half the national median value, while the 2M indicator defines them when the share of energy expenditure in income is more than the national median value. These indicators quantify the impact of policy-induced energy cost savings in the residential building sector, whether to enable financial access to energy services above the M/2 energy poverty threshold or decrease the share of expenditure in income below the 2M energy poverty threshold, thereby escaping energy poverty and its negative consequences [128], [129].

4.2.1.2. HEALTH

Heat Mortality & Morbidity

As widely evidenced in the literature, e.g. [141], [142] the effect of extreme heat can cause various health issues, very high ambient temperatures have been associated with an increase in mortality, hospital admissions, and other morbidity outcomes. It is expected that large increases in mortality will be a result of heat extremes due to warming associated with climate change [143]. Exposure to high daytime temperatures is known to increase the risk of death in vulnerable individuals. Heat waves are usually defined as “a marked unusual period of hot weather over a region persisting for at least two consecutive days during the hot period of the year based on local climatological conditions, with thermal conditions recorded above given thresholds [144].” Morbidity and mortality risk of people with pre-existing medical conditions get worse during heat wave episodes, young children and older people are more affected by high indoor temperatures [142]. Meanwhile, Murage et al [141] showed that high nighttime temperatures, especially when preceded by a hot day, can carry an additional risk of heat-related death, which may be highest in patients with heart diseases, and contribute to mortality risk in people below the age of 65 years.

In defining mortality, refers to the incidence of death or the number of deaths in a population, while morbidity refers to an incidence of ill health in a population [145]. Of these, IEA [122] research indicates a strong causal relationship between temperature-related deaths and respiratory and cardiovascular diseases. The temperature of the environment plays a major role in the fluctuation in mortality [146],[147] and morbidity [148] over time. In a critical review of atmospheric temperature and human mortality, Gosling et al. [149] elaborated on the three methodological approaches for calculation for temperature mortality studies, namely the calculation of excess mortality, the epidemiological approach, and the synoptic climatological approach. In comparison with the three approaches, the epidemiological approach is most common, where it involves explaining an outcome measure (ex. mortality) based upon a predictor (ex. temperature) and potentially confounding variables such as season, air pollution, other meteorological variables and socio-economic status [147]. Studies, such as Roldán et al [150], applied the epidemiological approach and studied the temperature threshold that triggers an increase in heat-induced mortality in Zaragoza, Spain. A longitudinal ecological study based on ARIMA (autoregressive integrated moving average) time series model for daily deaths was conducted and the relative risk of mortality for each degree above the temperature threshold was determined. Mortality showed a statistically significant increase when the daily maximum temperature exceeded 38oC. Their study resulted in identifying that a total of 107 heat-attributable deaths were estimated for the period 2002-2006, while in-hospital estimated costs of these deaths reached Euro 426,087 (95% CI Euro 167 249 – Euro 688 906). Another study, Gasparrini, Armstrong, Kovats & Wilkinson [151], contributed to assess heat-related mortality for a wide range of causes using data for England and Wales in the period 1993-2006. Heat-related was created by a combination of a time series analysis and an all-cause mortality model [152] that were gathered using parameterization, lag choices and maximum temperature index using Poisson distribution for a time series regression. Results show that there was evidence of increased mortality with heat for almost all cause-of-death groups examined, with an overall increase in all-cause mortality of 2.1% (95% CI 1.6%-2.6%) for 1℃ rise above the regional heat threshold. Meanwhile, Masselot et al. [153] used a three-stage method to estimate risks of temperature continuously across the age and space dimensions of urban areas in Europe. Results showed that an excess of 20 173 deaths from heat annually and according to age-standardised rates, 13 deaths per 100 000 persons per year occur respectively based on an analysis of 854 urban areas in Europe. There were different results across Europe and age groups, with cold and heat having the greatest effects in eastern European such as Croatia, Bulgaria and Romania. In terms of adaptive strategies, videos made by the government for heat wave awareness are most effective in reducing deaths, followed by newspapers and radio [154].

Meanwhile, morbidity statistics rely on disease registers, ad-hoc studies and self-reported information from the EHIS or EU-SILC surveys [155]. These either be self-perceived or diagnosed or reported by a professional. concentrates mostly on hospital admissions or heat-related emergency data [148]. Often, indicators of morbidity include administrative data on emergency department visits (EDV) and emergency ambulance dispatches (EAD). These indicators showcase vulnerabilities of the elderly and those with existing diseases such as ischemic heart disease, respiratory disease, cardiovascular disease and chronic obstructive pulmonary disease that are most susceptible to extreme temperatures, which typically occur with lags of less than 3 days for heat [149]. In the United States, Guirguis, Gershunov, Tardy & Basu [156] reported a 7% increase in hospital admissions during the peak heat waves in California Other recent metrics of heat-related morbidity use weight-sum daily water loss from patients suffering from heat-related illnesses together with integrated computational techniques, as what was used in Kodera et al. [157]. [157].

Similar to Energy Poverty Indicators, indicators towards health and comfort during winter were more common than those of summer indicators. Multiple studies have limited their view on thermal comfort only during winter [158] [159], and the recent HORIZON EU Projects, COMBI [117] and MICAT [140] have only focused on avoiding excess cold weather mortality. On measuring and quantifying heat-related mortality, Ballester et al. [160] used epidemiological models to estimate the sex- and age-specific mortality burden associated with the record-breaking temperatures registered during the 14 weeks between 30 May and 4 September 2022 (weeks 22–35). They then compared it within the broader context of the summer of 2003 and the accelerated warming episode observed in the continent during the last decade (2013-2022). The results estimated that there were 62,862 heat-related deaths in Europe in 2022; 61,672 of those deaths occurred between 30 May and 4 September. Italy, Spain, Germany, France, the United Kingdom and Greece had the highest summer heat-related mortality numbers.

In relation to adequate indoor cooling, the vulnerability of households towards extreme heat should be accounted for. Thomson et al [130] noted three aspects that characterize the vulnerability and risks of excessive heat in households, namely the risk of indoor warmth (measured by size and orientation of windows, presence or absence of shading, number and orientation of windows, building material and presence of absence of insulation), the capacity to adapt (based on the size of home, the accessibility of cool spaces, the incomes, tenancy relations and built environment flexibility), and the sensitivity to harmful consequences (based on age and health status). Other determinants of heat-wave morbidity include adaptation to heat waves (captured by adaptation score), urban/peri-urban background, family size, disease burden, and high income [161].

Passive solutions, such as adequate ventilation, shutters, and operable windows, in heat-vulnerable dwellings can significantly reduce heat-related mortality, as shown in the study by Taylor et al. [162]. The researchers modelled dwellings in the United Kingdom with and without energy efficiency, occupant behaviour, and passive overheating interventions, but did not include air conditioners since they are uncommon in the country. Metamodels were developed using EnergyPlus and artificial neural network models to create simulations on energy use and indoor temperature. Then, heat-related mortality was calculated by applying West Midlands-specific temperature-mortality functions to EHS occupant age data and corresponding estimated dwelling indoor temperatures, which was supplemented by proxies of heat-associated mortality from external sources (Probability of mortality from heat-exposed groups, temperature mortality slopes from relative and absolute temperature changes, age-specific all-cause mortality rates by season and meta-analysis on the nationally pooled estimates of high temperature effect on mortality). The resulting combination of the mortality and metamodels created the three summer weather scenarios (2030, 2050 and 2080), which resulted in showcasing that external shutters were most effective in reducing heat-related deaths by more than 43 per cent, 40%, and 37 per cent, respectively. These results indicate that external shutters are a more efficient and effective way of reducing internal temperatures in the summer. Additionally, these interventions must be easily accessible and operable for occupants, especially those who are heat-vulnerable or have limited mobility, such as vulnerable elderly occupants.

Monetization of the health impact can be done though estimation of costs of hospital care in the public budget. In determining the impact of extremely high temperatures on mortality and mortality costs, Roldán et al [150] reported that in-hospital estimated costs of these deaths reached Euro 426,087 (95% CI Euro 167 249 – Euro 688 906).

In MICAT [121], Heat Mortality and Morbidity are not included in its quantification and monetisation of multiple benefits of energy efficiency actions.

Health issues from overcooling

In addition to being exposed to high temperatures in the summer, suboptimal operation of conditioned buildings, for example, overcooling can also have adverse health effects. Liu et al [163] named indoor thermal factors of air temperature, humidity, and Liu et al [163] named indoor thermal factors of air temperature, humidity, and air movement as possible causes and divided health impacts into three categories, namely, sick building syndrome, metabolic syndrome, and respiratory disease. They suggested optimal temperature ranges in summer to prevent Sick Building Syndrome between 20-23 °C and 20%–60% but also concluded that heat exposure at temperatures above 30 °C can be regarded as anti-obesity and anti-diabetes treatment. The maximum summer indoor temperature to ensure cardiovascular health was suggested at 30 °C, but for patients with respiratory diseases maximum of 26 °C was suggested.

D'Amato et al [164] showed possible negative consequences on the respiratory system when the air temperature drops quickly without any gradual adaptation. Even for changes as low as 2°–3° C, but especially for changes greater than 5° C severe exacerbation of the symptoms of the person's chronic respiratory disease has a risk. Xiong et al. [165] studied the influence of different air temperature step-changes, when exposed to sudden temperature change (for example entering/exiting an air-conditioned building from/to outdoors). As a result of their study, perspiration, eyestrain, dizziness, accelerated respiration, and heart rate are sensitive self-reported symptoms in response to temperature step-changes.

Another study reported a significant increase in sickness absenteeism, 6 days/100 workers/month in a group moving from naturally ventilated to an air-conditioned office. [166] Ganji et al [167] also showed that sickness absenteeism is more common among AC users than non-AC users, but not equally among the genders: significantly more females were affected compared to males. [166] They conclude that the higher prevalence of SBS-respiratory and allergic symptoms in AC compared to people working in naturally ventilated buildings leads to absenteeism from work, however, this is not only associated with the temperature, but they emphasise the necessity of regular cleaning of AC devices to avoid health risks. [165]

Air Pollution

It has been seen in the literature that behavioural actions that are applied to maintain summer thermal comfort may also influence the air change rate in the building[168], [169]. In a review by Dimitroulopoulou [168], European ventilation measurements show ventilation practice often being poor and resulting in reduced ventilation rates, increased concentrations of indoor pollutants, and thus exposure to health risk. Fisk and Rosenfeld [170] suggested that better ventilation reduces the costs related to allergies, asthma and sick building symptoms. Kosonen and Tan [171] calculated with an estimate of 10% annual health related savings due to improved contaminant removal efficiency, the estimated productivity loss difference of 0.5–2% between mixing and displacement system could mean $3–12 billion savings. According to their results, the authors recommend increasing outdoor airflow, reducing emissions, and improving ventilation efficiency to improve productivity. The adaptive thermal comfort theory relies on opening windows for temperature control, in lack of mechanical space cooling. However, when installing active space cooling devices, window opening might be diminished.

In Portugal [172], a study on measured summer ventilation rates showed that the average ventilation rates in the flats with a mixed system were always greater than those in the flat with the natural ventilation system. In the CoolLIFE household survey, more than 90% of the respondents confirmed to limit the window opening to the coldest parts of the day. [3] When air-conditioning is used, limiting the window opening is reasonable for energy savings, however, this might reduce IAQ. Thus, ventilation and the cooling strategy does not only affect thermal discomfort and energy efficiency, but also has an effect on the indoor air-pollution. In British dwellings, A study on naturally ventilated households without air-conditioning devices [173] showed that these were better ventilated in summer, than in winter.

In the CoolLIFE household survey, more than 90% of the respondents confirmed limiting the window opening to the coldest parts of the day [2] When air-conditioning is used, limiting the window opening is reasonable for energy savings, however, this might reduce IAQ. Thus, ventilation and the cooling strategy not only affect thermal discomfort and energy efficiency but also affect indoor air pollution.

In commercial buildings, controlled mechanical ventilation is more widespread than in residential buildings. Kosonen & Tan [171] reported the impact of perceived indoor air quality on productivity loss in air-conditioned office buildings. Kosonen & Tan [171] reported the impact of perceived indoor air quality for productivity loss in air-conditioned office buildings. They applied a productivity calculation model based on pollution loads and contaminant removal effectiveness. Their next step was to estimate how the improved ventilation efficiency affected productivity. According to the results, dissatisfaction is a good predictor of productivity loss due to perceived indoor air quality in different office tasks. The authors recommend increasing outdoor airflow, reducing emissions, and improving ventilation efficiency to improve productivity.

Fisk and Rosenfeld [170] suggested that better ventilation reduces the costs related to allergies, asthma and sick building symptoms. Kosonen and Tan [171]Kosonen and Tan [171] calculated with an estimate of 10% annual health-related savings due to improved contaminant removal efficiency, the estimated productivity loss difference of 0.5–2% between mixing and displacement systems could mean $3–12 billion savings.

In MICAT [121], the impacts of air-pollution are measured by its air-pollution mortality and morbidity due to ambient PM2.5 pollution. It considers the relevant local air pollutants (SO2, NOx, primary PM2.5) that are typically emitted in combustion processes related to energy. These are monetised using the concept of the value of statistical life which the tool applied the method developed for the CarBonH calculation tool [174]. The tool related ambient concentration of PM2.5 to the number of hospitalizations and work days lost, which can be translated into direct costs, using country-specific values for unit costs.

Wellbeing benefits of Nature-based Solutions

Nature-based solutions (NbS) can address the challenges of UHI and heat waves, through the provision of cooling service, reducing the urban heat island effect up to 2 °C, which has direct benefits as reduction of space cooling energy use or increase in thermal comfort. The combination of both green and blue infrastructures in cities maximizes the environmental capital and cooling efficiency gained, which provides synergistic cooling and other ecosystem services to urban areas [175]. By providing better microclimate, the uptake of passive measures like daytime or nighttime ventilation can increase. In an literature review by He et al. [176], the authors identified the potential reduction of cooling and heating energy demand of different Nature-based solutions in different climate conditions and at different building scales. They examined different NbS, including green roofs, green walls, trees (trees, urban forests, greenbelt, etc.), and water features (wetland, lakes, etc.). Most of their analysis concentrated on green roofs, followed by green walls. Furthermore, their review revealed that NbS vary to having energy saving potential from 3% to 90%, and to having potential heating energy demand reducing from 0,58% to 60%. NBS type and climate determine the extent of the reduction in both cases. In an impact health assessment of 93 European cities, Iungman et al. [177] estimated that increasing tree coverage to 30% for each city would cool cities by 0,4ºC and prevent 2644 premature deaths. Their result showed the deleterious effects of UHI on mortality and highlighted the health benefits of increasing tree coverage in cities, preventing summer deaths.

Green Roofs have a significant impact in temperature regulation in buildings and in lowering the damaging effects of heat waves in human health. In Green roofs, the evapotranspiration of water from vegetation in green roofs induces the evaporative cooling, that disperse the latent heat associated with solar radiation, and thus, implies cooling energy saving[178]. This includes identifying the vegetation's Leaf Area index, which is a major parameter when considering the influence of evaporation rate affecting green roof [179]. Other factors of the green roofs that increase energy savings includes thicker soil and certain plant heights to act as additional thermal insulation and mass [180]. In Sicily, Ferrante [181] studied six typical vegetated species for green roof apparatuses, and depending on the given vegetated species, it was discovered that a higher leaf area index effectively decrease cooling energy consumption. Using simulation approaches, Avila-Hernández et al. [182] found that extensive green roofs could reduce cooling energy consumption by up to 90% in one residential building in Tlaxcala, Mexico. In terms of health, Marvuglia et al. [183] use a spatial microsimulation model to simulate the effects of heatwaves on green roof installations in cities. Their model simulates a 1.5 °C to 3 °C reduction in indoor temperature caused by green roofs (based on inferences from literature on green roofs) in four European cities: Szeged (Hungary), Alcalá de Henares (Spain), Milan Metropolitan City (Italy), and Ankaya municipality (Turkey). Besides reducing cooling energy costs, green roofs provide additional benefits such as reducing stormwater runoff, absorbing pollutants and CO2, providing natural habitat, and, in the case of intensive green roofs, providing recreational green space [184].

NbS has further social co-benefits that extend beyond cooling and mitigation of urban heating island effects. In a NATURVATION report [185], the authors identified and used six types of social and four types of cultural benefit from various studies [186],[187],[188] to create a selection criteria for their study on social and cultural co-benefits of NbS. For social benefits, this includes wellbeing enhancement, opportunities for social interaction, enhancement of equality, growth of employment, education development, safety advancement, while for cultural benefits, this includes aesthetic improvement, spiritual connection, preservation of cultural heritage and recreation opportunities.

4.2.1.3. PRODUCTIVITY (THERMAL DISCOMFORT)

Productivity has a substantial effect towards increasing the benefits for the industry and households. Metrics relevant to productivity include factors such as heating, ventilation, air-conditioning systems and modal shift towards active transportation [124]. Aside from reducing energy costs, industrial energy efficiency measures improve competitiveness, profitability, productivity, product quality, and working conditions while also lowering costs for operation, maintenance, and environmental compliance. The layout of the office environment and office comfort can influence productivity in the workplace. Haynes [189] emphasizes that office productivity takes into account both physical and behavioural aspects of the work environment. His model used seven distinct components to represent office productivity: Distractions, Environmental services, Office layout, Interactions, Designated Areas, and Comfort & Informal interaction points. Brophy et al. [190], in their report to create the net benefits using a cost-benefit analysis on the homes in Ireland, valued comfort by using the proxy indicator ‘proportion of energy forgone’, for individuals’ willingness to pay to increase comfort levels in their homes. Their analysis shows that the comfort benefits of the household stock in Ireland total £ 364 million at a 5% discount rate. According to the IEA report [122], It is possible to derive productivity and operational benefits worth 2.5 times (250%) the value of energy savings (depending on the value and context of the investment).

High temperatures, especially when coupled with high humidity, can cause discomfort. Studies suggest that reducing moderately high indoor temperatures from around 25°C, which is still within the comfort range, to 20°C has shown an improvement in the performance of tasks and also in test results [97]. In a study by Goodman et al [191], the student fixed effects were modelled from data gathered from 10 million PSAT-takers and found that without air-conditioning, each 1-degree Fahrenheit increase in a school year temperature reduces the amount learned by students that year by one per cent. Temperature remains one of the important factors to keep students comfortable and focused [143]. Apart from students, in a variety of industries, excessive heat in the workplace poses a serious health hazard to employees. A heavy price is also paid by employers for reduced productivity and increased sick leave due to cognitive and physical impairments [193].

Devices have a key role in reducing energy cooling, however these must be treated with caution. Air conditioning is one of the technologies that has revolutionized the world by improving comfort, health care, and productivity [194] and includes internationally recognized standards to address the complex relationship between comfort, temperature, humidity, clothing, and activity [195]. The work of Grignon-Massé [196] created a measure for summer comfort in the French context, to evaluate different energy demand management solutions, such as air conditioning- The author concluded that air conditioning rooms produce different results from the perspective of society or private individuals but maintained that when noise discomfort was considered, air conditioning was still socially optimal. Grignon-Massé [196] continued by monetizing summer discomfort through welfare monetization (willingness to pay) and scenario building. Their methodology was to compare the improvement in comfort and the electricity consumption generated by an air conditioner and a pedestal fan in a residential context. Despite significant limitations, their study verified that the discomfort cost defined for the tertiary sector (60 € cts per degree-hour of discomfort and occupant) was of the same order of magnitude as for the residential sector.

However, the use of air-conditioning has its downsides, especially during intense peak summer that results in severe strain on the national electricity system with peak electricity demand [197]. Jay et al. [193] argue that future reliance on air conditioning is unsustainable and further marginalizes vulnerable communities to heat. Conventional Space Cooling (AC), according to Thomas & Butters [198], is inequitable as the AC practice of richer citizens worsens the thermal environment of the urban poor by injecting more heat into the city. During peak-demand episodes when heat extremes coincide with peak-energy demands, air conditioning in residential and commercial buildings can severely strain electricity grids, such as the case in the US [199] and China [200]. Cutting power or other power disruptions, especially to countries with dependence towards air-condition such as Australia, would be estimated to increase the risk of dying from heat-related illnesses by 50% in Australia [201].

Other drivers of productivity in space cooling are passive measures to boost thermal comfort. Fisk, Black & Brunner [202] modelled the different amounts of outdoor air ventilation in the US offices to estimate their benefits and costs. Factors included changes in sick building syndrome symptoms, work performance, short-term absence and building energy consumption. Results show substantial benefits in magnitude and far exceed the energy costs for increasing Ventilation rates in offices above the minimum requirements. A study by Escandón et al. [203] identified which user behaviour reduces thermal comfort by using adaptive comfort models of office buildings. In-situ measurements were collected to monitor the building, which included air temperature, relative humidity, CO_2 level, energy consumption and thermal comfort levels of three housing units built in southern Spain between 1960s and 1980s. User pattern were also collected to identify the occupant's habits, etc. of each of the separate buildings. Based on the results, the case studies are in discomfort during a high percentage of occupied hours due to the severe climate and the use of passive measures such as natural night-time ventilation and solar protection that are unsuitable. The situation worsens due to the limited use of local cooling systems due to financial constraints.

In MICAT [121], thermal discomfort are not included in its quantification and monetisation of multiple benefits of energy efficiency.

4.2.2. Economic

4.2.2.1. ENERGY INTENSITY

In a report by the International Energy Agency [200], energy consumption for space cooling in buildings has tripled since 1990, more than any other building end-use. Air conditioning (AC) systems and electric-powered fans are increasingly contributing to global energy consumption for space cooling. There is already an enormous strain on electricity systems in many countries because of increasing demand for space cooling, as well as an increase in emissions as a result. Other articles alarm the use of AC as a primary solution for cooling. Randazzo et al [204] suggest that AC devices on average spend 35%–42% more on electricity than households which do not. They suggest, that the increasing number of CDDs due to climate change, could lead to a wider adoption of air conditioning, and therefore could lead households to spend a larger share of their income on electricity, which, through the high share of energy expenditure in income, increases energy poverty. However, if summer comfort was considered in the design and renovation of the building, the author emphasized that the use of air-conditioning could be avoided [196]. Other low-tech solutions exist that require less energy and have a high potential to reduce the interior temperatures of a house during summer [205].

In MICAT [206], Energy Intensity indicator is described as the necessary energy needed for an economy to produce one unit of GDP. It is quantified by dividing the difference between gross inland energy consumption and final energy consumption for non-energy uses by their gross domestic product.

4.2.2.2. GROSS DOMESTIC PRODUCT (GDP)

The GDP impact results of several effects, including employment, innovation, competitiveness, productivity, and health, thus, individual impacts and GDP are highly interconnected and overlapped. In MICAT, during quantification, to avoid double counting, only corporate, value-added, income, and social welfare taxes are included in the assessment of the impact on public budgets. In determining the impact of extremely high temperature on mortality and mortality costs, Roldán et al [150] reported that in-hospital estimated costs of these deaths reached Euro 426,087 (95% CI Euro 167 249 – Euro 688 906).

In MICAT [206], the indicator for GDP describes the impacts of energy savings on GDP or value added implications of planned polices or measures in a macro-economic perspective. Using an IO-Analysis, its quantification follows how much the total demand that will be generated by additional investments per 1 million Euros.

4.2.2.3. EMPLOYMENT EFFECTS

In MICAT [206], the indicator for employment effects describes the impacts of energy savings on employment or implications of planned policies or measures in a macro-economic perspective. Using an IO-Analysis, its quantification follows how much the employment that will be generated by additional investments per 1 million Euros.

4.2.3. Environmental

4.2.3.1. NATURAL RESOURCE USE

In general, the use of natural resources can be associated with fossil fuels extracted and used for both the building operation and the raw materials used during the construction of technologies and installing products for achieving energy efficiency. As detailed in D2.1 99% of the space cooling market is dominated by conventional Vapor Compression (VC) air-conditioning systems, that use electricity as the final energy carrier. The quantification methods of these have been developed taking into account both electricity and other fuel types relevant to the country-specific energy mix, thus addressing the impact of saving electricity by sustainable space cooling is covered in the existing methodologies.

However, in opposition to space heating, the use of water as a resource during operation for space cooling is required for some space cooling technologies. While from the technological aspect, in the residential sector packaged systems are predominant, the chillers mainly used in the non-residential sector may consist of air-cooled, water-cooled and absorption chillers, of which the latter two use water at the cooling tower. A recent paper [207] compared water use for cooling, power and total upstream water-for-electricity uses for the three chiller types in the US using a mass and energy balance model, with a result of an average total water consumption of 9.26, 8.32 ± 0.246, and 3.89 ± 0.336 m3 of total water per MWh of cooling, respectively. They argue that while the cooling and power water use is the lowest for the air-cooled chiller, there are tipping points for the total lifecycle water consumption of the power grid, below which the water-for-cooling of the water-cooled and absorption chillers can be less than the air-cooled chiller. As a similar study has not been found in the European context, further research is needed on the water impact of space cooling technologies, considering the European electricity mix.

Further on, passive measures, relying on Nature-based-Solutions (NbS) principles like vegetation, roof ponds, or urban scale solutions like pavement watering, evaporative surfaces, or behavioural measures like showering or drinking water all use water as a resource.

In MICAT [208], Material footprint is the difference (usually savings) between before and after energy-efficiency measures take effect (pre and post action) in the removal or extraction of material resources from nature. These savings include the savings of abiotic (fossil fuels, minerals, metal ores) and biotic raw materials from nature; including raw materials without economic use (unused extraction). Overall this indicator shows the material usage in the production phase and use phase, this shows how much materials has to be invested and is saved over time period of measure is introduced.

4.2.3.2. EMISSIONS

Green House Gasses related to the space cooling are emitted on one hand directly, due to the refrigerants needed for the operation of most widespread technologies, on the other hand, indirectly, that are emitted during the energy production. Direct emissions depend on the refrigerant types, characterized by their ODP and GWP values, while the indirect emissions are specific to the energy mix in a given country. GHG emissions are mainly expressed in tCO2eq.

Further pollutant emission of further pollutants also arise when combustion technologies are used for grid electricity production, in the form of NO_x, SO_2.

4.2.3.3. IMPORT DEPENDENCY

Import dependence as defined by MICAT *“describes the share of an energy carrier’s domestic consumption, which needs to be imported from abroad”.* [209] Import dependency can be reduced by reducing the quantity used for certain energy carriers. The importance of import dependency has risen in the last few years due to the energy crises and Russia’s war in Ukraine.

4.2.3.4. IMPACT ON RES TARGETS

In MICAT [208], the RES targets refer to the binding targets from the Renewable Energy Directive regarded as the share of energy originating from renewable energy sources. The indicator compares the gross available energy from renewable resources by the total gross available energy without energy savings from the same calculation with energy efficiency savings from intervention. This indicator is monetised using statistical transfer costs.

4.3. Quantification

4.3.1. Scenario development

The biggest methodological challenge in the quantification of multiple impacts arising from behavioural changes is the development of realistic scenarios. Uncertainties exist in the total final energy consumption for space cooling in the building sector, but also in the current uptake rate of behavioural measures. To estimate the possible impacts of increasing the uptake of behavioural measures, we have implemented a methodology of collecting and comparing different sources, as shown in Figure 56.

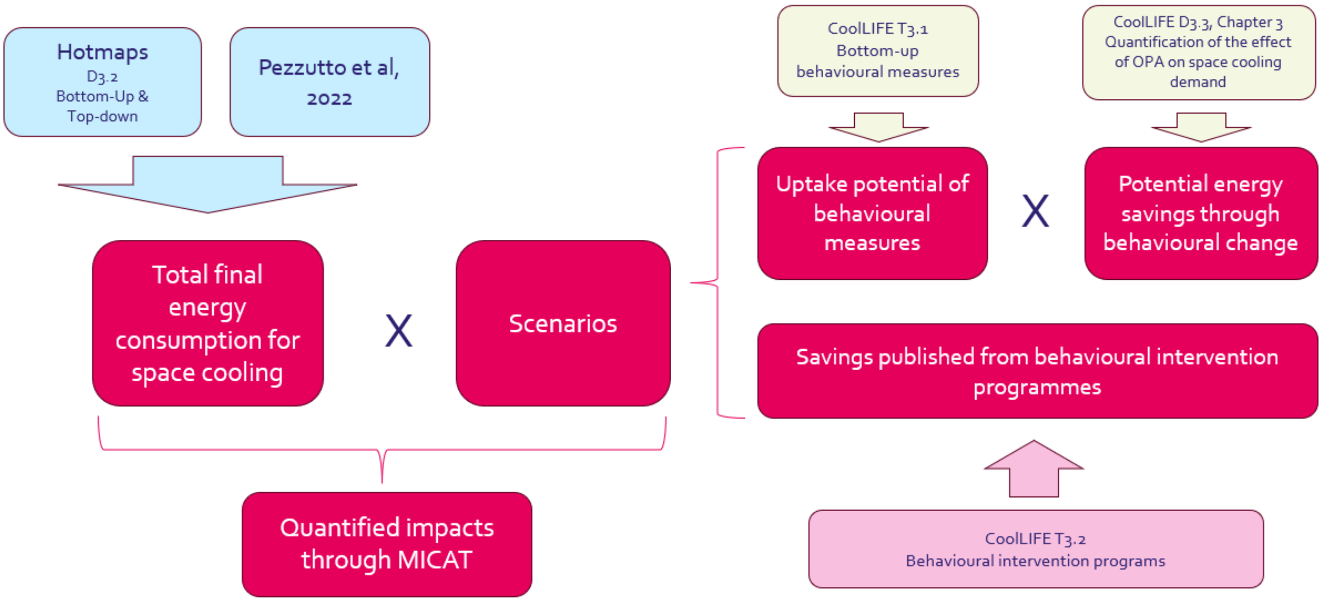


Figure 56. Quantification methodology of multiple impacts arising from behavioural interventions for space cooling

For the total annual final energy consumption from space cooling, the collected data through the top-down and bottom-up approaches of the HotMaps project [210] has been compared with the data from Pezzutto et al [211]. The final energy consumption of the EU27+UK territory, EU 27 without the UK and the top 5 member states with the highest space cooling energy use (Spain, Italy, Greece, France and Germany) are shown in For the total annual final energy consumption from space cooling the collected data through the top-down and bottom-up approaches of the HotMaps project [210] has been compared with the data from Pezzutto el al [211]. The final energy consumption of the EU27+UK territory and the member states with the highest space energy use are shown on Table 30. The top 5 countries with the highest space cooling energy use to cover 84-86%, 90-93% and 82-85 of the total space cooling final energy use of the EU, for the total building stock, residential and tertiary sectors respectively. In the quantification, the highest values coming from the sources have been used. The HotMaps project [210] bottom-up approach calculated the following distribution of space cooling final energy demand through the different building subsectors in the EU27+UK: The HotMaps project [210] bottom-up approach calculated the distribution of space cooling final energy demand through the different building subsectors in the EU27+UK Table 31).

Table 30. Final energy consumption for space cooling [TWh/year]

	Total building sector			Residential sector			Tertiary sector		
	[210] top-down	[210] bottom-up	[211] (2016)	[210] top-down	[210] bottom-up	[211]	[210] top-down	[210] bottom-up	[211]
EU 27+UK	95	113	106.10	26.82	16	22.06	68	97	84.04
EU 27	87.62		102.64	26.62		22.03	61		80.61
Spain	27		38.52	4.9		4.95	22		33.58
Italy	22		25.27	8.6		10.38	13		14.89
Greece	10		6.04	6.1		3.44	4		2.60
France	13		16.28	3.4		0.76	10		15.51
Germany	2		2.47	0.9		0.87	1		1.59
Top 5 countries coverage	84%		86%	90%		93%	82%		85%

Table 31. Distribution of Final energy consumption for space cooling per building sectors (EU-27+UK average) [210]

Sector	Final energy consumption (TWh/y)	Percentage
Residential	16	14%
Offices	19	17%
Trade	24	22%
Education	6	5%
Health	20	17%
Hotels and bars	27	24%
Sum	**112.63**	**100%**

In the previous sections, the quantification of SC energy demand with different lifestyle comfort and user behaviours has been explored. It has been shown that the user behaviour can reduce the cooling demand of the residential buildings. When applying the combination of behavioural interventions, there is a potential to reduce the space cooling demand of an individual residential building by 69-77% when a mitigative behaviour is followed, and between 97%-100% with the adaptive behaviour. The potential reduction of space cooling demand in the service sector resulted in the range of 67-84% for offices, 58-69% for educational, 38-48% for hospitals, and 48-69% for hotels for the spaces evaluated. However, while these results show that in the selected countries, building archetypes and scenarios it could even be possible to eliminate the use for space cooling demand in the residential sector, and significantly reduce cooling demand in the service sector, these values can only be considered as theoretical maximums of individual buildings.

The cooling demand savings in practice deviate from the potential shown with the theoretical conscious behavioural simulations, which cannot fully be realized in practice due to several limitations: i) Occupants already implement behavioural measures, but to different extent, ii) building stock: applying behavioural measures like the control of shading devices or effective ventilation is only possible if these devices are already installed, iii) the practical application of behavioural change interventions that need to change habits is a great challenge, iv) the rebound effect demonstrated in studies show that savings achieved by behavioural interventions are compensated by wasting energy, which results in the same amount of energy consumed.

To quantify these effects data in the literature is scarce. The survey done for the residential sector in Hungary within CoolLIFE shows that more than 75% of the respondents apply conscious ventilation strategies, night-time ventilation is already applied in nearly one-third of the households, nearly two-thirds of the respondents use fans, and nearly 80% of them use shading on hot days. It also confirms that around 25% of the households have no controllable effective shading systems, but only internal curtains.

As seen in the collection of behavioural intervention programmes in D3.2, that have proven to successfully result in energy savings, the realistic energy savings are much lower. The empirical examples showed a maximum 12% reduction in energy use for residential buildings and up to 15% reduction in energy use for offices, which is much lower than the potential shown by the simulations. The report from the UK Government on applying behaviour change and optimized operational methods for reducing energy consumption reported over 10% reduction in CO_2 emissions in one year. [212]

Taking into account the uncertainties of the input data a theoretical scenario has been used to quantify the multiple impacts from energy savings from behavioural measures, compared to the baseline, business-as-usual scenario incorporated in the MICAT tool, based on the maximum achievements reported in the empirical studies. However, while in the residential and office sectors, it is easy to find examples of successful behavioural interventions, within the non-residential sectors, there is a lack of coverage of other building types. The assumptions for the energy use reduction percentages for the education, hotel, and hospital sectors hence are built on the results of Chapter 3, applying a reduction of possible achievements based on the relative results from the energy modelling.

Within the scenarios, the energy savings have been given as 100% energy carrier. The calculation was done for 2023 as the reference year. Calculations are done for the EU-27 region, and the top 5 countries individually. The baseline within MICAT applied different energy mix and energy price values, hence the inputs were given for the energy savings in the tertiary sector and the residential sector separately.

Table 32. Inputs for multiple impact quantification scenario

Scenario	Sector	Reduction
Efficient	residential sector	12%
	office	15%
	education, hotel	14%
	hospital	6%

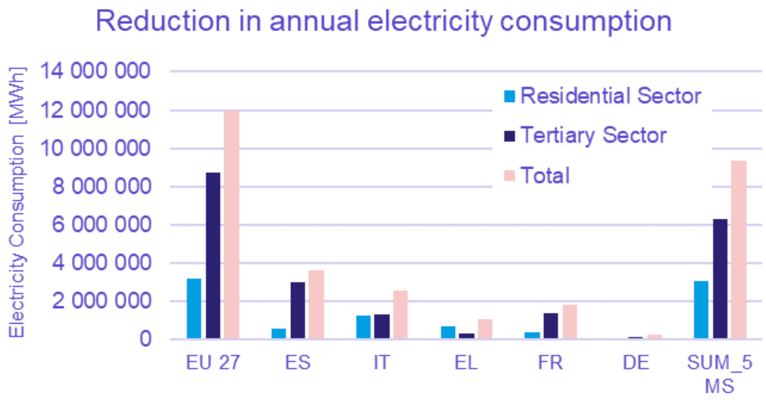


Figure 57. Inputs for the energy efficiency scenario (electricity savings per year)

Table 33. Greenhouse gas and NOx emission intensity of electricity generation

	Grid electricity CO2 emissons (2022) [gCO_2e/kWh] [213]	Grid electricity NOx emissions [g/kWh] [214]
EU 27	251	-
Spain	205	0,950
Italy	252	0,250
Greece	416	2,500
France	68	0,250
Germany	366	0,650

4.3.2. Indicators

Various indicators are quantified in the literature, each with its quantification approaches, dimensions, and governance levels (ex-ante, ex-post, top-down, bottom-up). In terms of behavioural measures the following indicators in Table 34 were selected that are affected by reduction of space cooling energy use., primarily based on MICAT.

Table 34. Quantified indicators

Sustainability Framework	Impact Category	Multiple Impacts (Indicator)	Physical Unit	Monetisation	Included in the CBA
Social	Health	Air pollution-related mortality	Number of deaths avoided	Yes	Yes
Social	Health	Working days lost (impact related to health)	Number of days gained	Yes	No
Environment	Airborne emissions pollution, GHG	GHG savings (savings of direct carbon emissions)	Mt CO2eq	Yes	Yes
Environment	Airborne emissions pollution, GHG	Reduction in air pollution emissions	tons	No	No
Environment	Natural resource use	Impacts on RES targets	%	No	No
Environment	Energy system / Security	Energy (cost) savings	MWh, ktoe	Yes	Yes
Environment	Energy system / Security	Import dependency	%	No	Possibly
Economy	Economic	Impact on GDP, and other macro-economic indicators (investment, consumption)	€ (or % change from a baseline)	Yes	No
Economy	Economic	Employment effects (by sector, country) and also capturing skill requirements	thousand persons (or % change from a baseline)	Yes	No
Economy	Economic	Energy intensity	ktoe/1000€	No	No

4.3.3. Limitations

Energy savings are calculated in comparison to a reference development (baseline). For the baseline, the scenario developed in the MICAT tool is used [11], and the EU Reference Scenario 2020 developed by E3M for measuring new policy proposals was implemented. At the national level, the baselines established by PL, IT and DE for their NECPs will be used. At the local level, MI assessment will be based on the scenarios established for SECAPs.

Context Dependency

EEI actions can be influenced strongly by the context in which they are implemented. Due to this context-dependency, impacts at different geographies may not necessarily be comparable, in terms of socioeconomic, technological, regulatory/policy framework, and environmental conditions. At the local level, these context-specific conditions can be taken into account more easily and more precisely, which should increase accuracy. In practice, however, local data availability is generally lower than national or EU data availability. Similarly, poor data or inaccurate assumptions at the local level can negatively impact the results (if an indicator can be quantified at all). As much as possible, it is important to take these contextual dependencies into account in the selection and development of methods for quantifying the indicators, assumptions, and data.

Non-linearities of impacts

For simplicity's sake, multiple impacts are often estimated by simplified impact factors based on a linear relationship. Cause-effect relationships are formulated as linear functions so that multiple impacts can be calculated using a simple impact factor. Based on the specific indicator analysed in MICAT, it is possible to justify a linear relationship since it produces fairly accurate results for the range of scenarios and policies that could be evaluated. However, it may be more appropriate to represent impact quantification as a function of multiple factors.

Double-counting

MICAT aggregates the physical impacts into a Cost-Benefit Analysis (CBA) by monetizing them through market prices, or proxies to market value (avoided costs or willingness to pay). As a result of these aggregations, double-counting of impacts in the cost-benefit analysis, overlaps, and interactions between indicators may occur, which makes estimating the total benefits difficult.

Examples in MICAT where double counting concern social and economic benefits, environmental and economic impacts and interactions among macroeconomic impact. For example, as a result of energy efficiency renovations, indoor thermal comfort, air quality are all positively impacted on health and productivity, which ultimately impacts the public budget (partial overlap between health, productivity, and economic impacts) [215]. Air pollution reductions result in reduced mortality and morbidity among whole populations, not just specific groups. A decrease in energy costs results in a reduction in financial burdens on household budgets (alleviation of Energy Poverty), which are already recorded in the monetised energy savings indicator.

There are several indicators that are simply specifications of energy cost savings. This is because the associated costs are internalised into the energy price. Among the other indicators, it applies to industrial productivity, and avoided investments in grid and capacity expansion.

4.4. Results

4.4.1. Social

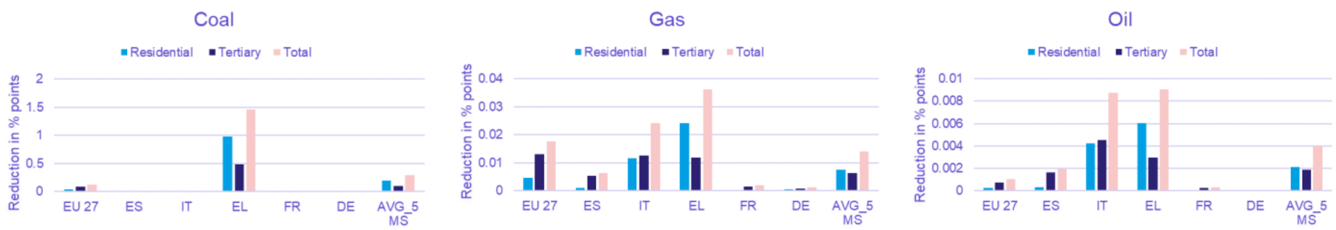
a) **b)**

Figure 58. Social impacts of the behavioural changes implemented in the energy-efficient scenario

On the EU-27 level, the premature mortality due to air pollution could be reduced by 15 per year, while the lost working days due to air pollution-related illnesses can be reduced by 4284 in total. From the top 5 countries, the impacts are highest in Italy.

4.4.2. Economic

The import dependency can be reduced by the highest percentage considering coal in Greece, up to 1.5 % points. The effect in the other countries and fuel types is low.

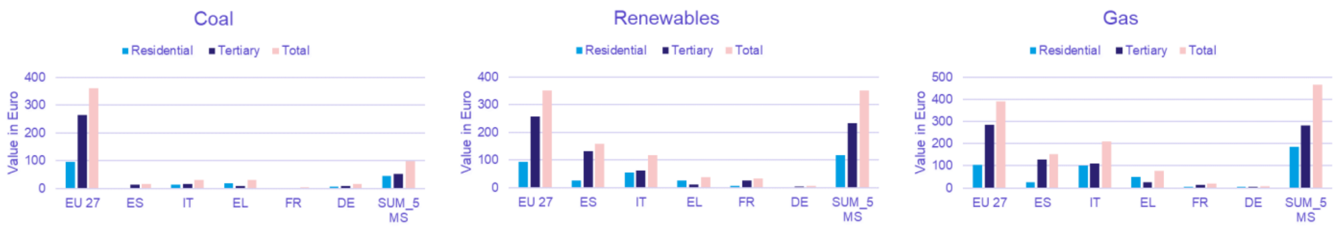


a) Coal b) Gas c) Oil

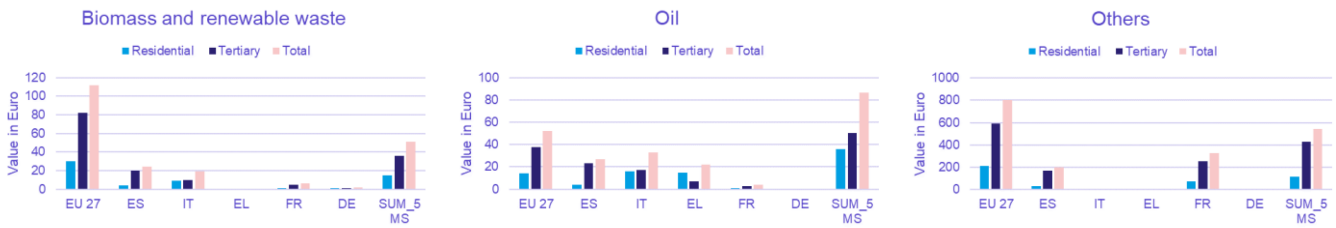
Figure 59. Impact on import dependency

4.4.3. Environmental

Primary savings by fuel type are the highest when behavioural changes are considered on the EU27 level for coal. Savings in renewables are highest in Spain, while the highest amount of gas can be saved in Italy. It is seen that the results defer when considered on the EU-27 level as a single input, and when only the 5 mostly impacted MSs are considered.



a) Coal b) Renewables c) Gas



d) Biomass and renewable waste e) Oil f) Other

Figure 60. Primary savings by fuel type

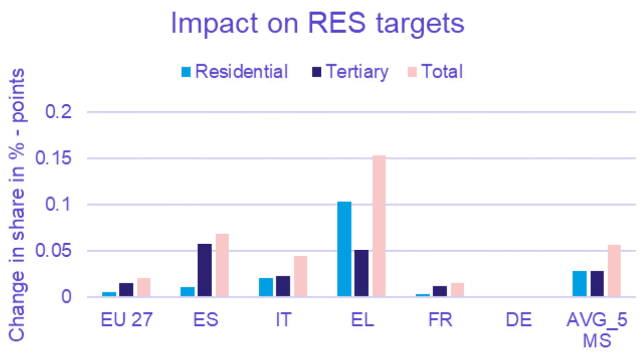
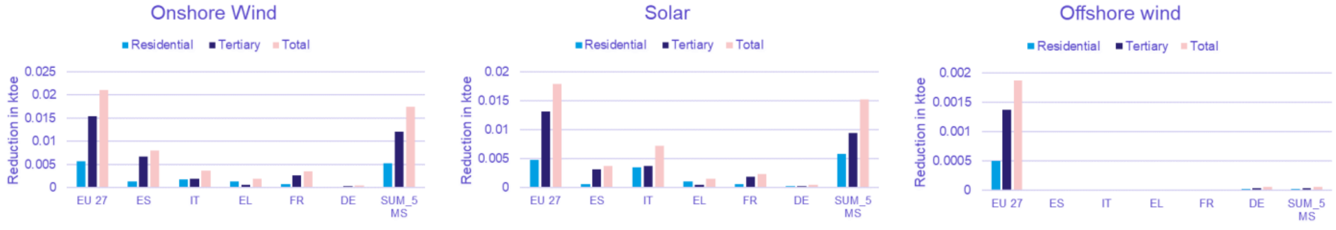


Figure 61. Impact on Share of Renewable Energy Targets

The RES targets of Spain can be impacted the most, by up to 0.15 % points. The reduction of additional capacities is in similar order of magnitude for the onshore wind and the solar plants. However, as seen on Figure 62, reducing electricity use in the five top countries that have the highest space cooling demand does not affect need for the additional capacities. This could only be affected if the savings through behavioural changes would be distributed among the EU-27 countries equally.



a) Onshore wind

b) Solar

c) Offshore wind

Figure 62. Reduction of additional capacities (ktoe)

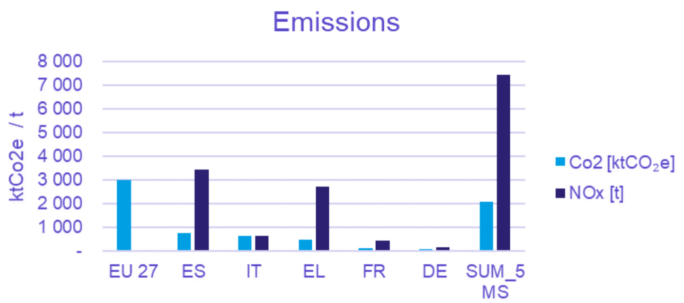


Figure 63. Reduction of CO2 and NOx emissions

4.4.4. Monetized multiple impacts

Based on the above, the additional savings from the multiple impacts were calculated, and shown on Figure 64. The additional savings are between 3-12%, above the savings that result directly from electricity savings.

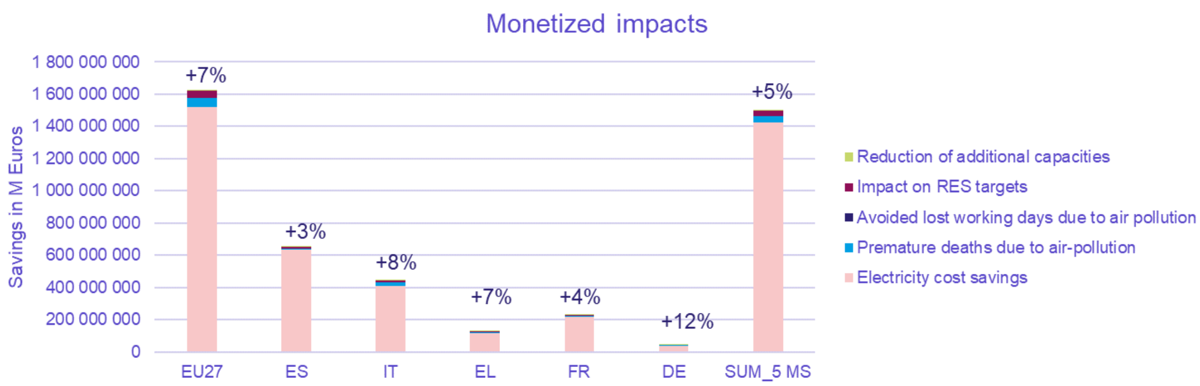


Figure 64. Monetized savings from energy cost savings and monetized multiple impacts

4.5. Conclusion and discussion

The social impacts arising from the improvement of summer thermal comfort or health-related impacts, as well as summer energy poverty, have been handled subordinate in the literature, compared to the effects of winter conditions and impacts arising from EEI actions in space heating, thus the development of robust quantification method is still lacking. Within this work we have contributed to the field of mapping the summer specific impacts caused by improvement of thermal comfort or reduction of space cooling energy use, which can serve as an indication of the topic complexity for policy-makers, and can serve as a basis for developing new quantification methodologies, outside the scope of the project. Nevertheless, impact quantification for general indicators relating to the reduction of electrical energy use have been included and results were presented.

First, impacts of summer behavioural measures have been collected and described, including summer heat-related mortality, morbidity, energy poverty, and water use, which information was used to extend the impact maps of previous MI projects. However, due to the complexity of the topic, no robust methodology currently exists for the quantification of these specific impacts, and the development of these would significantly exceed the scope of this project.

A theoretical scenario applying energy savings to residential and tertiary buildings through behavioural measures, compared with the energy simulation results but based on documented behavioural programmes has been developed to quantify multiple impacts stemming from reducing electrical energy use for space cooling for the EU-27 region and the 5 member states with the highest SC electricity use throughout Europe. While the uptake rate of behavioural measures has high uncertainties, by using data from real case studies, the magnitude of the results can be considered as a good indicator of what impacts behavioural change can have. These results highlight additional benefits of energy saving through behavioural changes, which can support policymakers in implementing behavioural programmes.

The social impacts that have been quantified are low compared to the overall health risks associated with the PM2.5 pollution on the EU level, which could have reached as high as 238,000 premature deaths in 2020 according to EEA's estimates [6], however, still high when the individual is concerned. However, the as detailed above, heat-related mortality and morbidity impacts associated with summer conditions are not included in these values in lack of robust methodologies. It is of high importance to develop methodologies to address this topic in the future.

The monetizable additional impacts of electricity savings have been shown to be between 3-12% above the cost savings from electricity, which could be directly considered within a CBA.

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Annex I - OPA models available related to space cooling

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
AC	OFF	Residential	Bedroom	China		obXML		[216]
AC	OFF	Residential	Living room	China		obXML		[216]
AC	ON	Residential	Bedroom	China		obXML		[216]
AC	ON	Residential	Living room	China		obXML		[216]
AC	ON	Office		Switzerland				[217]
AC		Office		Canada				[218]
AC		Office		No information				[219]
AC		Office		UK				[220]
Bilnd	Close (ON)	Office	Based on indoor temp.	Switzerland		obXML		[217]
Bilnd	Close (ON)	Office	Based on outdoor temp.	Switzerland		obXML		[217]
Blind	Close (ON)	Office	Private office	USA		obXML		[221]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Blind		Educational	Spread of three types of occupants with different energy use characteristics	USA			Agent-Based Occupant Simulation Model	[222]
Blind	Close (ON)	Office		Austria		obXML		[223]
Blind	Close (ON)	Office		Canada		obXML		[224]
Blind	Open (OFF)	Office	Morning	Canada		obXML		[224]
Blind	Close (ON)	Office	Based on solar altitude	UK		obXML		[225]
Blind	Close (ON)	Office	Based on solar radiation	UK		obXML		[225]
Blind	Open (OFF)	Office	Based on solar altitude	UK		obXML		[225]
Blind	Open (OFF)	Office	Based on solar radiation	UK		obXML		[225]
Blind	Open (OFF)	Office	light switch-on during different occupancy periods.	Canada	ESP-r		Lightswitch-2002	[44]
Blind		Residential		Denmark				[226]
Blind	Close (ON)	Office	Based on solar intensity. Independent of outdoor temperature.	UK		obXML		[227]
Blind	Close (ON)	Office	Based on solar intensity. Independent of outdoor temperature.	Sweden		obXML		[227]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Blind	Close (ON)	Office	Based on solar intensity. Independent of outdoor temperature.	France		obXML		[227]
Blind	Close (ON)	Office	Based on solar intensity. Independent of outdoor temperature.	Portugal		obXML		[227]
Blind	Close (ON)	Office	Based on solar intensity. Independent of outdoor temperature.	Greece		obXML		[227]
Blind	Close (ON)	Office	Based on solar intensity. Independent of outdoor temperature.	Pakistan		obXML		[227]
Blind		Educational	Laboratory	Switzerland				[228]
Blind		Educational	Laboratory	Switzerland				[229]
Blind		Office		No information		Implemented in the EMS application of energyplus		[230]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Blind	Open (ON)	Office	Carbon dioxide concentration, indoor relative humidity, and illuminance levels	Switzerland			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[231]
Blind	Open (ON)	Residential	Carbon dioxide concentration, indoor relative humidity, and illuminance levels	Germany			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[231]
Blind	Open (ON)	Residential	Carbon dioxide concentration, indoor relative humidity, and illuminance levels	Denmark			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[231]
Blind		Office		No information				[232]
Blind		Office		No information				[233]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Blind	Close (ON)	Office	Air temperature and relative humidity	Germany				[234]
Clothing		Office		No information		Implemented in the EMS application of EnergyPlus		[16]
Clothing		Office	The ATHB indices utilize estimated clothing levels derived from the running mean outdoor temperature. This means that with the ATHB models, it's possible to predict individual thermal sensation without needing to directly measure or obtain actual CLO values.	Germany				[234]
Blind	Close (ON)	Office	Air temperature and relative humidity	Germany				[233]
Heating	ON	Office		Sweden		obXML		[227]
Heating	ON	Office		France		obXML		[227]
Heating	ON	Office		Portugal		obXML		[227]
Heating	ON	Office		Greece		obXML		[227]
Heating	ON	Office		Pakistan		obXML		[227]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Heating	ON	Office		UK		obXML		[227]
Lighting	ON	Office	Arrival	Canada		obXML		[230]
Lighting	ON	Office	Arrival	Japan		obXML		[230]
Lighting	ON	Office	Arrival	Germany		obXML		[230]
Lighting	ON	Office	Arrival	USA		obXML		[230]
Lighting	ON	Office	Arrival	UK		obXML		[230]
Lighting	ON	Office	During the day	Canada		obXML		[230]
Lighting	ON	Office	During the day	Japan		obXML		[230]
Lighting	ON	Office	During the day	Germany		obXML		[230]
Lighting	ON	Office	During the day	UK		obXML		[230]
Lighting	ON	Office	During the day	USA		obXML		[230]
Lighting	ON	Office	Classrooms also	UK		obXML		[42]
Lighting	ON	Office	Private office 1	Canada		obXML		[235]
Lighting	ON	Office	Private office 2	Canada		obXML		[235]
Lighting	ON	Office	Single office floor	No information	ESP-r		LIGHTSWITCH	[236]
Lighting		Residential		UK				[237]
Lighting		Residential		Sweden				[238]

Cool LIFE

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Lighting	ON	Office	Focus on occupant schedules, incorporating daily lighting curves and annual distributions of lighting power levels.	China			Stochastic whole-building lighting energy use model developed, produce annual lighting energy use schedules that can be used as an input to building simulation.	[239]
Lighting		Educational	Spread of three types of occupants with different energy use characteristics	USA			Agent-Based Occupant Simulation Model	[222]
Lighting	OFF	Office	Afternoon and Morning	Canada		obXML		[224]
Lighting	OFF	Office	Morning	Canada		obXML		[224]
Lighting	ON	Office	Morning	Canada		obXML		[224]
Lighting	ON	Office	During the day	UK		obXML		[227]
Lighting	ON	Office	Arrival	Germany		obXML		[240]
Lighting	ON	Office	During the day	Sweden		obXML		[227]
Lighting	ON	Office	During the day	France		obXML		[227]
Lighting	ON	Office	During the day	Portugal		obXML		[227]
Lighting	ON	Office	During the day	Greece		obXML		[227]
Lighting	ON	Office	During the day	Pakistan		obXML		[227]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Lighting		Office		No information			Implemented in the EMS application of EnergyPlus	[230]
Lighting	Open (ON)	Office	Carbon dioxide concentration, indoor relative humidity, and illuminance levels	Switzerland			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[231]
Lighting	Open (ON)	Residential	Carbon dioxide concentration, indoor relative humidity, and illuminance levels	Germany			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[231]
Lighting	Open (ON)	Residential	Carbon dioxide concentration, indoor relative humidity, and illuminance levels.	Denmark			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[231]
Lighting		Office		No information				[233]
Lighting		Office		No information				[233]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Occupant presence		Residential	Occupancy time-series data Differentiate weekdays and weekends. Account number of active occupants.	UK				[241]
Occupant presence		Office		Switzerland				[25]
Occupant presence		Residential		Switzerland				[25]
Occupant presence		Residential		UK				[241]
Occupant presence		Office	Predicting user mobility patterns in buildings	USA			Agent-based models	[242]
Occupant presence		Office	Correlations between measured environmental conditions and occupancy status.	USA				[243]
Occupant presence		Office		USA				[244]
Occupant presence		Office		No information			Occupancy model based on the Markov-chain.	[245]
Occupant presence		Residential		France				[31]
Occupant presence		Office		No information				[246]
Occupant presence		Office		Austria				[247]
Occupant presence		Office		Austria				[248]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Occupant presence		Office		EU				[249]
Occupant presence		Office	Electrical ballasts triggered by passive infrared sensors.	USA				[250]
Occupant presence		Office		No information				[251]
Occupant presence		Office		Germany				[252]
Occupant presence		Office		Denmark				[253]
Occupant presence		Office		No information			Implemented in the EMS application of EnergyPlus	[230]
Occupant presence		Residential		China				[254]
Occupant presence		Office	Wireless video camera to monitor the entrance to the room and motion detection through a motion detection algorithm	USA			Multi-occupant multi-zone (MOMZ) model-stochastic agent-based model of occupancy dynamics in a building with an arbitrary number of zones and occupants. Covariance graph model - represents marginal dependencies among the occupancy of various zones.	[255]
Occupant presence		Office	Annual and peak heating and cooling demands	Austria			“small office” reference building model developed by the U.S. Department of Energy [10].	[48]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Occupant presence		Office	Using heating and cooling demands and peak loads	Austria			Observation-based stochastic models of occupants' presence	[256]
Occupant presence		Office		USA				[257]
Window opening	Open (ON)	Office	Based on indoor temp.	Switzerland		obXML		[217]
Window opening	Open (ON)	Office	Based on outdoor temp.	Switzerland		obXML		[217]
Window opening	Close (OFF)	Office	Arrival	Switzerland		obXML		[258]
Window opening	Close (OFF)	Office	During the day	Switzerland		obXML		[258]
Window opening	Close (OFF)	Office	Arrival	Switzerland		obXML		[230]
Window opening	Close (OFF)	Office	Cooling room	UK		obXML		[230]
Window opening	Close (OFF)	Office	During the day	Switzerland		obXML		[230]
Window opening	Open (ON)	Office	During the day. Based on outdoor temp.	Switzerland		obXML		[230]
Window opening	Open (ON)	Office	Arrival	UK		obXML		[230]
Window opening	Open (ON)	Office	During the day	UK		obXML		[230]
Window opening	Open (ON)	Residential	Physical environmental driven and contextual driven window opening office user profiles	Germany			Data mining techniques such as cluster analysis and association rules algorithms	[259]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Window opening	Open (ON)	Residential	Behaviour patterns for active, medium and passive occupant's typologies were combined	Denmark				[260]
Window opening	Open (ON)	Office	Draws from longitudinal field comfort and behavior data	USA			Agent-based model	[45]
Window opening	Open (ON)	Office	With night ventilation	UK		obXML		[261]
Window opening	Open (ON)	Office	With night ventilation	UK		obXML		[261]
Window opening	Open (ON)	Office	With night ventilation	UK		obXML		[261]
Window opening	Open (ON)	Office	No night ventilation	UK		obXML		[261]
Window opening	Open (ON)	Office	No night ventilation	UK		obXML		[261]
Window opening	Open (ON)	Office	No night ventilation	UK		obXML		[261]
Window opening	Open (ON)	Office	No night ventilation	UK		obXML		[261]
Window opening	Open (ON)	Office	No night ventilation	UK		obXML		[261]
Window opening	Open (ON)	Office	All orientations	UK		obXML		[262]
Window opening	Open (ON)	Office	East	UK		obXML		[262]
Window opening	Open (ON)	Office	North	UK		obXML		[262]
Window opening	Open (ON)	Office	South	UK		obXML		[262]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Window opening	Open (ON)	Office	West	UK		obXML		[262]
Window opening	Open (ON)	Office		Switzerland			A stochastic model using Markov-chains is proposed to generate time series of window angle	[263]
Window opening	Open (ON)	Residential	Identify the specificities of occupants' behaviour with respect to their interactions with windows, including the choice of opening angles for axial openings.	Switzerland			Predictive model which account for the specificities of window usage	[264]
Window opening	Open (ON)	Residential	Identify the specificities of occupants' behaviour with respect to their interactions with windows, including the choice of opening angles for axial openings.	Japan			Predictive model which account for the specificities of window usage.	[264]
Window opening	Open (ON)	Office	Indoor CO2concentration and outdoor temperature	Denmark			Model defining occupants' window opening behaviour patterns in simulation programs, based on measurements is proposed.	[265]
Window opening	Open (ON)	Office	south-west	Czech Republic			seven behaviour models for window opening and closing	[266]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Window opening	Open (ON)	Office	The building is naturally ventilated and cooled in summer and equipped with a night-time mechanical ventilation.	Germany			Four archetypal working profiles that can be used as input to current building energy modeling programs, such as EnergyPlus or IDA-ICE	[252]
Window opening	Open (ON)	Residential	Drive to open - Time of the day and Carbon dioxide concentration. Driver to close - Daily average outdoor temperature and the time of the day.	Germany			Models that can only be used within a simulation, when occupants presence profiles are available, as the model rendering focus on CO_2 concentration.	[267]
Window opening	Open (ON)	Residential		Denmark				[268]
Window opening	Open (ON)	Office	Outdoor temperature	Sweden		obXML		[227]
Window opening	Open (ON)	Office	Outdoor temperature	France		obXML		[227]
Window opening	Open (ON)	Office	Outdoor temperature	Portugal		obXML		[227]
Window opening	Open (ON)	Office	Outdoor temperature	Greece		obXML		[227]
Window opening	Open (ON)	Office	Outdoor temperature	UK		obXML		[227]
Window opening	Open (ON)	Office	Outdoor temperature	Pakistan		obXML		[227]
Window opening	Open (ON)	Office		UK				[269]
Window opening	Open (ON)	Office		Switzerland				[270]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Window opening	Open (ON)	Office		UK				[271]
Window opening	Open (ON)	Educational	Laboratory	Switzerland				[229]
Window opening		Residential		China				[272]
Window opening	Open (ON)	Residential		Denmark				[259]
Window opening		Office		No information			Implemented in the EMS application of EnergyPlus	[230]
Window opening	Open (ON)	Office	Carbon dioxide concentration, indoor relative humidity, and illuminance levels.	Switzerland			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[273]
Window opening	Open (ON)	Residential	Carbon dioxide concentration, indoor relative humidity, and illuminance levels.	Germany			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[273]

OPA type	Action	Building type	Comment	Country	Availability in energy modelling tools		Other model type	Source
					built-in	co-simulation		
Window opening	Open (ON)	Residential	Carbon dioxide concentration, indoor relative humidity, and illuminance levels.	Denmark			Stochastic models incorporate explicit probabilistic elements to anticipate how occupants interact with windows, shading devices, and electrical lighting in building energy simulations, accommodating the diverse behaviors of building occupants.	[273]
Window opening		Office	Controlled climate chamber	No information				[232]
Window opening		Office	Field laboratory	No information				[233]
Window opening	Open (ON)	Office	Air temperature and relative humidity	Germany				[234]