Energy & Buildings 351 (2026) 116754

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Cost-benefit analysis of technologies and measures for summer comfort – A case study of residential districts in the Paris region

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ARTICLE INFO

Keywords:
Cost-benefit analysis
Urban energy modelling
Space cooling
Summer comfort
Noise discomfort

ABSTRACT

Heatwaves in urban areas, such as Paris, substantially increase heat-related health risks and drive a growing demand for space cooling. However, most existing buildings are ill-equipped to cope with rising temperatures, highlighting the urgent need for effective adaptation strategies. This study presents a comprehensive framework to evaluate and compare space cooling solutions—including active technologies and passive mitigation measures—within urban contexts. Unlike prior approaches focusing narrowly on individual technologies or building-scale analyses, our method integrates both direct impacts (thermal comfort and energy consumption) and externalities such as noise pollution and urban heat island effects.

To thoroughly assess these multifaceted impacts, a combined model has been developed and implemented. Beyond energy consumption, the modelling framework considers heat rejection from cooling systems contributing to urban heat island intensification and greenhouse gas emissions during the use phase. Additionally, a bespoke sound propagation model evaluates noise discomfort caused by air conditioners in urban environments.

This paper introduces a novel multi-impact modelling workflow combined with cost-benefit analysis (CBA) to assess the overall performance of selected cooling options at the city scale. Results, aggregated at the district level and considering societal costs and benefits, reveal the broad applicability of fans across contexts and highlight the advantages of district cooling networks in the densest districts. This integrated approach offers valuable insights for developing sustainable and effective urban cooling strategies.

1. Introduction

«In Paris, heatwaves are the most perceptible manifestation of climate change» [1]. This perception is not neutral, since among the capitals of 30 European countries, Paris exhibits the highest heat-related mortality risk across all age groups during the period 2000–2020 [2]. This context contributes to the rising of space cooling needs and sales of air-conditioners in Europe [3,4]. Given the likelihood of these issues intensifying in the coming decades, it is essential to adapt housing to the changing conditions as swiftly and effectively as possible. With « 90 % of buildings in the [French] capital not designed to withstand hot climates » [1], there is an urgent need to identify solutions that can either prevent or alleviate summer thermal discomfort inside buildings. However, these solutions must be carefully selected to align with national objectives. European Union member states have committed to achieving climate neutrality by 2050, enshrined in a legally binding form within the European Climate Law [5].

Solutions to this challenge fall into two main categories: space cooling technologies and mitigation measures. Space cooling technologies consume energy to produce cooled air or water, thereby removing heat from the interior of dwellings, while mitigation measures reduce the need for space cooling by minimizing solar heat gains or internal heat production, promoting natural ventilation—especially at night—or modifying occupants' thermal perception through air movement, humidity control, or adaptive behaviours such as adjusting clothing or consuming cold beverages. Reviews of current and alternative space cooling technologies and measures [6–9] help to identify various space cooling options that are particularly suitable for the residential sector. Many studies [10–12] focus on the dwelling or building scale and seeking the best option for households according to the initial investment, operation costs, and building type. However, this approach often overlooks detrimental effects on the local environment, such as the heat

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https://doi.org/10.1016/j.enbuild.2025.116754
Received 20 May 2025; Received in revised form 24 October 2025; Accepted 10 November 2025
Available online 19 November 2025

release of the vapour compression technologies that exacerbate the urban heat island (UHI) effect on the neighbourhood or district scale, or other environmental effects such as noise pollution.

Hassid et al. [13], Pigeon et al. [14], and Theeuwes et al. [15] highlight the impact of the urban environment on actual temperatures in cities and consequently on the energy consumption of space cooling technologies. Since 99 % of space cooling technologies rely on classic thermodynamic cycle [16], conventional cooling production technologies reject the thermal energy extracted from cooled spaces, which is often released into the ambient environment. Over the past decade, studies have highlighted that the widespread use of air conditioners can increase outdoor urban temperatures [17]. Additionally, urban areas are often characterized by elevated noise levels. In this context, certain cooling strategies—such as opening windows to reduce thermal discomfort—may simultaneously increase noise perception [18]. Air-conditioners have thus been identified as contributors to the noise pollution by the Ile-de-France regional health agency [19] and the European legislator [20].

To address this issue holistically, cost-benefit analysis (CBA) provides a tool capable of accounting for both monetary and non-monetary costs and benefits associated with implementing solutions to maintain summer thermal comfort. Direct costs and benefits are monetary and typically considered by occupants. Conversely, externalities represent non-monetary costs and benefits arising from an individual's activities, which the individual does not bear or receive, and are thus borne by third parties [21]. Some externalities of space cooling technologies, notably greenhouse gas (GHG) emissions, cannot be disregarded: they have been extensively studied [22] and regulated [23].

By aggregating all costs and benefits into quantified indicators, CBA simplifies complex multidimensional problems, facilitating decision-making. Unsurprisingly, it has been widely applied across various disciplines and particularly within the energy sector. Furthermore, CBA has been promoted by European Union institutions for energy projects [24].

More specifically, some studies have applied CBA to evaluate solutions for space cooling needs. Whether addressing cooling or heating systems [12] or the building envelope [11], most analyses use a technology as a reference scenario. By comparing system costs and energy consumption, these studies assess the benefits of alternative solutions delivering equivalent energy services. However, this approach's main limitation is its inability to compare space cooling technologies with mitigation measures, as they do not provide the same level of energy service. In other words, this methodology ignores the option of not installing active air conditioning to achieve summer comfort. To integrate passive measures, it is necessary to evaluate thermal discomfort and monetize it within an aggregated cost-benefit framework. Such assessments are found mainly in literature focusing on productivity losses in tertiary buildings [10]. This approach was also included in Grignon-Massé's thesis [25], which assessed and compared costs and benefits of fans and air-conditioners.

This study aims to establish a framework for comparing various solutions—including technologies and mitigation measures—to address space cooling demand in urban contexts, considering both direct impacts (thermal comfort and final energy consumption) and externalities such as noise and heat emissions. This article presents a new modelling process for the multi-impact assessment of cooling technologies and measures. The originality of this process lies in a certain degree of coupling and simultaneous evaluation of the physical phenomena involved in space cooling in buildings: heat rejection into the environment, noise pollution generation and propagation, energy consumption, and thermal comfort in housings. This simulation then feeds into a comprehensive cost-benefit analysis (CBA) approach that allows different technologies and measures to be compared for the purpose of making recommendations to decision-makers. The proposed framework is applied to the Parisian context and to a selected set of technologies and measures, yielding insights relevant to addressing summer comfort at the Paris region scale in the coming years. Finally, results are analysed and discussed in light of specific limitations, and recommendations for decision-makers and perspectives for future research are outlined.

2. Method

The CBA relies on the assessment of various physical factors both at the dwelling and the district scales, which quite naturally leads us to choose a bottom-up physics-based approach to carry it out [26,27]. Smart-E is such an urban building energy model (UBEM) developed by the Centre of Energy, Environment, and Processes at Mines Paris – PSL University [28,29]. Sharing this approach with other works in the scientific community [30,31], this UBEM is based on an adapted resistance–capacitance thermal network model allows assessing space cooling needs, thermal comfort and final energy consumption of heating, ventilation and air-conditioning systems at the dwelling scale and, then, at a district or city level, through a bottom-up aggregation process.

For the present study, specific models have been developed and embedded in the already existing UBEM, to consider:

- the temperature dependency of the efficiency of space cooling technologies (section 2.1.2),
- the control of space cooling mitigation devices such as shading devices or the opening of windows for natural ventilation purposes representing building occupant actions (section 2.1.3),
- the impact of urban heat island (UHI) on the space cooling needs as well as the impact of waste heat releases from the air-conditioners (section 2.2.1),
- the impact of the ambient noise on the implementation of measures to maintain summer thermal comfort in an urban context as well as the contribution of the air-conditioners to the ambient noise (section 2.2.2).

By construction, this bottom-up physical modelling approach enables, to a certain extent, the coupling between these different phenomena that are significant for the impact assessment. Fig. 1 shows how the models feed into each other.

2.1. Technologies and measures energy modelling

2.1.1. Thermal modelling

The UBEM Smart-E is based on a resistance–capacitance thermal network modelling adapted to the simulation of large quantities of dwellings. Based on [32], thermal needs of dwellings are calculated with a mono-zone model and the various parameters of the model (internal and wall capacitances, thermal resistances of wall layers, air infiltration and ventilation rates) are retrieved or inferred from public open data as [33–35] (see Appendix 1). The housing stock has been built up from French national census describing the housings and households' characteristics [36]: one can thus get the diversity in construction periods, housings geometries and households' structures in a given territory in France [28]. The housing occupation and households' activity scenarios are determined on the basis of French Time-of-Use survey [37] and feed the thermal housing models with the required dynamic inputs (see Fig. 2).

This dynamic modelling approach allows also to get a picture of the thermal comfort in each housing from the temperature of the internal air node. A constant comfort temperature value is assigned to each dwelling, randomly around 25 °C (see Appendix 1). When the indoor air temperature exceeds this threshold, the cooling systems are activated and, to the extent of their capacity, reduce the indoor air temperature (space cooling technologies such as split systems or VRF) or the temperature as felt by the occupants (fans). Consequently, discomfort is locally understood as the difference between the required comfort temperature and the internal air temperature (or as felt by the occupants).

The model has been validated for HVAC consumption in buildings

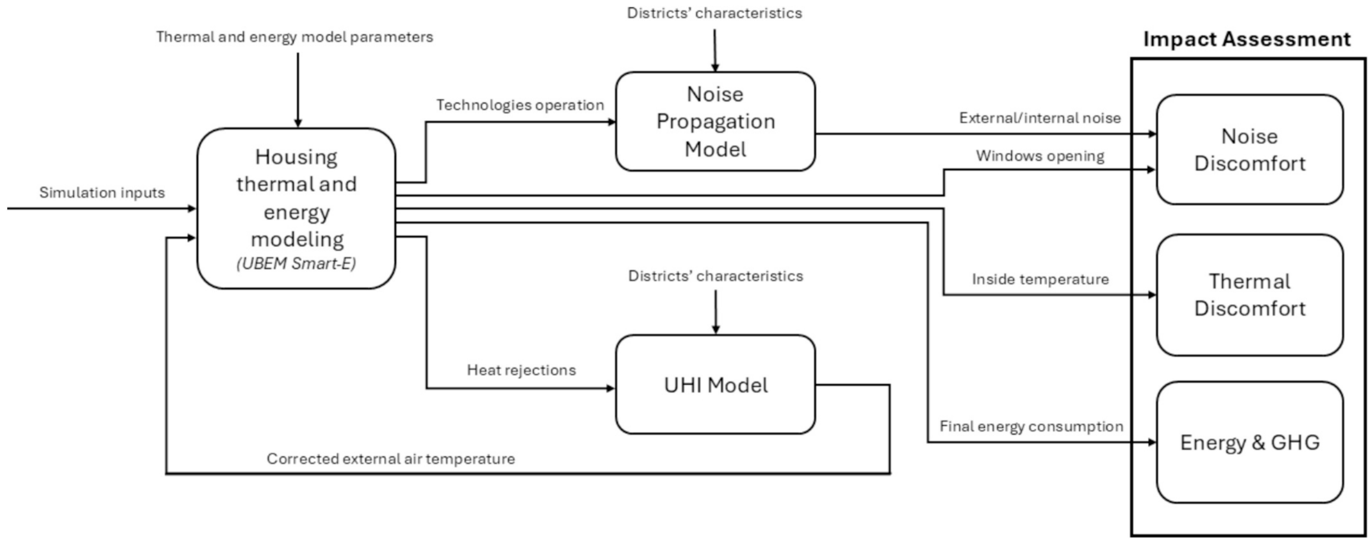

Fig. 1. Flowchart of the combined model.

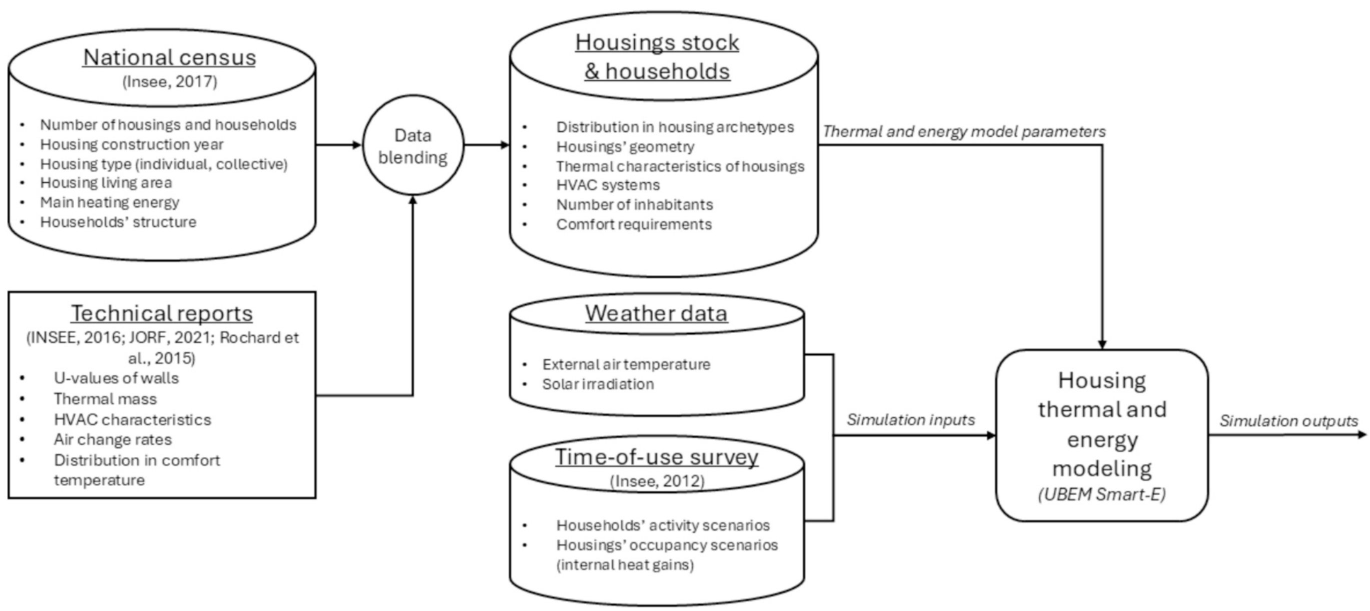

Fig. 2. Data processing principles for housings energy modelling purpose.

[32] and the time step can be set to investigate sub-hour energy indicators (10 min).

2.1.2. Technologies energy efficiency

The present study covers the four types of technologies suited for space cooling in households [38], listed below:

- Portable unit systems,
- Single and multi-split,
- Variable refrigerant flow (VRF),
- District cooling system.

All the technologies considered are conventional vapor-compression systems as this category covers almost 99 % of Europe's space cooling needs [16]. Portable systems are space cooling systems based on thermodynamic cycle of heat pumps where all components are contained in a single movable casing. Split systems comprise two units: outdoor units with the condenser and the indoor unit with the evaporator. Note that a part of split systems stock is made up of reversible heat pumps. Multi-splits have several indoor units providing space cooling in several rooms of a single dwelling. VRFs are centralised air-conditioners with an outdoor unit distributing refrigerant to indoors units in multiple dwellings. District cooling systems are designed to supply multiple buildings with chilled water through a distribution network connected to one or more chiller units.

In addition to their specific characteristics, these technologies have different efficiencies. To carry out dynamic simulations, the systems efficiency is modelled as a function of inside or outside temperature. These functions have been retrieved from the Ecodesign study ENTR Lot 6 "Air-conditioning and Ventilation Systems" [39] and based on the average efficiency of European units sold in 2020 [38].

Fig. 3 shows the efficiency functions of all the technologies considered as energy efficiency ratio (EER), the ratio between the cooling power and the electric power input. In addition to their cooling effect, portable systems releasing air to the outside increase air infiltration which decrease consequently their actual efficiency. Chillers are large

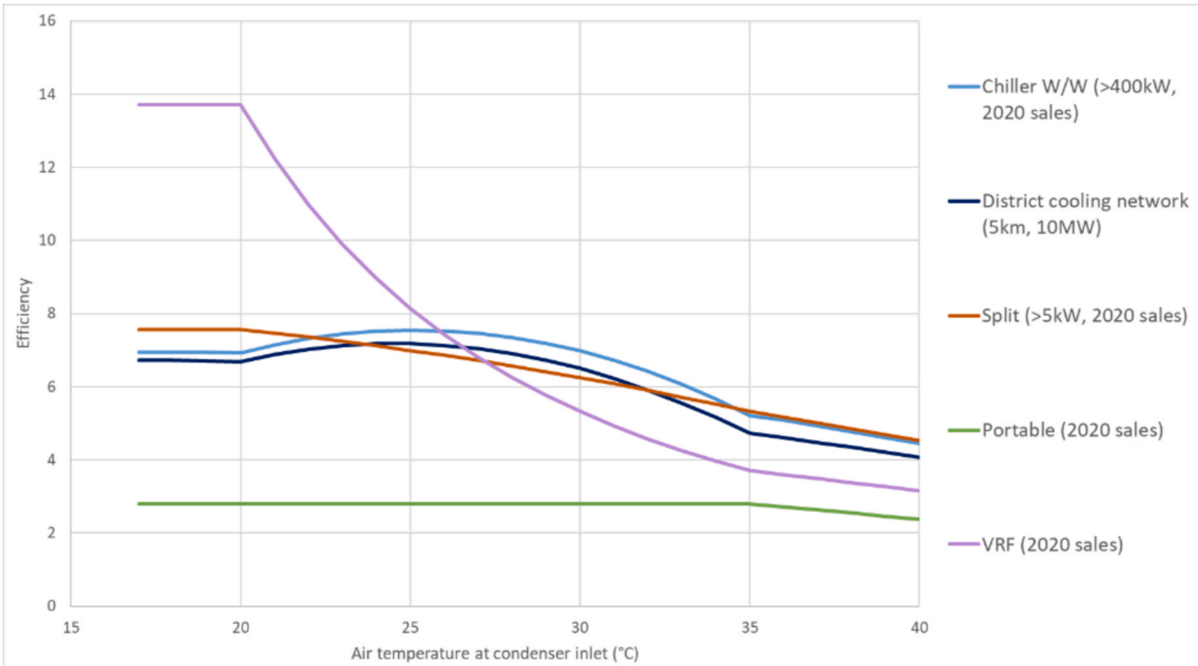

Fig. 3. EER of technologies depending on inside temperature for portable units, and outside temperature for others.
Adapted from [39].

systems typically used for district cooling application. The efficiency of district cooling network as a whole has been retrieved based on EER function for large capacity chillers and assumption regarding distribution network pumps consumption and heat losses [40,41].

2.1.3. Measures control scenarios

Several studies show that window opening strategies are highly appreciated by households when it comes to ensuring summer comfort at home [42]. For the purposes of this study, it has therefore been assumed that cooling by opening windows is systematically carried out by households and no longer an alternative for the mitigation of space cooling needs. When the indoor temperature is slightly below the comfort temperature of the dwelling but still higher than the outdoor temperature, a fraction of the occupants open their windows, according to a linear relationship with the indoor temperature as suggested by Grignon-Massé [25]. Opening windows in noisy neighbourhoods can contribute to occupants' indoor noise discomfort since they have a sound-damping effect when closed. Even if this aspect of interior comfort plays an important role and is considered in this study, it is not significantly correlated with window-opening behaviour [43].

Moreover, the present study covers three types of alternative measures, that can be widely implemented in already existing buildings [44], listed below:

- Shading device,
- Fans,
- White roof.

Shading devices help to reduce the solar gains through windows. Because of the luminance they provide and their flexibility of use [45], the simulated shading system among all available possibilities is Venetian blind. At a blind angle of 60°, their solar heat gain reduction factor, average among four European cities and the East, South and West façades in summer, is 72 % [46]. It is assumed that the solar gains reduction factor is equal to the lighting reduction factor because the shading device selected does not discriminate between wavelengths and because the heat absorbed by the device is neglected.

Nicol & Humphreys [47] highlighted the fact that the use of blinds is uncorrelated to outside or inside temperature in general. On the other hand, the use of shading device is determined by the external illuminance on the façade and modelled in the present work the external façade reach a certain value, a certain proportion of dwellings completely lower all their blinds (see Fig. 4).

Fans shift the occupant's thermal sensation, as the increased air speed induced by fans at the surface of the body leads to an increase in heat exchange between them and the surrounding air. In the frame of this work, it has been assumed that this phenomenon results in a reduction in temperature felt of between 2 and 3 °C [49–52], although above 33 °C indoors, the air blown is too hot and the fan become ineffective [53]. The power consumption of a ceiling fan in operation is considered constant at 30 W [54]. It is also assumed that the use of fans does not affect the control of windows when both actions can be done simultaneously.

Roof colour has an impact on energy consumption of buildings. It affects the way solar heat gain is absorbed by the roof surface of the building before being transmitted to the dwelling directly under the roof. By default, the albedo of building roofs is set to the 'aged black' albedo of 0.15 [55]. For assessing the impact of the "white roofs" measure, the albedo is based on the 'new white' albedo, set at 0.8.

2.2. Urban environment modelling

2.2.1. Urban heat island

To assess the intensity of the UHI effect in the present study, the diagnostic equation proposed by Theeuwes et al. [15] and presented below is retrieved.

$$\boldsymbol{UHI_{max}} = \left(2 - \boldsymbol{SVF} - \boldsymbol{f_{veg}}\right) \times \sqrt[4]{\frac{\boldsymbol{S} \times \boldsymbol{DTR}^3}{\boldsymbol{U}}} \tag{1}$$

Where UHI_{max} is the estimated maximum daily temperature difference between inside and outside the city, U is the daily average wind speed (in m/s), DTR is the diurnal temperature range at the rural site (in K), S is the daily average solar radiation (in W/m^2), f_{veg} the vegetation

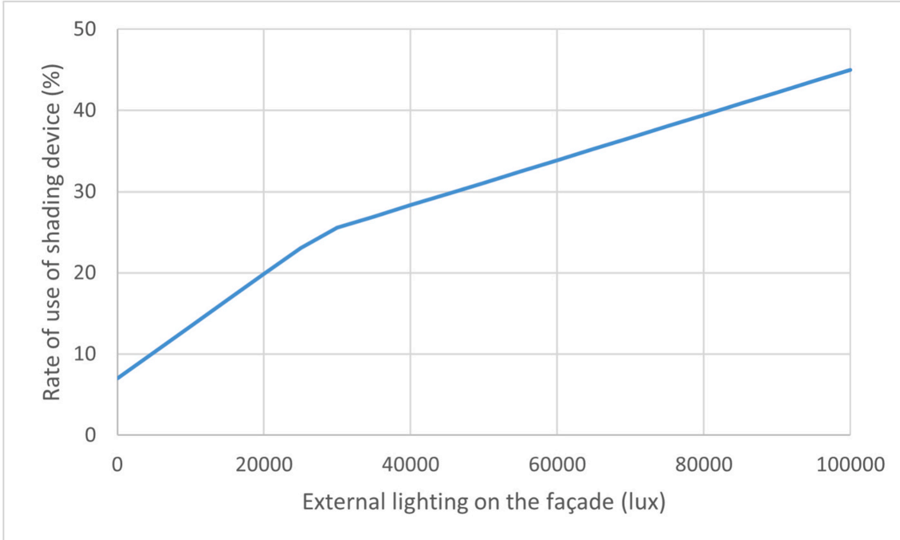

Fig. 4. Shading device use depending on the external illuminance [48].

fraction of the district (in %).

The SVF, or sky view factor, is estimated for each district based on Equation (2) [56].

$$\boldsymbol{SVF}_{mid-canyon} = \boldsymbol{cos}\left(\boldsymbol{atan}\left(2 \times \frac{\boldsymbol{H}}{\boldsymbol{W}}\right)\right) \tag{2}$$

H, the height of the buildings is assumed to be the average footprint-weighted height of each district, retrieved from the French topographical database [57]. W, the width of the streets is assumed to be the ratio between the unbuilt surface area of the district and the total length of its streets.

To move from a maximum daily value to hourly data, Equation (3) [58] is used, based on a rolling average UHI_{max} value over a week.

$$\boldsymbol{UHI}_h = \boldsymbol{UHI}_{max} \times \left(0.5 \times \boldsymbol{sin}\left(\boldsymbol{\pi} \times \boldsymbol{t}_i - \frac{\boldsymbol{\pi}}{2}\right) + 0.5\right) \tag{3}$$

Eventually, the heat rejection due to portable and split systems and the thermal contribution related to road traffic is added to the value of S, in watt per square meter of unbuilt surface area of the district. Road traffic contributions is estimated based on the work of Pigeon *et al.* (2007). As VRF outside units are located on the building roof, their heat release is supposed to be quickly dissipated at altitude. In addition, district cooling manages heat dissipation through latent heat or discharge into nearby water bodies. Only portable and split units are likely to have a significant effect on UHI, which in turn has a negative impact on system performance. The modelling of the units and the UHI is iterative, since one affects the other.

2.2.2. Ambient noise model

Outdoor ambient noise can be evaluated within the scale of a district, but even a single air-conditioning unit can generate noise disturbance for the nearest housings, particularly at night when ambient noise is lower, and people wish to open their windows to cool their overheated housings.

As no adapted model has been identified in the current literature, new specific models have been developed for assessing at the district scale, the additional noise disturbances created by space cooling technologies. The methodology presented hereafter is based on a simplified sound propagation model derived from operating technologies considered as point sound sources. Sound propagation in the urban environment considers reverberations on building facades and the ground, as well as the typical geometric characteristics of the environment. The model thus makes it possible to assess the resulting noise level at each window of the dwellings.

One model was developed for the districts mainly composed of multifamily houses and apartment blocks, and another for the district mainly composed of single-family. Both models (see in Fig. 5) are based on typical facades of buildings described in [59] and identified in the district archetypes used in the present study (see section 2.3). The facade arrangement is also identified according to the characteristics of the district archetypes.

Two typical façade arrangements have been defined to consider the difference in the propagation of sound in the streets and courtyards representative of the old urban centre and dense urban districts (Fig. 6).

The characteristic dimensions of these zones are the average height of buildings (H), the average number of floors (F), and the distance between two facades facing each other (W), as well as the length of the streets (A). The outside units of split systems are located on the façade: saturation is assumed to be reached with one air-conditioner for every two windows.

In the model designed for single-family houses areas, the distribution of typical façades is illustrated in Fig. 7.

In addition to W dimension, this distribution is characterised by S, the distance between houses located side by side. Building height and number of floors are based on the studied district. The outdoor units of split systems are assumed to be systematically placed on the side of houses, as is customary and often recommended. The installed stock saturation is assumed to be reached with one air-conditioner per house. Subsequently, the noise produced by the split units is shielded by the walls of the two houses that flank it. Therefore, it is assumed that each outdoor split unit can only disturb the houses in front of it, on the opposite side of the street.

The outdoor units of VRF systems, which also generate noise, are placed on the roof, in the middle of the facade, and set back by five meters. The saturation level is represented by one system per building. In the model for apartment block districts, they affect all windows they face in the street zone, but none of the windows in the courtyard zone, assumed to be shielded by the roof. In the urban periphery model, they also affect all windows that they face.

In each model, the sound level is estimated at each window from the sum of the sound intensities resulting from the units placed in the model. Windows and units are reduced to points in a three-dimensional coordinate system.

As a first approach, it has been implemented a model of sound wave propagation in a semi-open homogeneous medium, originating from

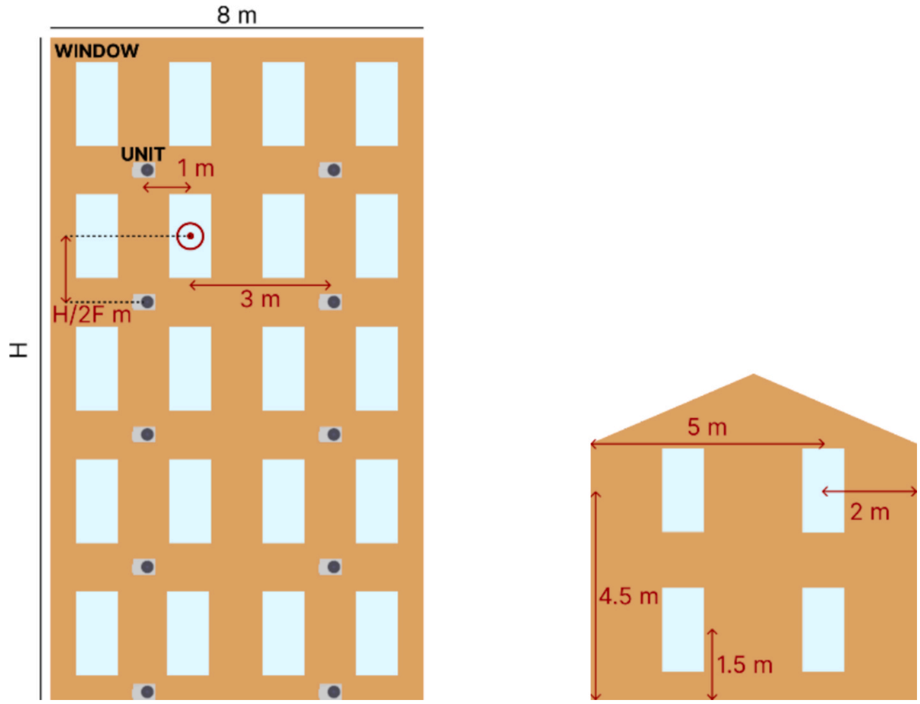

Fig. 5. Typical facades of noise discomfort models for apartment block (left) and single-family house (right) districts.

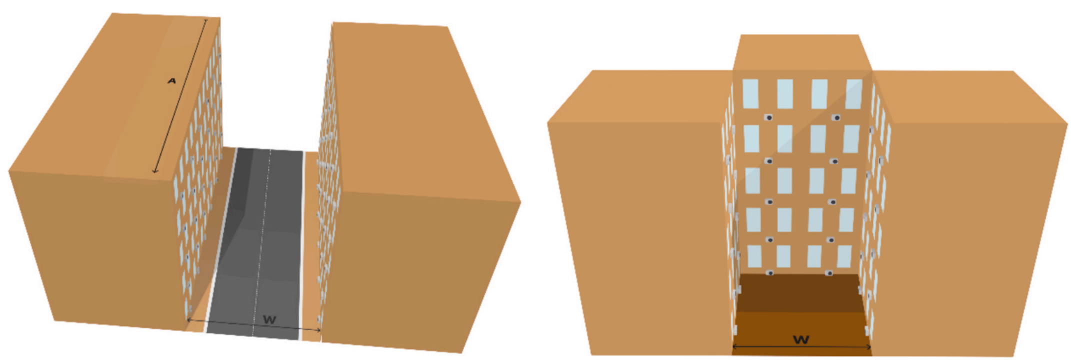

Fig. 6. Street (left) and courtyard (right) typical arrangements for assessing the noise discomfort model for apartment block districts.

Fig. 7. Illustration of noise discomfort model for urban periphery district.

decorrelated point sound sources. At a given window i, the sound level (L_i), in dB(A), received from the sound produced by an outdoor unit (L_{Psys}), in dB(A), is estimated using Equation (4) [60].

$$L_i = L_{Psys} + 10 \times \log_{10}\left(\frac{Q}{4 \times \pi \times r^2} + \frac{4 \times (S - A_{eq})}{S \times A_{eq}}\right) \quad (4)$$

Where Q is the sound directivity factor [61], which depends on the location of the sound sources on the facade (Q = 2) or on the ground, against a wall (Q = 4). r is the distance between the window and the unit, in m. S is the total surface of the outdoor volume studied, in m^2. A_{eq} is the equivalent area of absorption, in m^2, defined as:

$$A_{eq} = \sum_{i}^{st} \alpha_i \times S_i \quad (5)$$

Where α_i is the absorption coefficient of a defined surface *i*, *st* the total number of surface type, and S_i is the real area of the surface, in m^2. The outdoor material, chosen for their representativeness of the materials used in the districts studied, and their absorption coefficients are listed in Table 1.

2.3. *Design of experiments*

To provide a consistent cost-benefit analysis at the city scale, a

Table 1
Absorption coefficient used in noise discomfort models [60].

Surface type	Material	α coefficient at 125 Hz
Street floor	Concrete masonry / Tarmac	0.01
Opening	–	1
Windows	Glass (thick pane or double-paned)	0.15
Wall	Brick (unglazed)	0.02
Courtyard floor	Gravel	0.25

specific design of experiments has been developed based on a set of district archetypes which are statistically representative of the studied area: the Ile-de-France region. The work of Marty-Jourjon et al. [62], has made it possible to identify several building districts archetypes, representative of this region (Table 2).

The present study focuses on residential buildings in urban areas of varying density. Therefore, the following district archetypes are retrieved: large housing, old urban centre, dense urban district, and urban periphery (see Fig. 9), representing two thirds of the districts in Paris region: rural as well as industrial areas have been excluded from the scope. Two of them are located inside the city of Paris and the other two in Paris periphery (see Fig. 8). The geographical, town-planning, architectural and usage characteristics (e.g., number of occupants) of these districts are collected in the following databases: the topographical database from the French National Geographic Institute [57], national housing census of the French National Institute of Statistics and Economic Studies [36], Hotmaps project database [63], and Ambience project database [64].

The weather data comes from the meteorological station of Orly airport nearby the four districts (see Fig. 8). The reference year is 2030, based on forecast files (Data source *Meteonorm* V8). The projection scenario of climate change selected is the intermediate emissions one, SSP2-4.5, considering a radiative forcing of 4.5 W/m^2 in 2100, equivalent to a global averaged temperature higher by 2.1 °C to 3.5 °C compared to the end of the 19th century [65].

In that respect, the CBA is performed at the scale of an archetypal urban district on a selected set of summer comfort technologies and measures over their lifetime with a 2030 forecast weather file. In order to harmonize analysis periods, all systems will be analysed over a period equal to the longest lifetime of all the systems studied. In this case, this is 30 years, which is the assumed economic lifetime of cooling networks (see section 2.4.1) (Fig. 9).

Based on the modelling approach defined above, the installation of each technology and each measure is simulated separately with different diffusion rates scenarios: 30 %, 60 %, and 90 % of buildings is equipped with a given technology or measure. The distribution of technologies is based on the principle that the occupants most exposed to summer discomfort are the first to be equipped. Thermal modelling can be used to identify the most uncomfortable dwellings, classifying them by decreasing level of discomfort in order to select the dwellings equipped in the different scenarios. The simulation outputs are then compared to the outputs of the reference scenario which does not include any solutions other than allowing occupants to open or close their windows to ensure summer comfort.

2.4. Assessment of costs and benefits

Ones quantified using the models presented above, technologies and energy costs as well as non-monetary costs and benefits must be collected and monetised.

2.4.1. Technologies and measures costs collection

Investment and maintenance costs are presented in Table 3. For technologies, they are retrieved from Pezzutto et al. [66] and lifetimes are based on the assumptions of Dittmann et al. [38]. For district cooling, the reference cost of the cooling capacity is equivalent to that of large chillers. The investment cost for the cooling distribution depends on the district density as demonstrated in the framework of the European Stratego project [67] and shown in Fig. 10. Eventually, the installation costs of the equipment needed inside the buildings (i.e., substations, hydraulic networks, room units) has been assessed, as a first-order estimate, being at the same order of magnitude as the installation cost of the distribution system for large chillers plants [66]. Moreover, the annual distribution maintenance cost is assumed to be 4 % of the initial investment (purchase and installation)[68]. The sizing values are also retrieved from [38].

On the other hand, mitigation measures information is retrieved from expert interviews conducted in the scope of the CoolLIFE project [44].

As information on the costs of to these technologies and measures does not have the same reference year, all values prior to 2020 are deflated to that date, based on the consumer price index (CPI) data made available by the data management services of the Organisation for Economic Co-operation and Development [69].

2.4.2. Thermal discomfort

The assessment of thermal discomfort (expressed in °C.h) at the dwelling level consists in adding up, over the whole year, the difference, at each hour, between the summer comfort temperature of households and the indoor felt temperature when this latter is higher than the former [25]. As defined in the section 2.1.3, the indoor felt temperature is equal to the indoor air temperature corrected for the effect of ventilation caused by the operation of the fans. The thermal discomfort value is then weighted by the number of occupants of the dwelling, before being aggregated for all dwellings in the entire district, providing the corresponding value of the thermal discomfort at the district level. Finally, the thermal discomfort at the district level is valued using the selected monetary value (Table 4).

Eventually, based on a literature review on tertiary buildings, Grignon-Massé [25] suggests to assign a monetary value for thermal discomfort of 0.6 €/°C.h per occupant and considers this value as an estimate also for the residential sector.

2.4.3. Noise discomfort

The day-evening-night noise level (L_{den}) is used to assess ambient noise by categorizing sound levels during specific time periods of the day [70]: night-time noise is particularly penalized as shown in (6)

Table 2
Main characteristics of the district archetypes [62].

District archetypes	Living area density (*)	Average number of storeys	Buildings per block (**)	Number of buildings	Number of housings	Population	Distribution in Paris Area
Old urban centre	3,16	6	19,3	143	970	1758	7,5 %
Dense urban centre	2,17	6	7,5	171	1669	2989	12,5 %
Large housings	0,87	12	1,7	48	998	2321	30 %
Urban periphery	0,49	2	1,7	753	583	1410	16,4 %

(*) living area density is the ratio between the building floor area and the district area.
(**) blocks are defined as a rectangular area in a city surrounded by streets and containing several buildings.

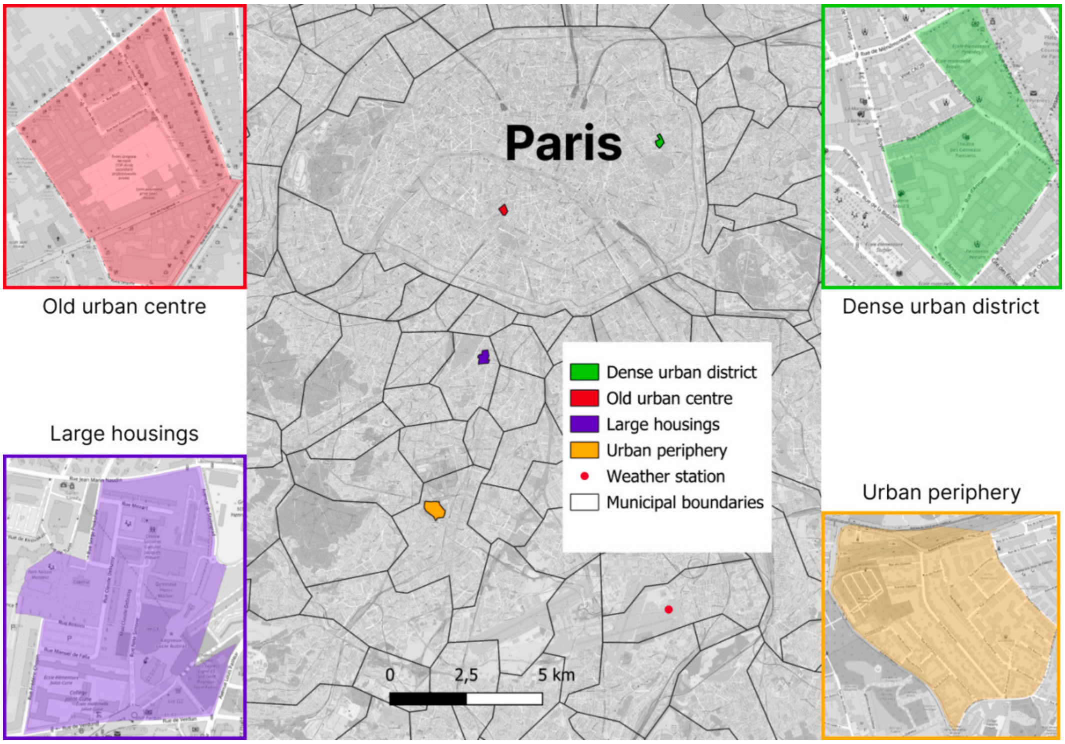

Fig. 8. Map of the four district archetypes and weather station location.

$$L_{den} = 10.\log_{10}\left(\frac{1}{24}\left(12*10^{\frac{L_{Aeq}(6h-18h)}{10}} + 4*10^{\frac{L_{Aeq}(18h-22h)+5}{10}} + 8*10^{\frac{L_{Aeq}(22h-6h)+10}{10}}\right)\right) \quad (6)$$

Where $L_{Aeq}(6h-18h)$, $L_{Aeq}(18h-22h)$ and $L_{Aeq}(22h-6h)$ are respectively the noise levels (in dB(A)) between, respectively, 6:00 and 18:00, 18:00 and 22:00 and 22:00 and 6:00. In the present work, the ambient noise results of the superposition of the already existing ambient noise that can be measured currently and the additional noise coming from the space cooling technologies and assessed through the aforementioned approach. Local ambient noise data finely measured and modelled by the regional observatory of noise [71] have be retrieved, averaged over the districts, and presented in Table 5.

For split system, the noise level of the noise sources is assumed to be the average of 62 dB(A) for 5 kW split and 66 dB(A) for 10 and 15 kW split [72], weighted by the number of each in the district. For VRF, the sound level of an outdoor unit is 82 dB(A) [73]. The resulting sound pressure level at each window is then retrieved and the L_{den} indicator is computed by applying penalties according to the time of day.

Eventually, various studies highlighted the relevance of using a threshold in decibels from which noise discomfort can be counted [74,75]. Based on European Environment Agency recommendations [76], sound level at windows is considered as a nuisance when day-evening-night noise level L_{den} is greater than 55 dB(A). A new noise discomfort indicator at district scale, N_{dis}, is then proposed and evaluated according to Equation (7) where n is the total amount of windows.

$$N_{dis} = \frac{\sum_i^n (L_{den\,i} - 55)_{,\ L_{den\,i} > 55dB}}{n} \quad (7)$$

In old urban centre and dense urban district, Ndis retained value is the average between the value obtained in the street zone and the value in the courtyard zone, weighted by the façade length of each zone in the district. This gives an average discomfort value at a window in a given district, depending on the time of day and the number of air-conditioning systems (split or VRF) switched on. The Ndis value assessed by the noise discomfort model is multiplied by the number of dwellings with open windows given by the thermal model. All the values obtained in this way at hourly time step are then averaged over the year and multiplied by 25 €/dB(A) per dwelling per year [25] to obtain the total noise discomfort cost coming from outside.

Indoor noise assessment is based on conventional methods of calculating the sound level in a room, using the sound level of the (point) source and the absorption of sound waves by the room's walls and furnishings. The noise level of these portable air-conditioning systems, as point noise sources, is considered as equal to 63 dB(A) [72] and assumed constant when the system is running. The indoor reverberation level is approximate by Sabine's formula [60] for a reverberation time of 0.5 s (typical value in housings). Furthermore, indoor noise due to the internal units of split systems or VRF, as well as fans are lower than the discomfort level threshold: they have thus been neglected. Eventually, internal noise discomfort is monetised as a direct cost of space cooling with the same methodology as external noise discomfort.

2.4.4. Greenhouse gas emissions

Two sources of GHG emissions are assessed in the scope of this study: the direct emissions related to the refrigerant fluid leaks during the use phase and indirect emissions related to the electricity consumption. The estimate of GHG emissions is limited to the use phase.

Refrigerant leaks from air-conditioners are estimated on the basis on several assumptions. Firstly, the assumption put forth by Grignon-Massé [25] of a 3 % leakage of the total system refrigerant charge per year is adopted for portable, split, and VRF systems. Secondly, the refrigerant charge for each of these systems is based on [72] as well as the types of refrigerants used which are R290 for portable systems and R410A for others.

The indirect emissions associated with electricity consumption directly depend on the considered electricity mix. In France, due to electricity production from nuclear and renewable sources (hydropower, wind, and solar), the average emissions factor for electricity is relatively low: 57 $gCO_{2\ eq}$/kWh in 2020 [77]. This value was considered

Old urban centre (Paris 6ᵉ)

These districts are very characteristic of Parisian Haussmann architecture, the urban fabric features a very high density of buildings, with around 7 storeys and interior courtyards

Dense urban centre (Paris 20ᵉ)

These districts are characterised by a dense urban fabric, with lower buildings than in the old urban centre. Located between the urban centre and the suburbs, this urban fabric is usually named as “faubourgs” and mainly made of continuous blocks and collective housings

Large housings (Antony - 92)

These districts are specific to the urban fabric of large cities. It is composed of large bars and high-rise buildings, built around 1960 and 1970. They are usually located at the periphery of the city centre.

Urban periphery (Bagneux – 94)

These districts are mainly composed of individual housings developed between the large cities and the rural areas. It is mainly composed of individual housings and features small to medium collective buildings.

Fig. 9. Description and pictures of the four district archetypes (pictures from Google “Streetview”, digital images, Google Maps, captured in 2021).

Table 3
Investment and maintenance costs of technologies [38,66,68].

Technologies	Energy source	Cooling capacity for sizing	Purchasing cost	Installation cost	Maintenance cost	Lifetime
Portable	Electricity	2.5 kW	429 €/unit	172 €/kW	0 €/unit.y	10 years
Single split	Electricity	5 kW	1 102 €/unit	314 €/kW	44 €/unit.y	12 years
Multi-split	Electricity	10/15 kW	1 773 €/unit	237 €/kW	71 €/unit.y	12 years
VRF	Electricity	70 kW	20 886 €/unit	827 €/kW	827 €/unit.y	15 years
District cooling	Electricity	500 kW	105 k€/unit + €/MWh delivered (see Fig. 10)	156 €/kW	4 % of CAPEX	30 years

constant throughout the assessment period without taking into account any future decarbonization trajectory compatible with France’s long-term decarbonization objectives. Finally, the cost of one tonne of $CO_{2\ eq}$ emitted is projected at 100 €/t$CO_{2\ eq}$ in the medium term.

2.4.5. Cost-benefit indicators

All evaluated values are presented in comparison with the reference scenario, in which no technology is installed, and no mitigation measure is adopted. (see section 2.3).

The two indicators that are used to summarise CBA results are the

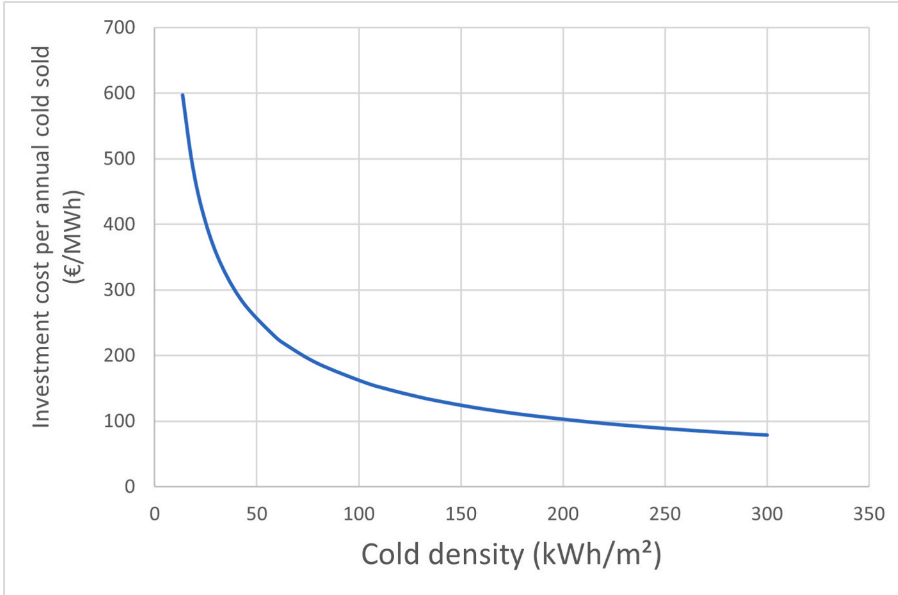

Fig. 10. Specific investment cost of district cooling per cold annually sold as function of the cold densities related to the corresponding land area [67].

Table 4
Investment and maintenance costs of space cooling mitigation measures [38,66].

Measures	Energy source	Sizing information (average value)	Purchasing and installation cost	Maintenance cost	Lifetime
Shading device	–	4 devices/dwelling	175 €/unit	0.0 €/unit.y	10 years
Fan	Electricity	2 devices/dwelling	275 €/unit	15.0 €/unit.y	10 years
White roof	–	Full building roof area	19 €/m^2	0.0 €/unit.y	10 years

Table 5
L_{den} indicators for the sound ambient level in the four studied district [71].

District	L_{den} (dB(A))
Old urban centre	62.7
Dense urban district	59.2
Large housings	59.5
Urban periphery	62.5

benefit-cost ratio (BCR) and the net present value (NPV). Their definition is given below.

$$BCR = \frac{\sum_{i=t_0}^{t_0+T} \frac{B_i}{(1+a)^i}}{\sum_{i=t_0}^{t_0+T} \frac{I_i+C_i}{(1+a)^i}} \quad (8)$$

$$NPV = \sum_{i=t_0}^{t_0+T} \frac{B_i - C_i - I_i}{(1+a)^i} \quad (9)$$

Where a is the discount rate, B_i are benefits achieved in year i, C_i costs in year i, t_0 is the year of implementation, T is the evaluation period duration in years (here, 30 years), and I_i is the investment costs in year i. In the context of social or macroeconomic cost-benefit analyses conducted in the EU, the choice of discount rate is left to the discretion of Member States. Based on the work of [78], the average value of 3.3 % used by EU Member States has been retained. When the BCR is higher than 1 or when the NPV is a positive value for a scenario, it means that this scenario fulfils the cost-benefit criterion and can be, theoretically, implemented.

3. Results

First, the effects of technologies and measures on thermal and noise discomfort are presented in dedicated sections of this part, before detailing the BCR and NPV results.

3.1. Thermal discomfort reduction

The objective of each technology or measure is to reduce thermal discomfort, but they do not reduce it to the same extent: the reduction in thermal discomfort by each of the technologies or solutions is presented in Fig. 11 depending on their rate of diffusion in the population. The results are given as percentages of the baseline level in each district (Fig. 12).

In each district archetype, shading is the solution with the least effect on the thermal discomfort endured by occupants. A closer look at the simulation results shows that only a small fraction of dwellings with blinds installed use them actually: for instance, in the old urban centre district, when 90 % of dwellings have shading measures, only 9.4 % of residents actually use the blinds when space cooling is required. The use of white roofs also remains of limited interest. The reduction in thermal discomfort must be interpreted in the light of the average height of buildings in the various districts and, more specifically, the ratio between the available roof area and the density of housings: while the old urban centre and dense urban districts have in average 6 floors buildings, this number increases to 11 for the large housings district and decreases to 2 for the urban periphery district. Consistently, this measure has a more significant effect in a district primarily composed of single-family houses.

The effect of fans does not appear to be strongly linked with the district archetype. However, it is the measure studied that systematically demonstrates the most significant effect in terms of reducing thermal

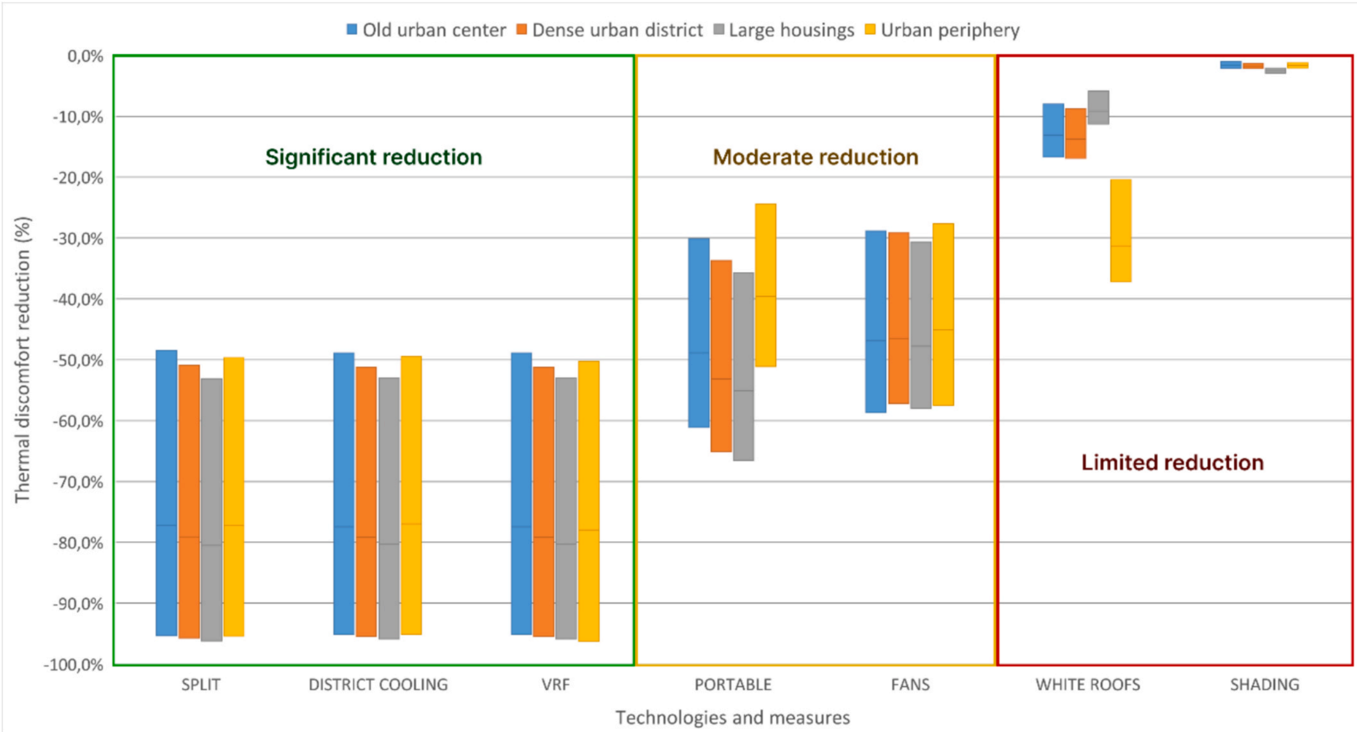

Fig. 11. Thermal discomfort reduction for the technologies and measures considered in the four district archetypes, as a percentage of the thermal discomfort baseline in each district.

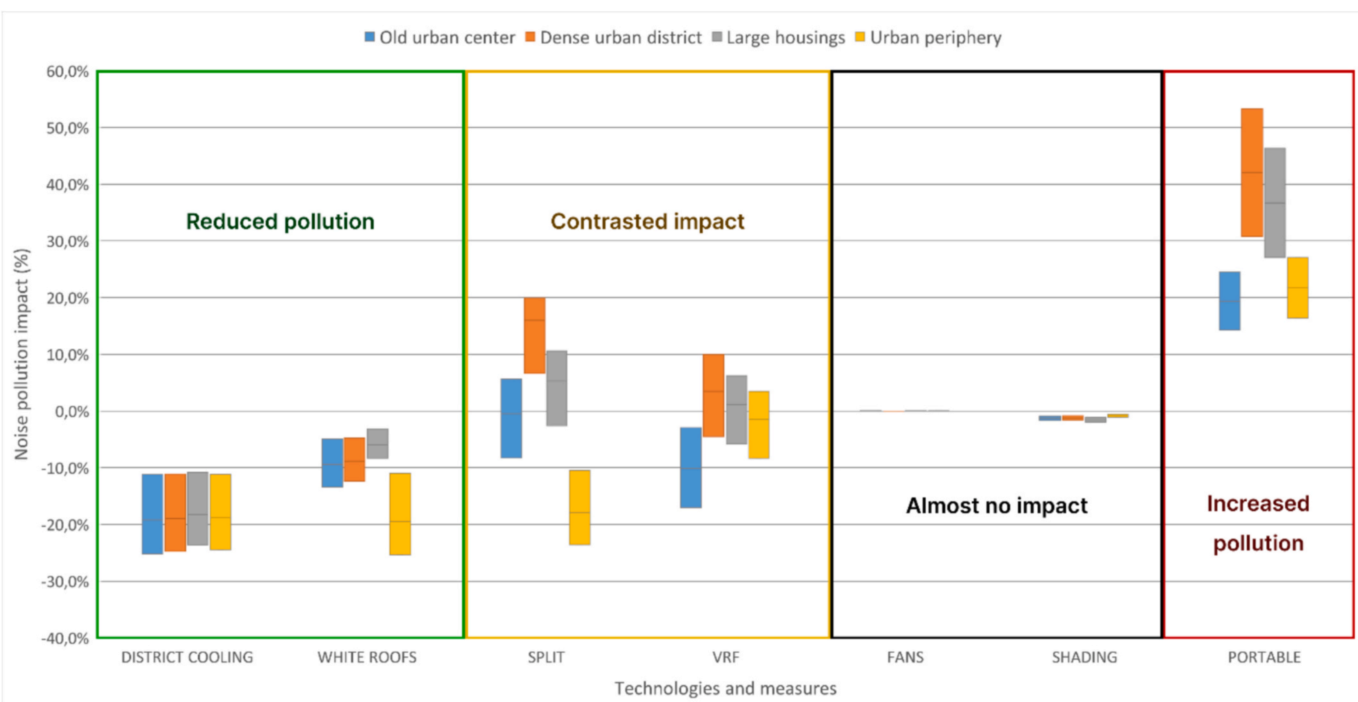

Fig. 12. Noise pollution impact (reduction or increase) depending on the space technology or measure considered in the four district archetypes as a percentage of the noise level baseline in each district.

discomfort. This clearly shows that this measure is very well suited to the normal summer weather conditions, when extreme temperatures are rarely encountered: indeed, the outdoor temperature exceeds 33 °C – when the cooling effect of the fans wears off – "only" during 3.5 % of the time.

Penalised by their lower cooling capacity, portable air-conditioning systems have the least significant effect among the studied space cooling technologies, whereas split systems, VRF, and district cooling network have almost the same effects on thermal comfort (Fig. 11). However, in the urban periphery district, VRF systems demonstrate higher effect compared to splits and district cooling network, because of their oversized cooling capacity when they are installed in single family houses.

3.2. Noise discomfort effect

The occupants of the dwellings are exposed to a noise level resulting from a combination of indoor and outdoor noise. However, given the modelling assumptions, indoor noise only occurs when portable air conditioners are running, while residents are only exposed to outdoor noise when they open their windows to cool their homes. Finally, the opening of windows is controlled exclusively by thermal discomfort. As in the previous section, the noise discomfort level N_{dis}, in dB(A)/(dwelling.year), resulting from the implementation of the solutions and measures is compared with the noise discomfort level in the reference situation (cf. Table 5).

One can observe that for most space cooling technologies or mitigation measures, the more they are installed or adopted, the more summer comfort is globally achieved among housings, and the less occupants open their windows to activate cooling by natural ventilation: consequently, the more the exposure of these occupants to outside noise is reduced. In contrast, the results highlight the negative impact of portable systems on acoustic comfort, whatever the diffusion scenario or the district considered. Indeed, the increase in their diffusion rate leads to a global increase in inside noise that far exceeds the reduced exposure to outdoor noise when summer comfort increases.

It should also be noted that, in dense districts, the installation of split systems – as well as VRF systems to a lesser extent – in a limited proportion of housings leads to an increase in noise pollution, particularly for occupants of other non-air-conditioned housings who open their windows to cool their housing. Indeed, the installation of split or VRF systems has two opposing effects on noise disturbance: on the one hand, it allows the occupant who operates the space cooling system to keep the windows closed more often but, on the other, it increases outside noise, particularly for people who depend on natural ventilation to cool their housing. It is only once most housings have been equipped with split systems that acoustic discomfort diminishes compared with the reference situation. Moreover, in that respect, VRF systems are often more attractive than split systems. Indeed, even if the acoustic power of a VRF outdoor unit is greater, there are fewer of them for the same number of dwellings connected in most district archetypes, and their location on the roof reduces the consequences of noise propagation. However, this situation is reversed on the Urban Periphery district, where VRF systems cannot be shared between homes.

Eventually, the effect of cooling network is always positive and achieves the greatest noise discomfort reduction, since it is assumed that this system locally produces no outside noise.

The effect of mitigation measures on noise discomfort is limited. This is mainly because they do not produce noise and have a limited impact on thermal discomfort, which therefore limits their effect on window opening. This is confirmed by the significant effect of white roofs on noise nuisance exposure in the urban periphery, in line with their effect on thermal nuisances. The impact of the fans on noise discomfort is null, as it is assumed that this measure does not affect the window opening at all.

3.3. Benefit-cost ratio

The benefit-cost ratio (BCR) values over the lifetime of each technology and measure are presented in Fig. 13. Apart from VRF systems and white roofs in the urban periphery district, all the BCR values are greater than 1, which confirms that each of the technologies and measures under study are reliable solutions to enhance summer comfort by households in urban context.

In every scenario, fans emerge as the solution with the highest BCR values. It stands out as the measure having the most significant effect on thermal comfort and one of the least costly solutions. Despite their low efficiency, portable air-conditioning systems have high BCR values and are often an attractive alternative thanks to their low investment costs. Conversely, despite the investment costs involved, district cooling

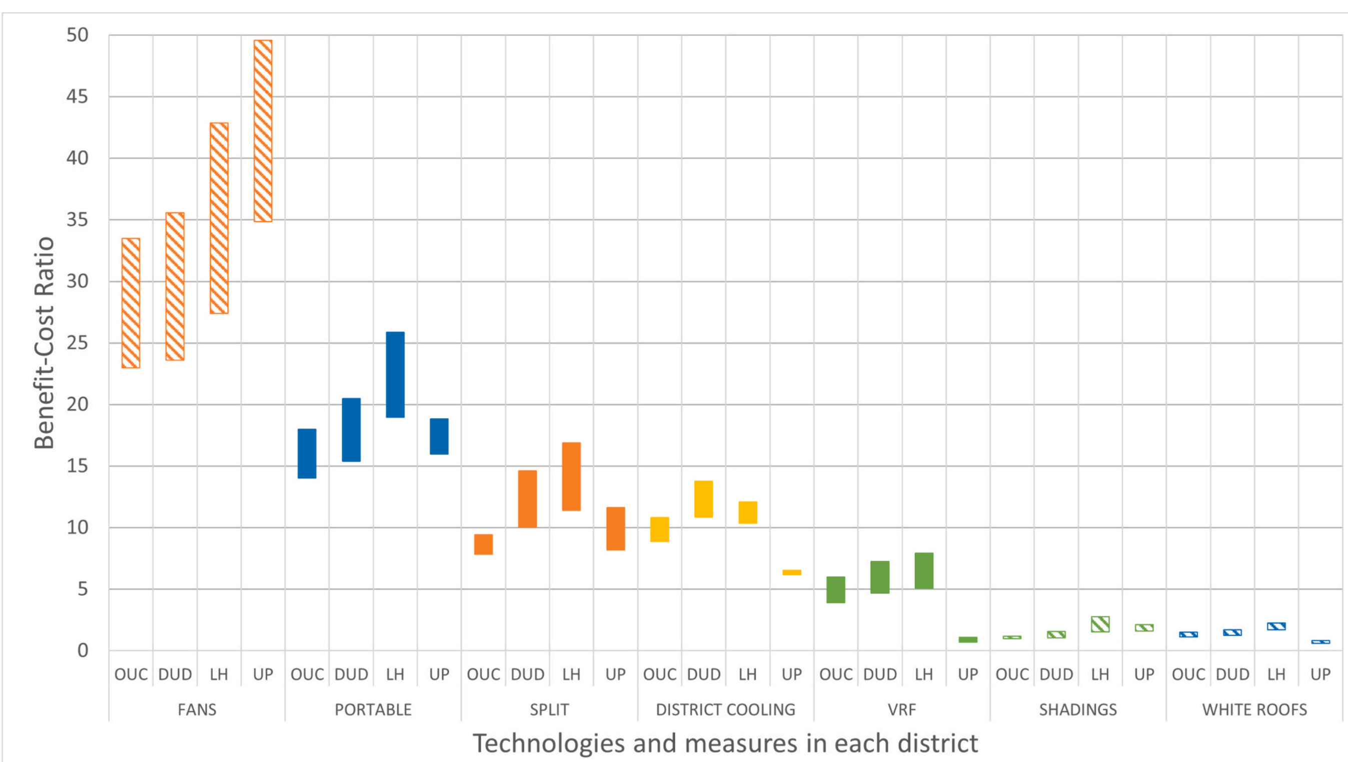

Fig. 13. Benefit-cost ratio of space cooling technologies and measures depending on in the four district archetypes (Old urban centre (OUC), Dense urban district (DUD), Large housings (LH), Urban periphery (UP)). The ranges of values shown are due to variations in the diffusion rate of the technologies and measures.

networks are proving their worth in densely populated areas (ie. in OUC and DUD). By contrast, split systems are more attractive in less densely populated areas and strike a good balance between a relatively low cost and a significant reduction in thermal discomfort. VRF systems have always the lower BCR values among space cooling technologies due to their high investment costs and especially their installation cost. The relevance of VRF systems disappears in urban periphery mostly made of individual houses.

A closer look at the behaviour of the BCR indicator reveals that, firstly, all solutions have lower BCRs when their diffusion rate increases (see Fig. 14). As the most uncomfortable homes are the first to be equipped, each additional solution installed meets a lower cooling requirement. Thus, the marginal space cooling benefit decreases as the penetration rate increases. There are however two exceptions. The first one concerns the implementation of district cooling in suburban districts: each connected dwelling, even if it only experiences slight discomfort, contributes to increasing the density of cooling demand—which is very low in this type of district—which is a key factor in the economic profitability of district cooling insofar as it helps amortize installation costs. Nevertheless, even with maximum densification, district cooling remains less attractive than split systems in these suburban districts ("large housings" and "urban periphery" districts). On the other hand, the analysis highlights the relative superiority of district cooling over split systems in the most densely populated districts ("old city centre" and "dense urban district" (as soon as the equipment rate exceeds 50 % for the latter). The second exception concerns split systems in "old urban centre" districts, for which the benefit-cost ratio is degraded with a modest equipment rate: this is directly due to the noise nuisance caused by outdoor units on non-equipped dwellings. Noise pollution then decreases with the rate of equipment, as the more homes are equipped, the less residents use free-cooling by opening windows to cool their homes. In so doing, exposure to outside noise also decreases.

Finally, shading devices and white roofs also have a low BCR value (between 1 and 3) in most scenarios and districts. Their evaluation is heavily penalized by their inability to provide the same level of thermal comfort as air-conditioning systems.

3.4. Net present value

According to the net present value indicator, district cooling and split systems are the two most relevant solutions (see Fig. 15): district shows relatively higher benefits in space cooling in the dense areas, whereas split systems show greater relevancy in large housings and in urban periphery. Thanks to a quite high energy efficiency and a certain degree of sharing of cooling capacity between housings, VRF seems to be a more attractive alternative than portable systems, except in less dense area (the "urban periphery" district shows high proportion of single-family homes), where these systems are totally irrelevant,

In addition, portable systems are in direct competition with fans, which compensate for their lower efficiency in reducing thermal discomfort with lower noise levels and lower investment costs. Here again, space cooling mitigation measures have low NPV values due to the low value of the discomfort reduction they provide.

4. Discussion

For the sake of clarity, this part is divided into three discussion sections. The first section is devoted to the modelling method, the second to the monetization assumptions, and the third to the implementation of the cost-benefit analysis.

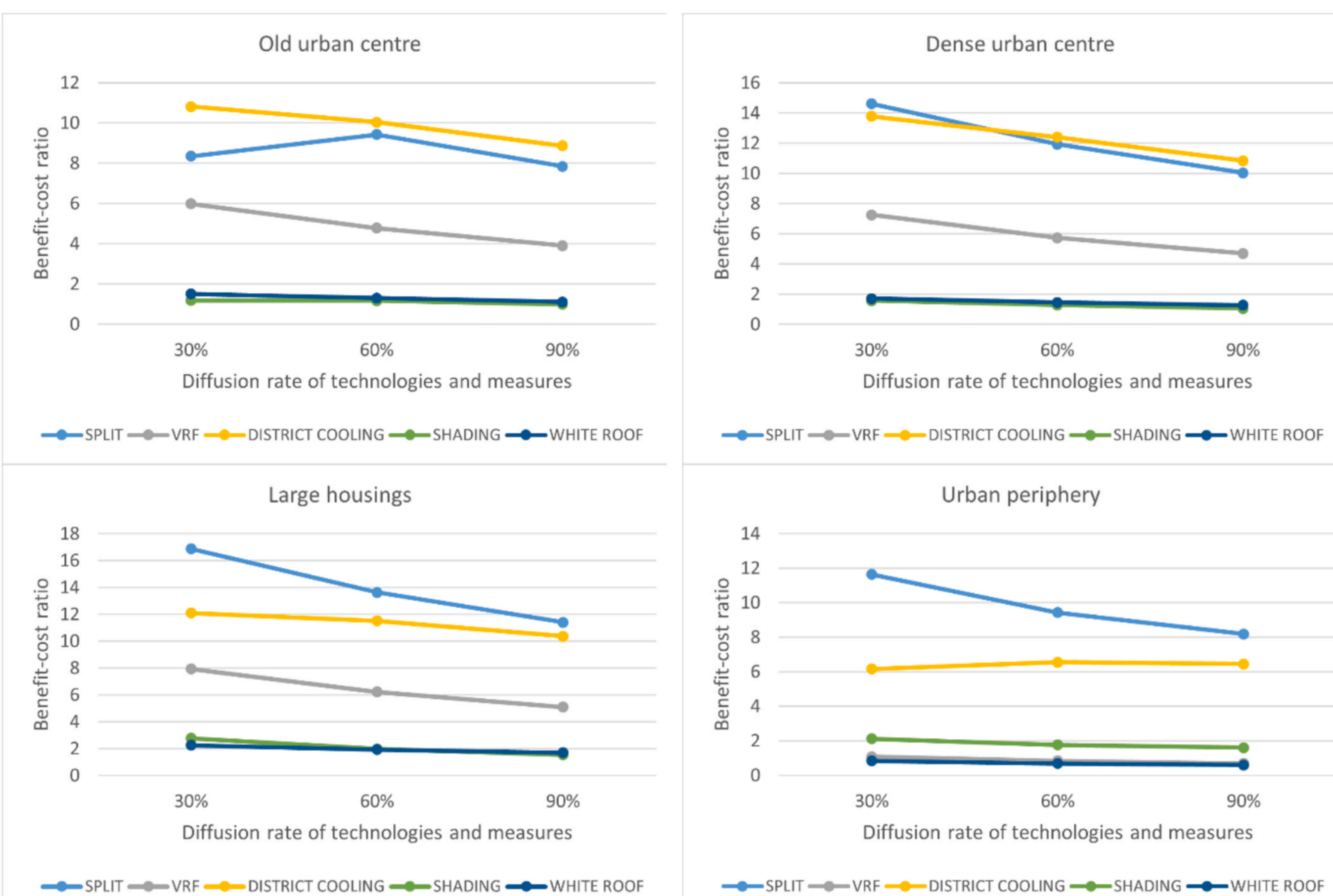

Fig. 14. Benefit-cost ratio of space cooling technologies and measures (excepted fans and portable).

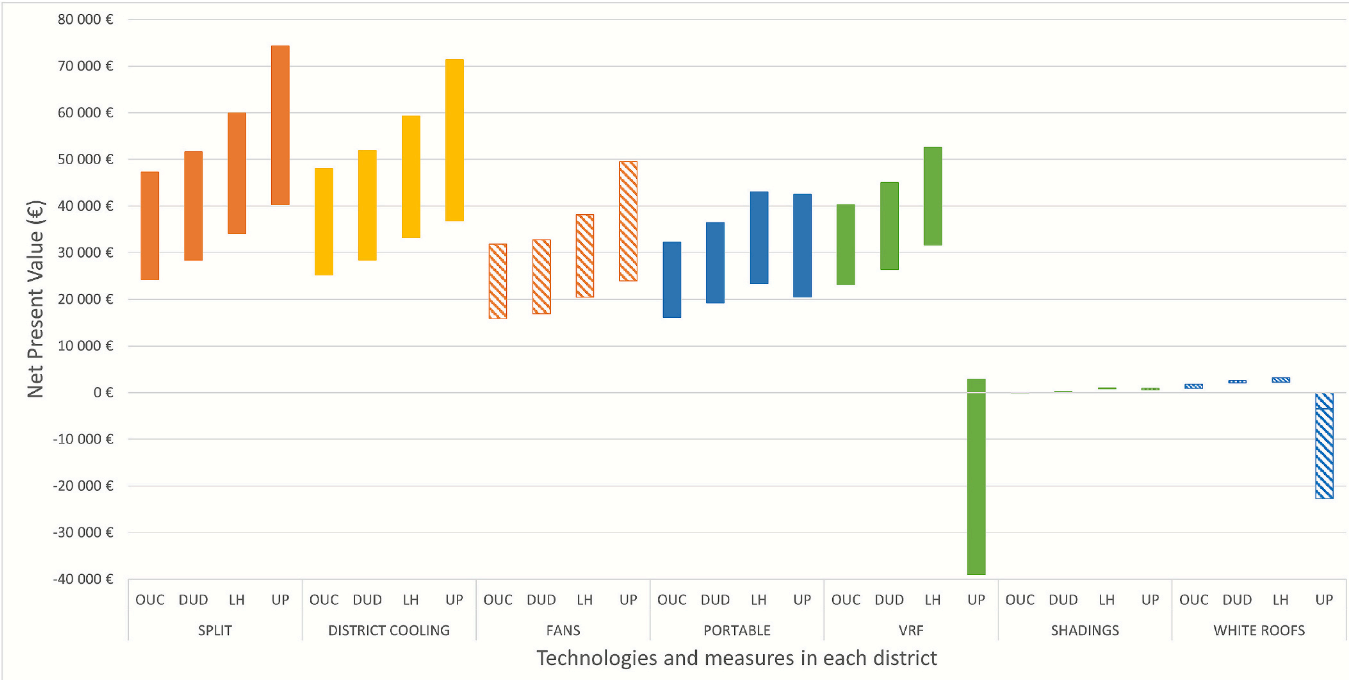

Fig. 15. Net present value for all technology and measure depending on the diffusion rate of the solution considered in the four district archetypes (Old urban centre (OUC), Dense urban district (DUD), Large housings (LH), Urban periphery (UP)). The ranges of values shown are due to variations in the diffusion rate of the technologies and measures.

4.1. *Limitation on modelling method of thermal and noise discomfort*

The results obtained are based on the assembly of different models adapted to the simultaneous modelling of several thousand dwellings in an urban context. This adaptation required a number of simplifications, in terms of the dynamic thermal behaviour of the dwellings, the representation of the heat island phenomenon and the propagation of noise disturbances. The modelling of these phenomena can certainly be explored in greater depth with the aim of improving their characterisation and quantification. The use of single-zone thermal models gives only an approximate idea of the actual thermal condition of a dwelling, particularly for air-conditioning use, which is very often restricted to a fraction of the dwelling. Similarly, the simplified representation of dwellings reduces the possibility of quantifying more accurately the cooling of premises by natural ventilation or the reduction in cooling requirements through the use of shading devices. With regard to the aforementioned point, the model implemented from Alessandrini et al. (2006) has been developed for office buildings and suggests that they are used very infrequently. This use may be relevant throughout the year, but its relevance is likely to vary with the season. For example, during the summer period and in particular during extreme heat waves, occupant behaviour may change. However, no formal usage rules have been identified. A key area for modelling improvement is to consider the trade-offs that households make between thermal and visual comfort.

In this study, a particularly elementary UHI model was used, because of its ability to optimise computation time management. New, more sophisticated approaches to modelling the urban climate should be coupled with the thermal and acoustic propagation models used to date. This would enable us to better characterise the urban environment as part of the study of summer comfort. The initial model developed to estimate noise discomfort is based on fundamental acoustic equations and standard references. However, it remains largely simplified and relies on schematic floor plans and layouts, without taking into account the actual environment of each building. However, these preliminary assessments indicate that acoustic discomfort appears to be relatively minor in comparison to thermal discomfort. Conducting a sensitivity analysis of the results obtained would assist in determining the reliability of the method.

Beyond physical modelling, the method of quantifying thermal discomfort is open to discussion. The assessment of thermal discomfort is based on degree-hour values and therefore assumes linearity in the discomfort caused by one degree. However, if exposure to temperatures above 25 °C for a long time can cause discomfort and heat stress, temperatures above 35 °C, even for a short period of time, can be lethal [79]. Therefore, the linearity of degree-hours does not appear to be consistent with the impact of heat on health. Future work could examine the possibility of adopting an approach based on temperature steps. Noise discomfort could also be assessed with a similar approach. However, no such indicator has been identified in the literature.

In addition, the evaluation of discomfort in degree-hour was used to compare technologies and measures that do not provide quite the same service. Their impact on the ambient air in terms of heat, humidity or air displacement has been reduced to an evaluation in degrees. This method, although relevant for assessing thermal discomfort, ignores the discomfort that can be caused by overly dry air or excessive draughts. Even in the current literature, there are more precise comfort models, incorporating adaptive comfort [80,81] or humidity and air movement [82]. However, adapting them to an urban building energy model which tackles simultaneously thousands of dwellings remains to be studied.

4.2. *On monetisation of discomforts and externalities*

After the physical modelling stage, the process of monetising thermal and acoustic discomforts constitutes a crucial step in the cost-benefit analysis. The monetary values used have a decisive impact on the results obtained: 0.6 €/°C.h per occupant, 25 €/dB(A) per dwelling per year, 100 €/t$CO_{2\ eq}$.

The cost of thermal discomfort is very high compared with other external costs. For instance, for portable systems with a 90 % diffusion rate in the old urban centre district (see Fig. 16), the investment costs have been evaluated at 1 270 € per dwellings and related energy consumption at 940 €. But, in one year, the benefits allowed by thermal

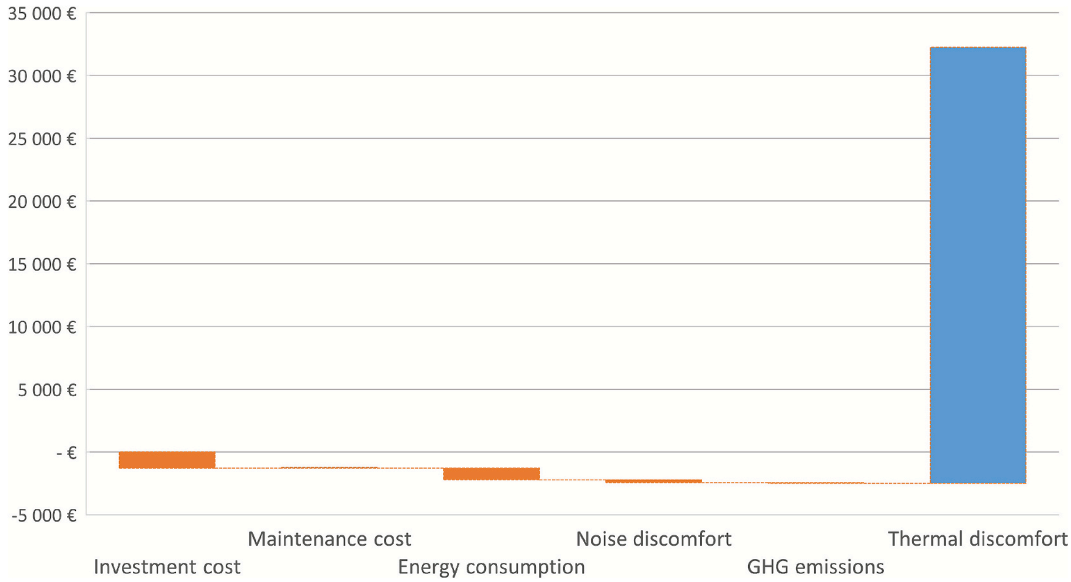

Fig. 16. Breakdown in net present value. The example of portable systems in old urban centre districts.

discomfort reduction over the system's lifetime is evaluated to 34 714 € per dwelling, while the cost of noise discomfort is 214 € and the reduction of GHG emissions is valorised only at 50 €. It should also be noted that the value of the latter is necessarily overestimated, given the expected decarbonization of electricity generation in the medium and long term.

It appears that thermal discomfort is the key factor in this analysis. In addition to the constraints involved in modelling, it is crucial to acknowledge that the literature used to ascertain the cost of thermal and acoustic discomfort is somewhat dated. But primarily, it was developed within the context of studies on tertiary buildings. So even though the gap between these assessments is very significant, it seems relevant to improve the method of quantifying and monetising noise and thermal nuisances for households.

This also has the effect of making the NPV results insensitive to variations in data specific to side-effects (e.g., noise or GHG). Since this indicator is calculated as a sum, the thermal discomfort reduction term crushes the other monetary values. In this respect, the BCR has an advantage. By separating costs from benefits to calculate their ratio, this indicator makes it easier to appreciate the variation in costs, even though the benefits considerably exceed them. Eventually, this internalisation method, based on average observations for intangible results, does not enable sensitivities diversity to be reflected in terms of costs. Not all occupants are equally sensitive to thermal and noise discomfort and disparities have been observed, between men and women [83] and according to the age of studied population [84].

4.3. *Cost-benefit analysis at the district scale*

In this study, values were evaluated at the neighbourhood level, with the diversity of situations to some extent excluded. It appears that all costs and benefits are distributed equally across all dwellings. In particular, the results pertaining to discomfort were understood to be the aggregate of all individual discomfort values, irrespective of whether the dwelling is equipped with the technology or measure. This approach enabled a fair comparison between districts and provided results on a stock scale. However, it does not permit a personalised evaluation of situations. For instance, the results obtained for white roof scenarios are low. This measure is only relevant to dwellings located underneath the roof. Therefore, it was not possible to observe the potential benefits of this measure if it were implemented individually by the occupants of these dwellings. It would therefore be relevant to extend this work by proposing a more individualised analytical framework to highlight the consequences of the diversity of situations on the choices of technologies and measures.

5. Conclusions

In order to provide a comprehensive comparison of the available solutions to the issue of summer comfort, this article proposes a method for assessing the effects of each on a neighbourhood scale. Applied to specific districts in the Paris region, the methodology is unique in its integration of models tailored to this scale for evaluating benefits and externalities of various types, which are typically used separately in the literature. Additionally, the approach is designed to facilitate decisions that benefit the wider society rather than individual interests.

Fans represent an effective, cost-effective solution that is suitable for all of the cases studied but they do not provide the same cooling service as space cooing technologies. District cooling networks present a noteworthy alternative to split systems, offering effective summer comfort and a longer service life, while minimising environmental impact and noise pollution. However, this solution is less suitable than individual air-conditioning systems for low-density areas and requires a collective implementation frame. The results of this study provide decision-makers with information on the influence of residential density on the outcome of competition between district cooling systems and split systems in urban centres and suburban areas. Nevertheless, further work is needed to further clarify the relative competitiveness threshold of these two space cooling technologies.

The benefit-cost ratio is a valuable metric for comparing solutions, especially in contexts where different monetary values are assigned to different outcomes. Thermal discomfort is the primary motivator behind the implementation of a technology or measure, and it appears to be the predominant factor in its monetary evaluation. The benefit-cost ratio values obtained are sometimes significant, particularly for fans, which is in accordance with insights from the literature [10]. However, it was also possible to identify conclusions specific to certain urban situations. For instance, in areas where noise is a particular concern, the use of portable air-conditioners is not recommended.

From a societal point of view, it can be concluded that white roofs do not represent a relevant solution for dealing with summer comfort issues on a district scale. However, the use of an aggregated indicator, as employed here, has inherent limitations that exclude the diversity of individual situations in a multidimensional problem. Further research is required to consider methodology evolutions to address specificities among the population while retaining the district level as the relevant analysis scale for local authorities.

CRediT authorship contribution statement

Théodore Fontenaille: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Bruno Duplessis:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Adrienn Gelesz:** Writing – review & editing, Validation. **Simon Pezzutto:** Writing – review & editing, Funding acquisition.

Funding

This work has been funded by the European Union through the research LIFE project "CoolLIFE – Open Source Tools to face the increase in buildings' space cooling demand on EU level" (code project: Project: 101075405—LIFE21-CET-COOLING-CoolLIFE).

Declaration of competing interest

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

Acknowledgements

The authors also would like to thank all the partners in the CoolLIFE consortium for their collaboration and the valuable technical insights.

Appendix 1. Urban building energy model: building characteristics and main input data

This appendix collects the main data used to configure the housing energy model implemented in this paper. Thermal characteristics

Walls U-values

The surface heat transfer coefficients for vertical walls, roofs, floors and windows are derived from the conventional method used to issue the building energy performance certificates [34]. Their value depends on the construction year of the building, the main heating energy source as well as their location. Here are given the figures for Paris area in W/(K.m^2).

Table 6
Building walls U-values (W/K.m^2).

Construction year	Vertical walls		Roofs		Floors	
	Main heating energy source		Main heating energy source		Main heating energy source	
	Electricity (direct Joule)	other	Electricity (direct Joule)	other	Electricity (direct Joule)	other
Before 1974	2.5		2.5		2	
From 1975 to 1977	1		0.75		0.95	
From 1978 to 1982	0.8	1	0.7	0.75	0.84	0.95
From 1983 to 1988	0.7	0.8	0.4	0.55	0.55	0.7
From 1989 to 2000	0.45	0.5	0.35	0.4	0.55	0.6
From 2001 to 2006	0.4		0.3		0.3	
From 2006 to 2011	0.36		0.27		0.27	
Since 2012	0.34		0.21		0.25	

Furthermore, in order to take into account the thermal renovations carried out in older buildings (built before 1975), the U-values of vertical walls or roofs can be adjusted based on the 2013 "Housing" survey [33], which estimated the frequency and quality of renovations, as well as figures from TABULA project [35].

Table 7
Renovated building walls U-values (W/K.m^2).

Thermal renovation	Vertical walls		Roofs	
	Stock distribution	U-Value	Stock distribution	U-Value
No renovation	16 %	unchanged	31 %	unchanged
Poor-quality	30 %	1.5	39 %	1.5
Medium-quality	54 %	1	30 %	1

Windows U-values

Eventually, windows U-values were determined using the same process to account for the relatively high probability that they had been renovated (from [33]).

Table 8
Windows U-values (W/K.m^2).

Windows performance	U-Value
Single glazing	5.8
Double glazing	2.25

Table 9
Single glazing distribution in French building stock [33].

Construction year	Single glazing occurence (%)
<= 1975	23 %
1975–1977	15 %
1978–1982	15 %
1983–1988	15 %
1989–2000	0
2001–2005	0
> 2006	0

Thermal mass

The following figures have been used for thermal mass.

Table 10
Thermal mass of buildings based on the construction year.

Construction year	Thermal mass (Wh/m^2.K)
Before 1948	100
From 1949 to 1974	60
From 1975 to 1977	20
From 1978 to 1982	50
From 1983 to 1988	50
From 1989 to 2000	50
From 2001 to 2006	60
From 2006 to 2011	60
Since 2012	120

Air change rate

The air change rate has been set as follows based on the construction year of the building:

Table 11
Air change rate of buildings based on the construction year.

Construction year	Air change rate (volume/h)
Before 1948	1
From 1949 to 1974	0.6
From 1975 to 2005	0.5
From 2005	0.4

Occupancy modelling

Comfort temperature

The comfortable temperature for dwellings varies from one household to another. Based on public surveys, [85] considers that the distribution of comfortable temperatures in winter follows a normal distribution with an average of 20 °C and a standard deviation of 1 K. For summer comfort, the distribution is centred around an average of 25 °C (see Fig. 17).

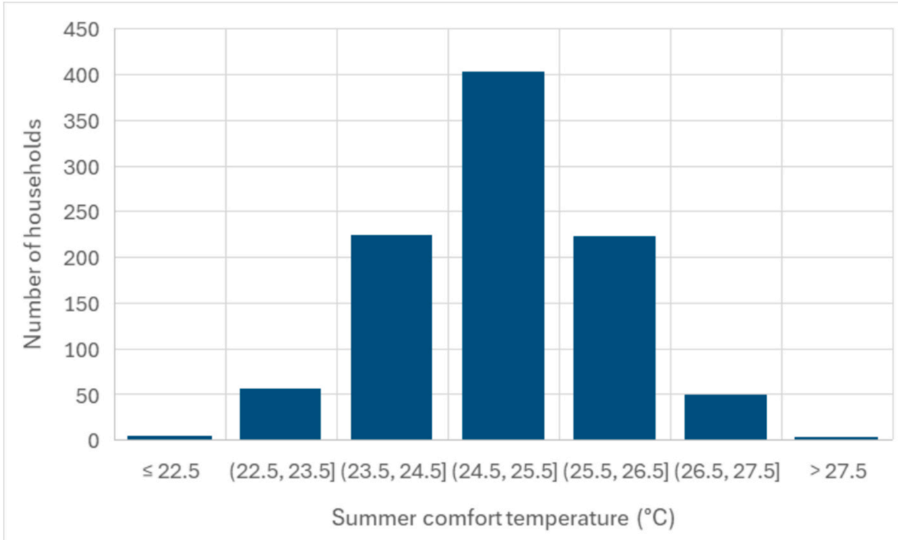

Fig. 17. Distribution of summer comfort temperature among the households in “Old Urban Centre” district

Occupancy scenarios

French Time of Use survey is used to simulate occupants’ activities [37]. The database consists of 19,000 24-hour records with more than 100 possible activities lasting at least 10 min. These 100 activities have been reduced to nine main uses, most of which consume energy: cooking, digital activities, personal care, dishwashing, laundry, other household chores, leisure, meal and rest. Consequently, the nature of these activities or the absence of housing draws an occupancy scenario of the housing and a potential management scenario of the required comfort temperature in the dwelling for the purpose of HVAC energy modelling.

From this database, a weekly activity schedule derived from the concatenation of 24-hour records is assigned to each inhabitant of each dwelling. Each activity is assigned an energy consumption value from [86]. People in the same household do not interact with each other, but if two occupants of the same household perform the same activity at the same time, the energy consumption associated with that activity remains the same.

Data availability

Data will be made available on request.

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