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Evaluation of passive strategies, natural ventilation and shading systems, to reduce overheating risk in a passive house tower in the north of Spain during the warm season

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ABSTRACT

During the last decade in the European Union, some targets have been set to reduce energy consumption in buildings, promoting the construction of nearly Zero Energy Buildings and under certificates as Passivhaus.

Different regulations define indoor comfort, also Passivhaus standards, considered in this study. Previous studies research the risk of overheating in these buildings, particularly during hot seasons, recommending multiple strategies that are described in this project.

This study aims to detect the best natural ventilation and shading strategies to mitigate overheating issues during the hot period in a Passivhaus certified residential tower in Bilbao. The study will be carried out by dynamic simulations. It has been analysed different factors in order to quantify their direct impact on the indoor temperature, proving that overheating can occur, especially during the hot season.

The research will conclude that corner-oriented and crossed-oriented flats work better than the single-oriented for natural ventilation, producing more renovations per hour. Shading systems work better when located outside and are mobile. When combining the best previous strategies, the temperature achieves Passivhaus limitations, but high airspeed rates occur, preventing users' comfort. To achieve Passivhaus limitations is necessary to regulate different opening strategies to avoid high airflow rates and combine different passive strategies.

1. Introduction

During the last decade, energy consumption in the European Union related to buildings reaches 40% of the total consumption [1]. In Spain, considering only residential buildings, it represents 18% of the total national consumption [2], and 17% in the Basque Country [3].

The EU has adopted several strategies and targets to reduce energy consumption. The most relevant in this area are 2020 [4], 2030 [5] and 2050 [6] objectives. The main instrument has been the Energy Performance of Building Directive [1], which promotes buildings with zero or nearly Zero Energy Building (nZEB). In Spain, some policies have also been established to achieve a reduction in energy demand in buildings, implementing the directive on energy self-consumption generated by renewable energies [7]. Furthermore, in response to the shared health crisis due to COVID-19, new energy measures have been approved in 2020 [8]. They promote the necessity of encouraging the decarbonisation and sustainability agenda, to ensure that investments in renewables, energy efficiency and new production processes act as a green brake for economic recovery.

Looking for energy demand reduction, a followed trend, not only in Spain but also in Europe, has been to build under some energy certifications. This is the case of the Passivhaus (PH) certificate, which was developed in Germany and Sweden as a research project to minimise the total energy demand [9,10]. The concept of PH consists of designing with low energy consumption, low energy demand and airtight buildings. Some studies show that buildings with this certificate consume 80%–90% less energy for heating and cooling than conventional buildings, with only an increase in construction cost of 5%–10% [9,10].

To achieve this comfort balance and low energy demand, the PH establishes the minimum criteria for residential buildings, where internal gains and heat recovery systems ensure the thermal balance in the ventilation systems during cold periods and shading systems in the warm periods. It must also have appropriate thermal insulation and windows.

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To evaluate thermal comfort, different models exist, two of the most accepted are the Thermal Balance Models or empirical models (UNE-EN ISO 7730:2006 and UNE-EN 16798:2020), based on studies in climatic chambers, and adaptive models proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), defined by studies in situ. However, there is no absolute value that defines thermal comfort. The most widely accepted definition is "the mental condition that expresses satisfaction with the thermal environment". Based on these models, various norms and standards have been established to define comfort values [11–16]. In the case of the PH standard, the comfort ranges are based on a steady-state equation that predicts the average operating temperature values [17]. In cold climates, the number of days with overheating during the summer and percentage of annual hours above 25 °C is estimated not to exceed 10%, recommending a value of 5%.

Concerning this overheating and, because of the predictions of current climate change towards global warming, several studies have explored the current risks of overheating in highly insulated buildings (PH or nZEB) to investigate strategies to mitigate it [18–20]. Among them, it is worth to highlight those that study comfort in climates with warm summers, such as Spain [21,22], Italy [21,23,24], United Kingdom [21] or Portugal [25]. These studies suggest different improvement strategies to mitigate the overheating problems that have been detected and analysed. Furthermore, it is observed that most of them do not reach comfort 100% of the time and need corrections.

Most of the studies are made in single-family housing, and only a few have been made for collective housing built under PH or similar standards. It has been detected that comfort is higher in single-family houses than in residential buildings, where the discomfort is incredibly high during warm periods. This discomfort is due, among other reasons, to the difference in surface area per person in each typology, which is lower in collective housing [21].

According to the literature, different strategies can be established to mitigate the risk of overheating during warm periods depending on the cause [18,26]:

- Occupation: limiting internal gains [21,26].
- Limit indoor temperatures: use a thermostat to control the ventilation system with a specific temperature range [21].
- Building location: exterior shading systems, automatic systems or green roofs [21,27,28].
- Orientation: if the window-wall ratio is high, preferably orient it to the south. Considering the advantages during the winter period as a source of solar thermal gains, however there is a risk of overheating during the summer [29].
- Building configuration: night ventilation instead of an active cooling system in summer and mechanical ventilation with heat recovery in winter [21,27,28,30].
- Thermal insulation thickness: depends on the climate. When the buildings are highly insulated, it is sometimes better to reduce the thickness of the roof and façades [21,24,26].
- Type of glass: in some cases, it is better to use low-emissivity window glazing (low-e) and double glazing [24,27].
- Building systems: improve the performance and insulation of domestic hot water production and storage systems, avoiding centralised heating systems in dwelling blocks [21].

1.1. Solar protection in passivhaus residential buildings

An optimal shading system must be able to provide not only correct visual comfort, but also correct thermal comfort, allowing the solar gains during the cold period and protecting enough to avoid overheating in the warm period. It must also be economically affordable. Other variables to be taken into account are high reliability, the aesthetic requirements determined by each project, coherence with the technical conditions (such as dimensions of assembly or folding) and fire resistance, possible noises, weather and theft protection [31].

From the literature on shading systems, it has been determined the parameters taken into account and the conclusions reached on each case study. They will be considered as a reference for the analysis and selection of the most accurate systems to reduce the risk of overheating in the case study. First of all, it is demonstrated that energy savings increase when external shading elements are used compared to internal systems [32,33]. Moreover, Kim et al. [33], in their study about the behaviour of different strategies in high-rise residential buildings in South Korea, analysing the impact of the heating and cooling demand, they have concluded that, during the warm season, the louvre inclination of any sunscreen has a direct effect on the cooling demand; due to the relation between louvre's inclination and sun's altitude. Those with a more significant angle to the horizontal have a better energy performance. Alzouby et al. [32], establish that there is an optimum orientation for every shading system, allowing natural lighting to be retained in an acceptable range with a minimum solar thermal gain.

Vertical shading systems provide excellent natural daylight and good visibility from the inside to the outside but do not prevent solar thermal gains influencing in the choice of a preferred system. Wang [26] presents a control strategy for shading systems oriented to the south. If it guarantees 70% shade during warm periods, it shows a reduction in cooling demand. Moreover, automated systems significantly reduce overheating compared to manual systems [34,35]. Furthermore, Bellia et al. study [36], taking into account the orientation, the effect of external shading systems on insulated office buildings in three different Italian climates and their influence on heating, cooling and lighting. In their study, they achieve a reduction in the demand for cooling, but an increase in heating and lighting demand proving that shading systems are more efficient in climates with hot summers. In addition, Palmero-Marrero [37], studies the application of an overhang for south-facing façades and louvres to the east and west sides, concluding that it is convenient to orient the long sides of the building to the north and south. Similarly, on the south-facing one, the width of the overhang should be determined by the height of the window. For example, if the window is 1,5 m in height, a 1, 0 m overhang is appropriate, nevertheless, if the window is heightened, the overhang width should be increased.

1.2. Ventilation in PH and/or nZEB buildings

Ventilation systems aim to regulate the indoor air quality: temperature, distribution, air exchange rate and concentration of pollutants [38], always taking into account the regulations related to each location in terms of air quality, maximum and minimum ventilation rates.

According to several studies [38,39], ventilation is one of the strategies that provides correct air quality and supplies fresh air from the outside to the indoor space. Different methods can carry out this process: mechanical ventilation [38], which is mandatory in Spain [12], using a fan or extractor; natural ventilation, which is a result of the variation of temperature and pressure between the outside and inside generating a current of air [38,39]; or hybrid (mechanical-natural) ventilation, used to compensate the weaknesses of natural ventilation when conditions are not favourable [38–40]. The current project will focus on the study of the most appropriate natural ventilation strategies to mitigate overheating in the warm season.

There are ongoing investigations aimed at improving the efficiency and performance of ventilation systems, used to predict air behaviour, indoor air quality (IAQ) and reduce health problems [38,41]. To this end, researchers are developing multiple energy-efficient ventilation methods and performing dynamic simulations to analyse how they affect indoor comfort (especially thermal comfort) and energy savings [17]. In the case of natural ventilation, essential points to consider are:

- Efficiency and performance of ventilation methods depend on the use and type of the room [42].

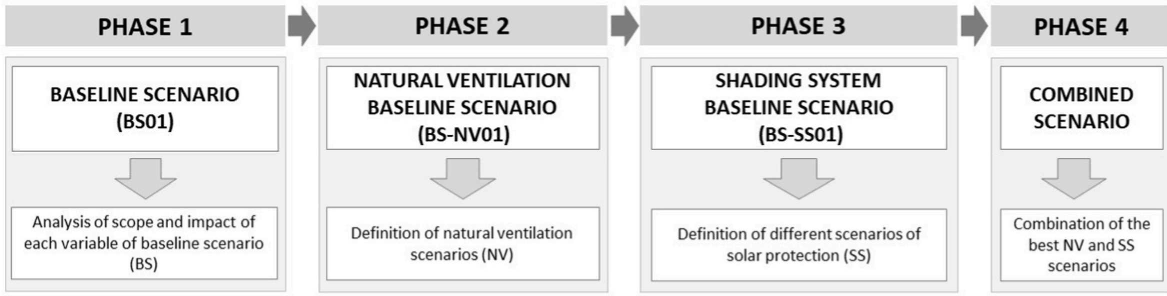

Fig. 1. Diagram of the phases of the study.

- The factors to be taken into account are the width of the room concerning the windows, free height, thermal mass, location of the building (considering factors such as pollution or noise), thermal and environmental gains [43], climate conditions and the microclimate [24].
- Natural ventilation can have limitations and reduce its efficiency when the internal thermal gains are higher than 40 W/m^2 [43].
- The efficiency of summer cooling and thermal comfort is strongly related to natural ventilation strategies. Control of openings is crucial in these cases [17].
- Special attention is required on the amount of airflow (percentage opening of windows) and the control of opening hours to achieve comfort [44].
- In the future, with climate change, the ventilation will not be able to cope with the overheating predictions and will need to be complemented with other methods [45].
- The impact of natural ventilation, from the point of view of energy consumption and climate impact, is lower than with mechanical solutions [38].
- It makes it easier to achieve comfort with natural than with mechanical ventilation [46].
- Natural ventilation can reduce the use of cooling up to 20% per month [47], not depending exclusively on comfort needs. It also influences the perception of safety, natural lighting conditions or acoustic comfort. Moreover, it can also cause problems of discomfort, due to the high speed of the indoor air.
- The integration of passive cooling strategies and blinds, combined with natural ventilation, achieves a reduction of over 50% in almost all regions [44].

In the case of overheating risk in highly insulated and airtight buildings (PH and nZEB), the literature [45,48–52] indicates that it is crucial to analyse natural ventilation at nigh-time as one of the main strategies. Since it allows the indoor temperature of buildings to be reduced, having a more positive effect in arid regions and in regions where there are large temperature differences between night and day. Its effectiveness is strongly related to three parameters: the difference between indoor and outdoor temperature, the airflow rate and the thermal capacity of the buildings. Building optimisation (thermal mass, opening ratio, solar and internal gains, orientation and others) can reduce office cooling consumption by around 20–25% [52].

Many studies have been carried out in recent years [48,52–58], from ventilation experiments, simulations (simple analytical and empirical methods to computational fluid dynamics (CFD)) to monitoring real cases, in which it has been determined how efficient the natural night ventilation as a cooling system is in warm periods. In these studies, a temperature reduction in the hottest room up to 5 °C has been possible, saving between 10% and 40% in cooling consumption. They also concluded that the combination of PCM with night ventilation and free cooling is enough. Furthermore, the use of solar chimney allows passive night crossed ventilation without the need to open the windows.

The main objective of the present work is to detect the best passive shading and natural ventilation strategies to mitigate, as far as possible, overheating issues during warm periods in residential buildings built under PH standards and construction strategies based on nZEB values. For this purpose, three representative flats from the PH certified residential tower in the Bolueta neighbourhood of Bilbao have been selected as a case study. The study has been carried out using dynamic simulations, evaluating the impact of these strategies on indoor comfort, both individually and when they are combined.

2. Methodology

Dynamic simulations have been carried out in this study with Design Builder (DB) [59]. It has been determined, which variables have a direct effect in the overheating risk according to previous literature. These variables are infiltration, mechanical ventilation, natural ventilation, shading system, cooling, occupation (no. of people/m^2) and occupation time:

- **Infiltration**: in order to simplify the calculations, it is required to determinate if the airtightness values of Passivhaus buildings can be considered to have a significant impact on indoor temperature variations or not [60].
- **Mechanical ventilation** provides air quality indoor by introducing fresh air in a controlled way. Even the aim of this system is not to control the indoor conditions that could have an effect on the indoor temperature, the current study pursues to determine the relevance of such effect [61]. In the DB it is defined as a simple HVAC where the following data is required: air changes (ac/h), schedule and heat recovery efficiency.
- **Natural ventilation,** as well as mechanical ventilation, its purpose is to introduce fresh air indoors, but, this time, it is operated manually by the user [62]. Due to the diverse flat typologies in the case study, it is important to define the range and capacity to exchange air and its influence on indoor temperature variation and airspeed. Two different assessment modes of natural ventilation have been executed in DB [59], *Scheduled* and *Calculated* mode. The first one predefines a maximum air change rate and an operation schedule. In the second one, ventilation rates are calculated using wind and buoyancy-driven pressure, indoor and outdoor temperature difference, opening sizes and operation, crack sizes among others.
- **Shading system** reduces solar gains and therefore the increase of indoor temperature. It is crucial to evaluate its potential depending on its location and schedule operation [33].
- **Cooling system** controls overheating risk and ensures suitable temperature indoor conditions. In this regard, even if the case study has not a cooling system, it has been calculated one scenario with, in order to establish if it could accomplish Passivhaus energy demand and its peak load limitations [63]. Energy calculations driven in DB have been settled as *Default system* and limited by flow rate and capacity, the Coefficient of Performance (COP) and Electricity source.
- **Internal gains** have also a great impact and can influence the increase of indoor temperature. On this purpose, occupation **density**

Fig. 2. Location of the case study [68].

(no. of people/m^2) and **occupancy time** will be analysed considering Spanish regulation *Código Técnico de la Edificación* (CTE). Other internal gains produced by appliances and lighting will also be taken into account [19].

A 3D model of the entire building has been designed, considering all floors as adiabatic, except for the three flats typologies selected on the case study. The common areas at the entrance of each studied flat are also modelled. Due to their high temperature caused by the hot water and heating installations and lack of ventilation; it has been believed that it could have an influence on indoor flat temperature. These areas have been considered with a constant temperature of 28 °C. This temperature has been confirmed by the monitoring that is currently being carried out [22]. The adjacent housing tower (Tower II), which casts a shadow over the case study building, has also been taken into account. Different scenarios have been simulated in four different phases as shown in Fig. 1.

In phase 1, the defined parameters of the base scenario have been modified one by one, in order to be able to quantify their individual impact on overheating during the warm period.

Once the effect of each parameter has been analysed separately, the baseline scenario has been defined (equivalent to the real case study situation), BS-NV01 and BS-SS01, from which the hypotheses of improvement strategies using passive natural ventilation (phase 2) and shading systems (phase 3) will be carried out. In each scenario, the variation on indoor temperature has been assessed. For the analysis, indoor operative temperature, solar gains, direction and speed of indoor air and air changes per hour (ac/h) data have been taken into account. Indoor airflow data has been obtained by CFD simulations in DB.

After each strategy of natural ventilation and shading systems has been analysed, the most favourable ones are studied on a combined scenario (phase 4).

This study is focused on overheating risk, for that purpose only the operative temperature variation has been analysed. Moreover, the other variables that have an impact on comfort, have been only taken into account to determine the operative temperature variation, such is the case of the air changes per hour or solar gains in phases 2, 3 and 4.

To assess the results has been considered insignificant the variation of operative temperature when this value is lower than 0,5 °C on the different scenarios from the baseline scenario.

3. Case study

The selected case study is a PH certified residential tower in the Bolueta neighbourhood of Bilbao, built in 2018. The climate database selected is Meteonorm [65] (based on the radiation period of 1991–2010 and the temperature period of 2000–2009), as it is closer to the reality of Bilbao's climate.

The methodology used to classify the climate of Bilbao is Köppens classification, which considers several variables [66]: mean annual precipitation, mean annual temperature, temperature of the hottest month, temperature of the coldest month, number of months where the temperature is above 10 °C, precipitation of the driest month, precipitation of the driest month in summer, precipitation of the driest month in winter, precipitation of the wettest month in summer and precipitation of the wettest month in winter. As projected in Köppen's letter it has been studied the climate evolution of Bilbao, which will change from the current Cfb (warm temperate, fully humid, warm summer) to a Csa (warm temperate, dry and hot summer) in 2100 [67]. In the simulations, the summer period was defined as from 21st June to 21st September. The analysis carried out is on an hourly basis.

The building is located in the neighbourhood of Bolueta, in the outlying of Bilbao. Surrounding the building, as seen on Fig. 2, on its east side there are under construction another 4 towers with similar shape: a higher tower combined with a longitudinal prism. Towards the south, the building faces a river and green spaces. Facing the north, it is distanced from the rest of the buildings by the railway tracks, which acts as a divider.

The case study building has 171 flats, 108 public housing and 63 social housing units, all public promotion. Due to its public ownership, the construction reports [69] have been accessible and facilitated by VISESA, a public society that manages the public housing construction in the Basque Country, in Spain.

It has twenty-eight floors in height, a ground floor and three

Table 1
Construction composition of the case study [69].

	Composition	*U value* W/(m^2·K)
Façade	Façade Black aluminium composite panel 4 mm Rock wool 10 cm 1,5 cm water-repellent mortar Perforated brick Plasterboard with 5 cm of rock wool 1 cm plaster coating	U = 0,25 W/(m^2·K)
Interior partitions	Laminated plaster 1 cm Rock wool 4,5 cm Laminated plaster 1,5 cm	U = 0,55 W/(m^2·K)
Interior partitions (flat-common areas)	Laminated plaster 1,5 cm 12 cm solid brick 1 cm plaster plate Rock wool 8 cm Laminated plaster 1,5 cm	U = 0,39 W/(m^2·K)
Windows	Triple glazed PVC windows SHGC = 0,57 Windows glazing clear	$U_{glazing}$ = 0,55 W/(m^2·K) U_{frame} = 1,00 W/(m^2·K) U_{window} = 0,64 W/(m^2·K)
Solar protection	Internal roller blind Opacity = 100%	

underground parking levels. Built according PH standards, it is a highly insulated (see Table 1) and airtight building (0,353 ac/h at 50Pa). It has a structure of reinforced concrete, and interior partitions are made of highly insulated gypsum boards. All these values have been obtained on the construction report [69].

The heating installation and the production of hot water are centralised while the mechanical ventilation system is individual for each flat, with a double-flow system and heat recovery. It has three power levels to be set according to the user's requirements. These have been considered as the position 1 = 25%, 2 = 50% and 3 = 100%. In addition, the external air supply is located in the outdoor laundry area of each flat. The same black aluminium panels that cover the façade also cover these areas. Moreover, in the case of the south-facing outdoor laundry areas, they have an opening of 0,82 m x 1,09 m and a handrail glassed lower part of 0,82 m x 0,85 m (considered as 6 + 6 mm in the simulations). While in the case of the western outdoor laundry areas, the opening and glass are replaced by a fixed micro-perforated black aluminium panel. In addition, the building has no cooling system.

It has been detected that the homes suffer from overheating during the warm season, reaching indoor temperatures over 34° according to the users; meanwhile, outdoor temperatures are lower. As indicated in the study by Rodriguez et al. [22], carried out in the same building, among the main issues found are the mechanical ventilation installation, which is not working correctly, and the orientation of the dwellings to the south without an adequate solar protection system to reduce the internal gains from solar radiation (it only has an interior roller blind).

After a detailed study of the features and typologies of the existing flats in the case study building, from 16 possible ones, it has been selected three typologies which have been considered more representative (see Fig. 3): typology II (single-orientation to the south and outdoor laundry area with an opening to the south), typology V (two façades in the south-west corner and with an outdoor laundry area with a micro-perforated panel to the west) and typology XIII (two crossed façades north-south and with an outdoor laundry area with an opening to the south). Typology II and XIII have been analysed on the 8th floor and Typology V on the 27th floor. Heights selection has been made related to the monitored houses, in order to be able to make a future comparison between the results obtained by simulations and those collected by monitoring the current situation.

For the case study, 39 different simulations have been carried out (see Fig. 4): in phase 1, one baseline scenario and eight variations of it, has been simulated to determine each variable influence on overheating. In phase 2, 17 scenarios with different natural ventilation strategies have been defined to determine which combination of window opening system (considering schedule, opening percentage and temperature conditions) and opening indoor doors (opened or closed depending on the room) works better to decrease overheating risk. In phase 3, it has been considered 13 scenarios with different shading systems strategies (varying position, operation and schedule), to determine the effect of each system on the decrease of the inner temperature. Lastly, in phase 4, it has been studied a single combined scenario with the best solution of shading system and natural ventilation, to observe if, in this way, it is possible to achieve, during the warm season, the indoor temperature conditions settled by Passivhaus label.

Each of the phase 1 scenarios have been defined attending the following parameters in Table 2.

In addition, in phase 2 related to natural ventilation, other seven variables have been defined as presented in Table 3.

As in the two previous cases, different variables have been defined for phase 3 shading simulations, as shown in Table 4.

Fig. 5 shows the different scenarios and variables. The variable that changes from scenario number 1 of each phase, is represented by a light grey colour. Those that remain constant are represented by dark grey colour. Even if cooling doesn't exist in the case study, it has only been taken into consideration in phase 1 to determine the cooling demand and cooling peak load and be able to check if activating cooling system PH standards are accomplished.

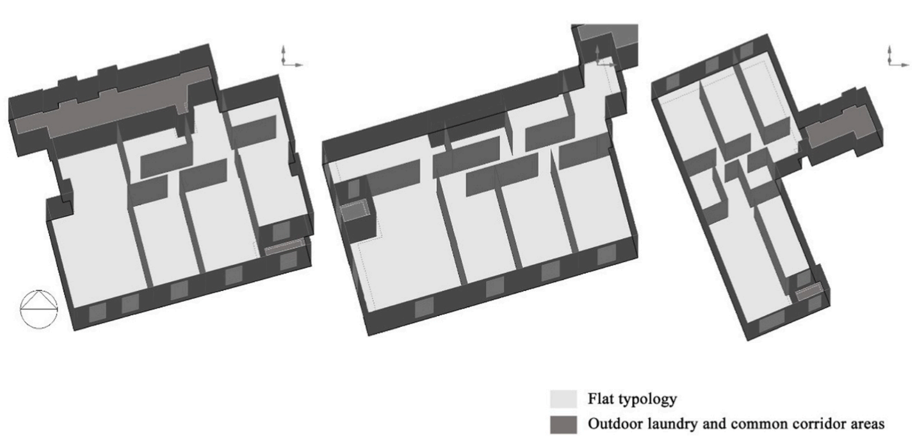

Fig. 3. From left to right Typology II, Typology V and Typology XIII, respectively.

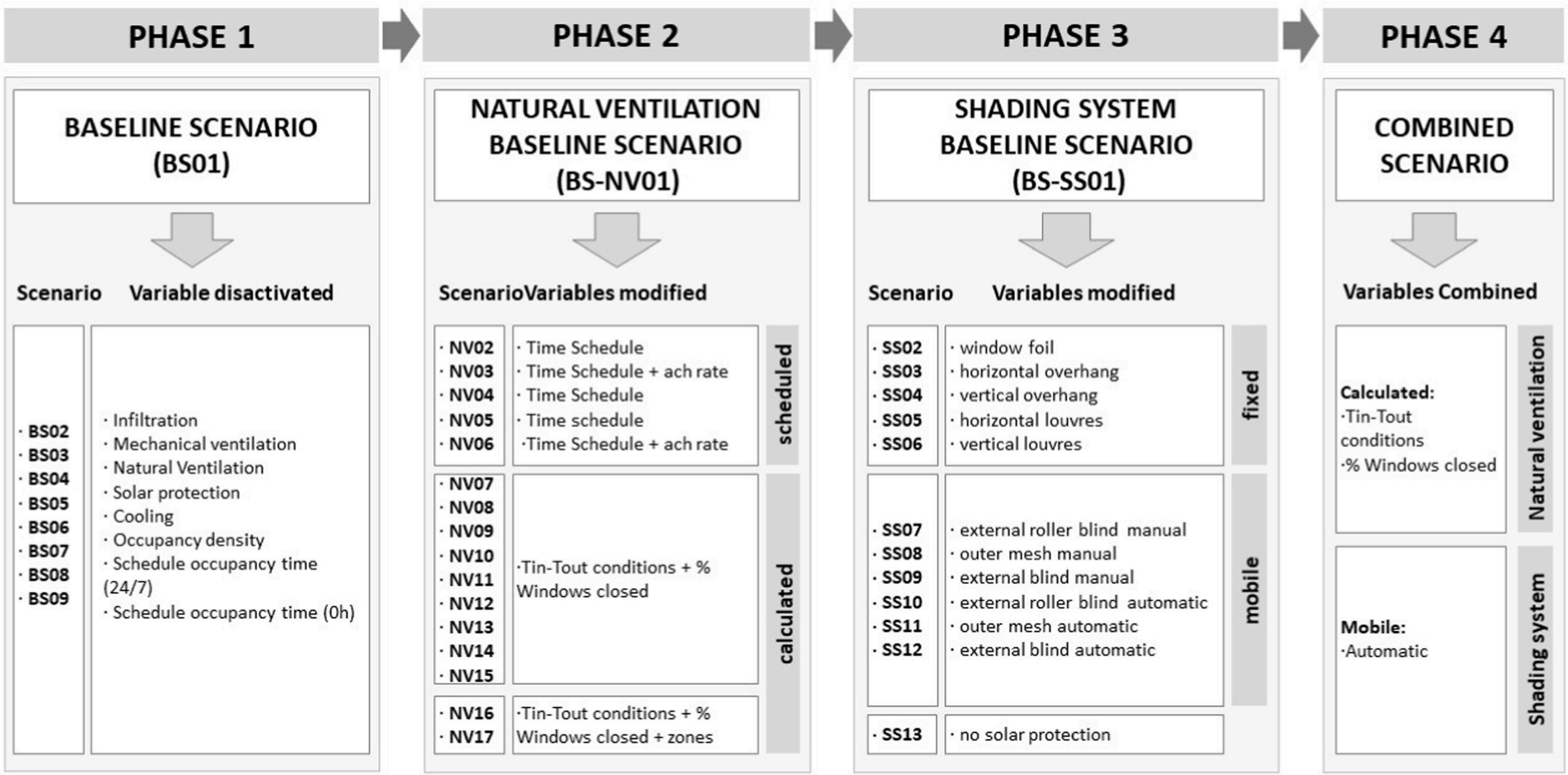

Fig. 4. Diagram flow of the scenarios and variables simulated in different phases.

Table 2
Parameters for phase 1.

Variable	Definition	Sub-scenarios
Infiltrations	Defined as 0,353 ac/h at 50 Pa in the building report [69], will be calculated as 0,4 ac/h.	Infiltrations: ON = 0,4 Infiltrations: OFF = 0
Mechanical ventilation system	Working 24/7 and power changes depending on occupancy based on the CTE. The machine has three positions indicated on the following sub-scenarios, where no economizer was considered. The model has been defined on DB as a *basic system*, considering the air intake exterior and not on the outdoor laundry room as currently is.	Power: 1 (25%) • Occupancy 25% • M-F: 7h–15h Power: 2 (50%) •Occupancy 50% • M-F: 15h–23h Power: 3 (100%) • Occupancy 100% • M-F: 23h–7h • Weekend: 24h
Natural ventilation	The windows are opened at 20%, in a hinged position, with a maximum of 1 ac/h. In this stage, the calculation mode selected is scheduled.	Natural ventilation: OFF = 0 Natural ventilation: ON • Summer: 20h–8h
Solar Protection	The current roller blind is installed on the inner side of the window.	Roller blind: OFF = rolled up Roller blind: ON = pulled down •100% down •Summer: 10h–19h
Cooling	COP considered: 4,5 Electricity from the grid	Cooling: OFF = non-existent Cooling: ON = activated • Cooling temperature: 23 °C • Cooling setback: 25 °C
Occupancy density (no. people/m^2)	It analyses how occupancy affects inner gains. Differentiate between occupancy calculated by the CTE and occupancy obtained by surveys (REAL).	Occupancy: CTE • 0,05 people/m^2 Occupancy: REAL • 0,03 people/m^2
Occupancy time	As previously mentioned, to study occupancy influence on inner gains	Occupancy time: CTE [19] • 25%: M-F: 7h–15h • 50%: M-F: 15h–23h • 100%: M-F: 23h–7h and weekends 24h Occupancy time: None • 0%: 24/7 Occupancy time: Permanent • 100% 24/7

Table 3
Parameters for natural ventilation scenarios.

	Definition	Scenarios
Opening control	It depends on how the natural ventilation system is controlled, manually (by the user) or automatically (activated according to the indoor operative temperature).	Automated Manual
Zones	In order to simplify DB calculations, in every simulation (except NV16 and NV17), it has been considered that the flat is a single communicated zone where the doors have been replaced by an equivalent opening from floor to ceiling (Z1). In NV16, each room of the flat has been considered as a single area as if all doors were closed (Z2). Finally, in NV17, combining the previous ones, the living room, kitchen and main room act as a single zone while the other rooms and bathrooms are closed creating separated zones (Z3).	Z1: one single-zone Z2: each room is a zone. Z3: living-room, kitchen, hall and mean bedroom are a single zone. The other rooms are each a zone.
Schedule	Four different schedules are defined in order to determine the best schedule to open the windows to reduce the indoor temperature and mitigate the overheating risk.	N/A: not applied T1: 20h–8h T2: 22h–8h T3: 00h–10h T4: 24h/7
Temperature conditions indoor-outdoor	In order to study the difference between opening the windows with a schedule and with a temperature indoor-outdoor condition (Tin-Tout), three possibilities are defined.	CIE0: there are not temperature conditions CIE1: • T_{indoor} - $T_{outdoor}$ ≤ 1 °C: windows are closed in “a%“. • T_{indoor} - $T_{outdoor}$ > 1 °C: windows are open in “b%“. CIE2: • T_{indoor} - $T_{outdoor}$ ≤ 1 °C: windows are closed in “a%“. • T_{indoor} - $T_{outdoor}$ > 15 °C: windows are open in “b%“.
Close percentage (a%)	It defines the percentage in which the windows are closed concerning the opening position.	N/A: not applied 0%: totally closed 50%: closed 50% concerning open position (b%) 100%: closed position is equal to an open position (b%)
Opening percentage (b%)	It defines the opening percentage of the windows, in order to determine the best relation air flow-heat reduction.	OP20: windows open 20% of its surface (hinged) OP50: windows open 50% of its surface (swing) OP100: windows open 100% of its surface (swing)
Renovations per *hour control*	When an opening scheduled is set, it is not possible to define the percentage of the opening area. Therefore, renovation per hour is determined, defining the maximum hourly renewals per window.	N/A: not applied R1: 1 maximum ac/h R4: 4 maximum ac/h

Table 4
Parameters for shading system scenarios.

	Definition	Scenarios
Schedule	Depending on the mobility of the chosen shading system, a single schedule has been determined for the summer period applicable to all mobile solutions.	N/A: No shading system T1: fixed position T2: • 100%; 10–19h • 50%; 15–20h • 0%; 20-7h
Position	The shading systems have been divided into two main groups: those with a fixed position and those that allow freedom of movement.	Fixed Mobile
Control	In addition to the schedule, the mobile shading system can be operated manually (operated by the user in the defined schedule) or automatically controlled (activated during the schedule according to the indoor operative temperature).	Automatic: T_{indoor} > 22 °C + schedule Manual: Only schedule
Strategies	Different strategies have been chosen according to the above variables to study their impact and regulation of the indoor temperature.	Window foil Horizontal overhang Vertical overhang Horizontal louvres Vertical louvre External blind Outer mesh External roller blind

4. Results and discussions

The results have been analysed and classified by phases (see Fig. 5) and flat typologies. As commented in the methodology, the results have been assessed as significant impact when the variation of temperature between scenarios is higher than 0,5 °C. Also, it has been taken into consideration the PH standards limitation set for indoor temperature, which should not surpass 25 °C of 10% of the annual hours, recommending under 5%. The study is mainly focused on operative temperature variation during the warm season. Others features such as airspeed and ac/h have been taken into account to determinate de feasibility of the NV and SS best scenarios to alleviate the overheating risk.

4.1. Phase 1

In the BS01, as seen in Table 5 the flats are over 25 °C during all the summer period. In this phase, for each typology analysed, the temperature difference between scenario 01 and the rest of the scenarios (BS02 to BS09) has been compared. The negative value means that the temperature on the studied scenario is lower than scenario n° 01, and if positive, the temperature is higher. Also are presented the hours when the indoor operative temperature is higher than 25 °C, as can be seen in all scenarios, during the summer period, the temperatures are greater than 25 °C a 100% of the time.

This first phase of simulations has confirmed each variable's level of impact on overheating risk (scenarios from BS02 to BS09). The variation of infiltration from 0,4 ac/h at 50 Pa to 0 ac/h (BS02) can not be considered as a relevant repercussion in the indoor temperature. By contrast, inner roller blinds (BS05) and occupancy factor (BS07, BS08 and BS09) have a significant effect on indoor temperature. Blinds are able to decrease the indoor temperature up to 1,12 °C. Reducing users' occupancy density, the temperature decreases around 0,6 °C and there is 3,09 °C difference between an empty and all-day occupied flat. Natural ventilation (BS04) and mechanical ventilation (BS03) are the variables with higher impact, being able to bring down the temperature by up to 5 °C and 10 °C respectively.

Regarding cooling system (BS06), has been detected that, in order to maintain indoor temperature under 25 °C, the flats do not accomplish the exigencies of PH cooling standards. Cooling demand and cooling peak load are hitting values up to 46 kWh/(m^2·year) and 30 W/m^2 compared to the standard values like 15 kWh/m^2·year and 10 W/m^2 respectively.

4.2. Phase 2

Concerning the natural ventilation scenarios simulated, according to the variation of the variables explained in Table 3, as can be seen in Fig. 6, it is detected that:

Flat typology II: natural night ventilation is not enough to palliate the overheating risks in the flat. The outdoor laundry area has a negative impact on the increase of indoor temperature during the warm season, due to the intake of overheated air of this area into the main bedroom, which prevents correct ventilation. Because it is single-oriented, it does not achieve high airflows, not over 8 ac/h (under 0,2 m/s), and in consequence, the air does not flow through the whole volume of the flat, so the indoor air quality is worse than in double-oriented flats.

The best results for overheating mitigation during the warm season are obtained by strategies where windows are open permanently (NV14 and NV15). Both stand on the same percentage of hours above 25 °C, 29%, and the average and minimum temperatures are similar (see Table 6).

When the simulations are running with doors closed and rooms are considered as different zones in DB, it is observed how, in the dining room (NV16a), the absolute minimum temperature hits the lowest, 22,22 °C. However, maximum temperatures are around half degree higher than on NV14 and NV15 and the average temperature is similar.

Flat typology V: as in TII, natural night ventilation is not enough to mitigate the overheating risk in the flat. The best strategy is where the windows are always opened (NV15), and the flat is considered as a single-zone (all doors opened). This scenario is able to decrease up to 14% the hours with indoor temperature over 25 °C.

Regarding the scenario with all doors closed and windows open 24/7 at 100% (NV16), as well as the previous typology, the living room obtains lower temperatures than other options with doors open, 0,75 °C less. Nevertheless, bedrooms reach high temperatures, achieving 94% of hours above 25 °C (see Table 6).

Due to the shape of the flats, two façades in the south-west corner, a better airflow than in TII is obtained. Nonetheless, high airflow rates and turbulences are hit as can be seen on Fig. 7, obtaining values up to 0,8 m/s that impact negatively on users' comfort [70]. Therefore, none of these strategies is a viable solution, and it is necessary to find solutions to regulate, manually or mechanically, the windows and doors to limit the air velocity under 0,8 m/s.

Flat typology XIII: as in the other typologies, natural night ventilation is not enough to mitigate the overheating risk in the flat. When the windows are open 100% if Tin-Tout > 1 °C and they are closed if Tin-Tout > 1 °C (NV13), the lower indoor minimum and maximum absolute temperatures are obtained. Besides, only 13% of the hours during the warm season surpass 25 °C (see Table 6).

To have two crossed façades facing north and south facilitates a correct airflow on the flat. Despite this, when the flat is considered in DB as one zone (doors open), air changes per hour rise to 150,77 ac/h and, therefore, airspeed much higher than 0,8 m/s is registered. It is so, necessary to find alternative solutions to regulate the doors and windows openings at those moments where the airspeed goes over 0,8 m/s.

Regarding the strategy with the doors closed NV16 (Fig. 8), the living room and bedrooms reach between 70% and 75% of hours below 25 °C.

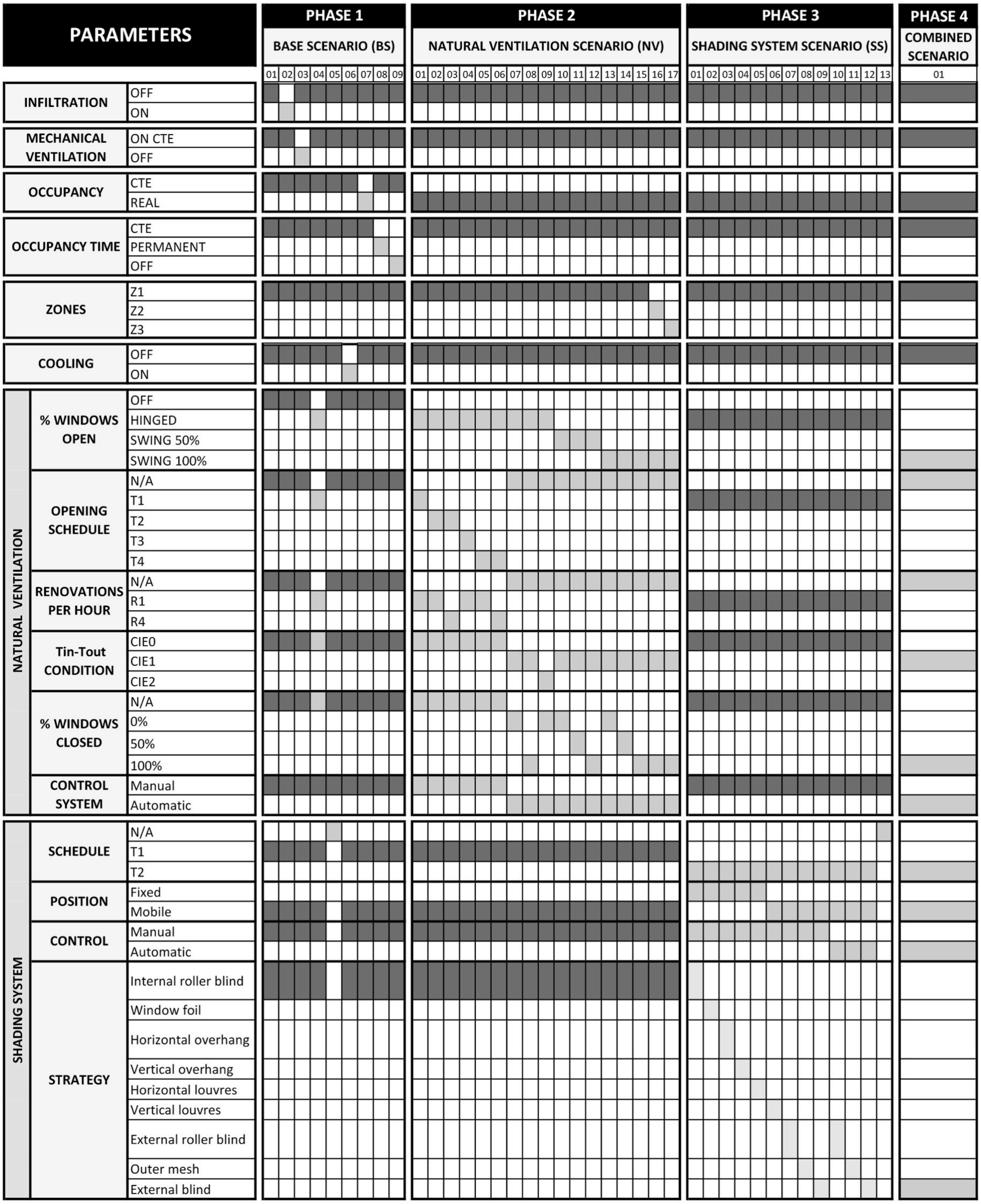

Fig. 5. Summary of the simulated scenarios in the study.

In addition, the airspeed is kept below 0,8 m/s (under 13 ac/h) in the whole flat but the kitchen temperature is 92% of hours over 25 °C. The reason is that the only opening in it is to the overheated air in the outdoor laundry area, which does not enable correct fresh air ventilation.

4.3. Phase 3

The results of the different shading systems scenarios are represented in Fig. 9. In there, comparing the results obtained by the fixed and mobile shading systems, it is observed that the temperature is lower on scenarios where mobile systems were applied. Nevertheless, all scenarios remain above 25 °C, almost 100% of the analysed time. It is also observed that those solutions with the fixed positions in the south single-oriented typology (TII) represent the worse results, being the TV, west and south corner-oriented, the one with the better improvement.

Between the fixed-position strategies, the one with the lowest indoor temperature (see Table 7) is the implementation of a reflective foil added to the inner side of the window (SS02), which reduces 75% the solar factor (from a 0,6 to 0,15). However, during the summer period, the results are still far from PH limitations, registering minimum temperatures all around 26 °C in the three typologies. In contrast, the installation of a vertical opaque hanger (SS04), the equivalent of

Table 5
Operative temperature (To) and percentage of the number of hours above 25 °C during the summer period.

	To (°C)			To (°C)			Total n° hours above 25 °C		
Scenarios	*TII*	*TV*	*TXIII*	*TV*	*TV*	*TXIII*	*TII*	*TV*	*TXIII*
BS 01	29,99	29,92	29,86	35,34	35,84	**35,89**	100%	100%	100%
	Minimum To difference with no. 01 (°C)			***Maximum To difference with no. 01 (°C)***			***Total n° hours above 25°C***		
BS 02	−0,01	−0,04	−0,02	−0,08	−0,12	−0,13	100%	100%	100%
BS 03	2,29	2,18	2,35	7,55	6,73	**10,6**	100%	100%	100%
BS 04	−3,36	−3,26	−3,54	−4,18	−4,15	**−4,82**	100%	100%	100%
BS 05	0,45	0,51	0,54	0,77	**1,12**	1,09	100%	100%	100%
BS 06	−6,99	−6,92	−6,86	−9,99	−10,43	−10,76	1,08%	0,67%	0,13%
BS 07	−0,56	−0,54	**−0,6**	−0,25	−0,21	−0,22	100%	100%	100%
BS 08	0,45	0,42	0,48	0,16	0,13	0,11	100%	100%	100%
BS 09	−1,52	−1,43	−1,61	−0,88	−0,76	−0,88	100%	100%	100%

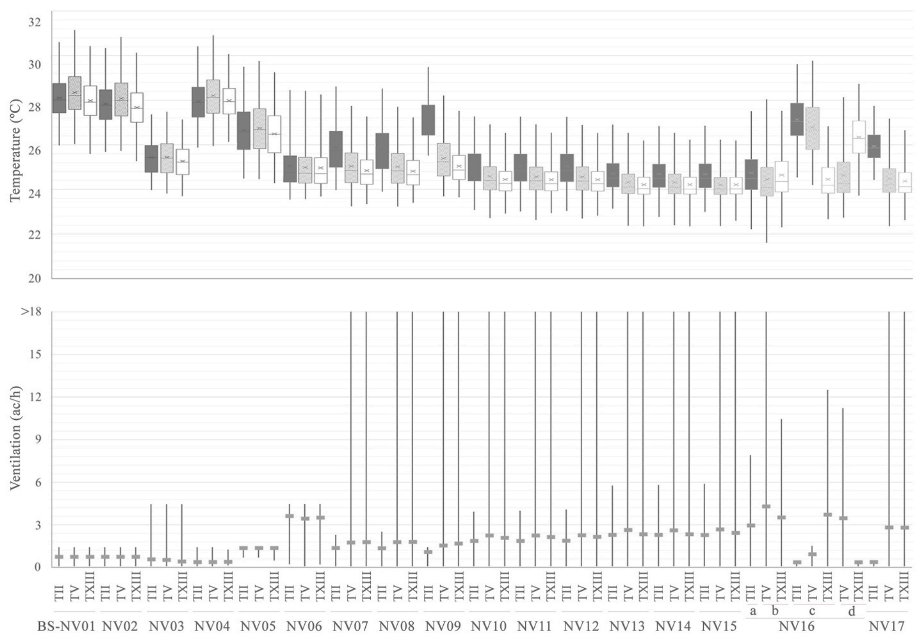

Fig. 6. Results of the simulations of the different strategies for natural ventilation. Absolute maximum, absolute minimum, median, average, first and third quartile of indoor operative temperatures (°C) and absolute maximum, absolute minimum and median renovations/hour in each typology of the case study (TII, TV and TXIII).

Table 6
Best natural ventilation scenarios indoor operative temperature (°C).

	NV13			NV14			NV15		
	TII	*TV*	*TXIII*	*TII*	*TV*	*TXIII*	*TII*	*TV*	*TXIII*
Minimum T_o	23,14	22,37	22,35	22,77	22,40	22,35	23,00	22,36	22,60
Average T_o	24,49	24,09	24,02	24,47	24,08	24,00	24,48	24,01	24,01
Maximum T_o	26,91	26,53	26,20	26,84	26,54	26,23	26,86	26,23	26,20

reducing 0,5 m the height of the window, obtains the worst results which are very similar values to the no shading system scenario (SS13). The use of horizontal louvres (SS05) and vertical louvres (SS06) comparing with the results obtained with the current internal roller blind (BS-SS01), the temperatures obtained are higher.

Regarding the mobile shading systems, in all the scenarios the maximum temperatures are still high, around 28 °C in almost all the scenarios. Nevertheless, the best solution to TII and TV has been the roller external blind (SS07 and SS10), registering minimum absolutes close below 25 °C; in the case of TXIII, the scenarios with the lower temperature are those with external blinds (SS09 and SS12) as seen in Table 7. It is also observed that despite differentiating manual (only schedule) and automatic control (schedule plus temperature control), because the setpoint temperature was considered 22 °C and the temperature is permanently above this value, the results for the manual and automatic scenarios are identical, SS07 with SS10, SS08 with SS11 and SS09 with SS12.

Analysing the values for solar gains, when no shading system is used (SS13), the maximum registered values reached are 12,99 W/m^2 in TII, 17,45 W/m^2 in TV and 9,05 W/m^2 in TXIII. In comparison with it, the implementation of external mobile roller blinds (SS07 and SS10) to TII and external blind with automatic control to TV and TXIII (SS12) have

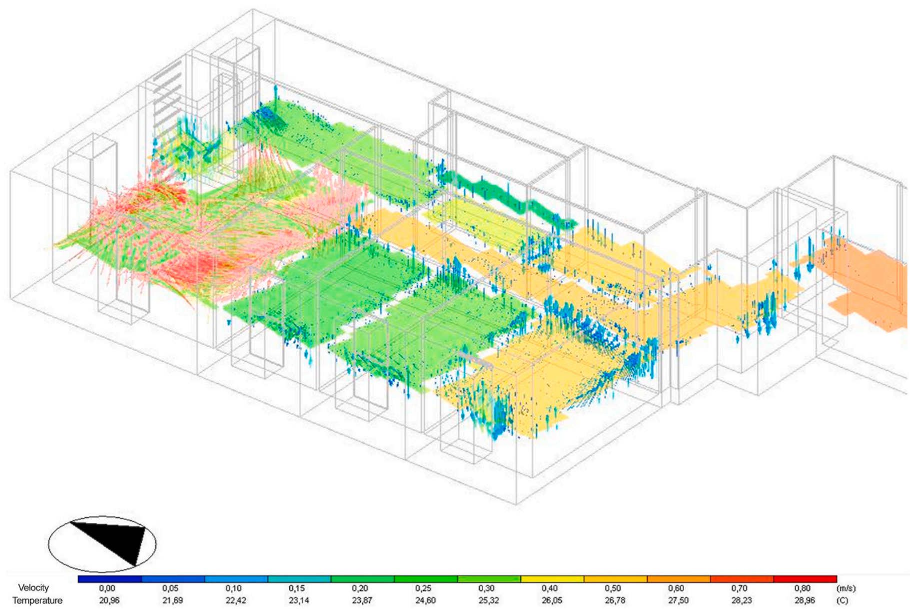

Fig. 7. CFD analysis in TV in scenario NV16, 2nd August at 16:00.

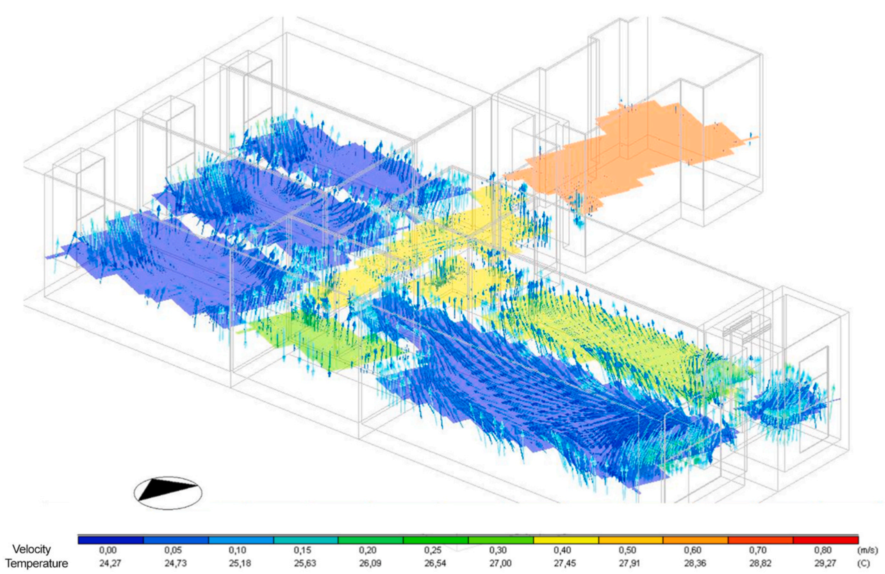

Fig. 8. CFD analysis in TXIII in scenario NV16, 2nd August at 16:00.

obtained the lowest results, 0,79 W/m^2, 2,6 W/m^2 and 4,34 W/m^2 respectively. In addition, for the fixed shading solutions, the installation of an inner reflective foil on windows (SS02), obtained the maximum reduction of solar gaining in the three typologies with values of 5,76 W/m^2 in TII, 7,73 W/m2 in TV and 4,01 W/m2 in TXIII.

This reduction in solar gains has a positive impact on indoor temperature but impacts negatively on the amount of natural light on the inside of the flat, which could cause an increase in artificial light demand.

As commented before, the mobile systems have obtained better shading protection compared to the fixed ones. Also, they are controllable and adjustable by the users, reporting better improvement chances. There is also a possibility for improvement on the fixed systems, although it has not been studied some possible variations like different sizes or positions. Otherwise, there is limited space for improvement. All the analysed strategies are performed on the outside of the building, being compatible with the current shading system, the inner roller blind.

4.4. Phase 4

In the case of the combined strategy (see Fig. 10), a simulation has been made combining the natural ventilation where the windows are always opened at 100% (VN15), and external blinds with automatized control (SS12). The results show that temperatures have a greater reduction, decreasing the overheating risk. The registered number of hours above 25 °C annually reaches 9,59% in TII, 4,58% in TV and 3,34% in TXIII. These values do not overpass the 10% limits established by the PH. However, the problem of elevated airflow velocity and a high

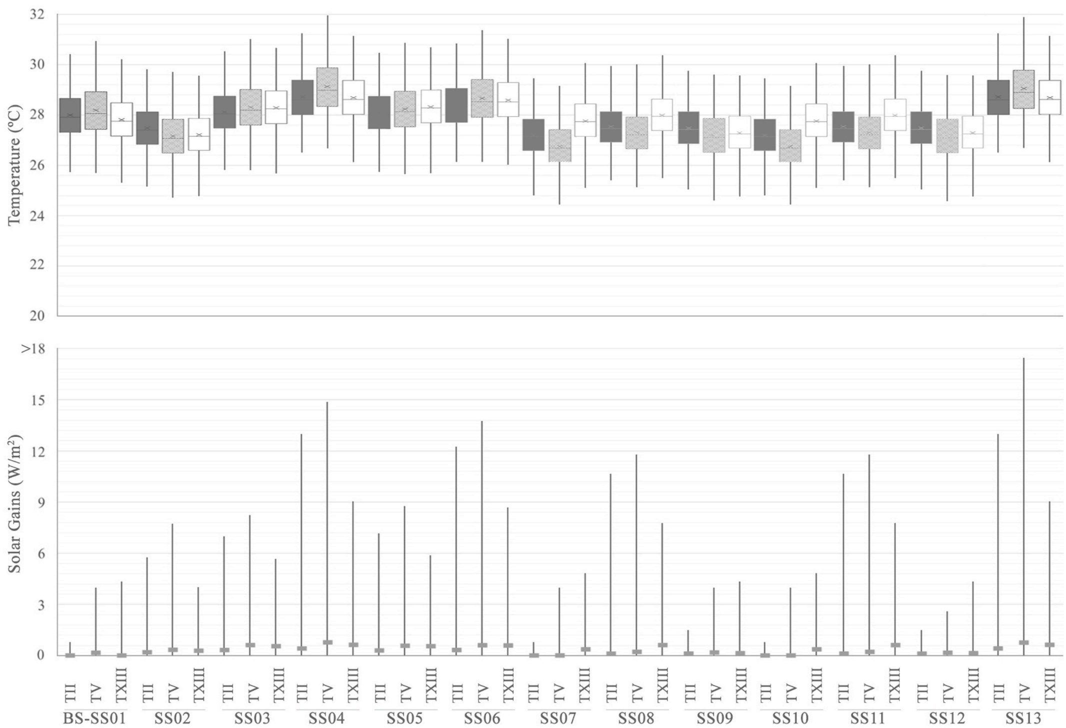

Fig. 9. Results of the simulations of the different strategies for shading systems. Absolute maximum, absolute minimum, median, average, first and third quartile of indoor operative temperatures (°C) and absolute maximum, absolute minimum and median solar gains in each typology of the case study (TII, TV and TXIII).

Table 7
Best shading systems scenarios indoor operative temperature (°C).

	SS02			SS10			SS12		
	TII	*TV*	*TXIII*	*TII*	*TV*	*TXIII*	*TII*	*TV*	*TXIII*
Minimum T_o	25,16	24,72	24,78	24,80	24,45	25,11	25,04	24,57	24,76
Average T_o	27,40	27,07	27,15	27,14	26,68	27,73	27,42	27,08	27,24
Maximum T_o	29,82	29,71	29,56	29,46	29,16	30,07	29,76	29,59	29,57

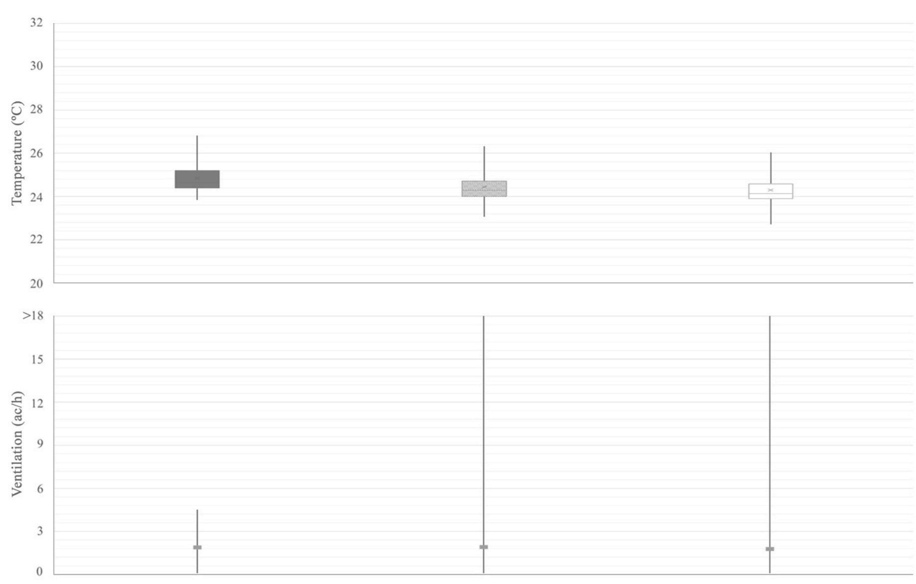

Fig. 10. Results of the simulations of the combined strategy. Absolute maximum, absolute minimum, median, average, first and third quartile of indoor operative temperatures (°C) and absolute maximum, absolute minimum and median renovations/hour in each typology of the case study (TII, TV and TXIII).

number of air changes per hour, previously explained in the natural ventilation strategies, remains. Consequently, a system to control the air velocity and peak renovations should be studied, which in this simulation arrives up to 90 ac/h in the case of TXIII and TV. In Fig. 10, it is observed that TV and TXIII stand in a lower range of temperatures than TII during the summer period. Either way, the three typologies get maximum indoor operative temperatures over 26 °C. During this period, the typology with better temperatures is the TXIII caused by its double-orientation and crossed ventilation.

5. Conclusions and future perspectives

The construction of highly insulated and airtight buildings is increasing in order to minimise the energy demand and the environmental impact of the buildings. Nevertheless, due to climate change and the use of this construction typology in warm and template areas, overheating problems have been detected. It is necessary to research additional measures that could be implemented and be efficient to minimise overheating and assure correct indoor temperature, such as passive strategies based on natural ventilation or shading systems. The correct strategy depends on the location, climate conditions, orientation, activity, shape and use of the building.

A limitation of this study is that only a narrow number of variables and scenarios were calculated. For instance, the weather data file used in DB was not assessed its influence on the current results, whereas the variation of this file could have an impact on them. Mitigation strategies were also calculated in a limit number of simulations, delimiting the possibilities based on the schedule, size or movement for instance. In addition, the study has been focused on the influence of different variables on overheating risk strictly related to indoor operative temperature variation. The aim is to determine if the flats achieve the percentage of hours over 25 °C settled by PH standards which have to be below 10% of the annual hours, recommending 5%; focusing this study on the warm season. Airspeed has been only assessed to survey if the natural ventilation strategies are feasible considering ASHRAE air velocity limitation to achieve users' comfort (maximum 0,8 m/s) [70]. It has not been evaluated the different variables that have an impact on thermal comfort. No adaptive analysis or Fanger's models have been carried out to establish whether thermal comfort is met or not.

Considering these estimations, this study has identified the effectiveness of different strategies, while mechanical ventilation, density and time of occupancy have a significant impact on the indoor temperature. It is highly recommended to consider them during the design phase to guarantee to reduce the number of hours above 25 °C. Also, it has been detected the beneficial effect of mitigation strategies like natural ventilation and shading systems to reduce the indoor temperature and avoid overheating.

Natural ventilation is not enough to bring down indoor temperature during the warm season, and opening the windows during the day reaches better results. Furthermore, shading systems have a positive effect on indoor temperature reduction, being more effective those located on the outside rather than on the inside. Mobile solutions increase the reduction of indoor temperature and have better regulation of solar gains than fixed solutions. However, none of the strategies studied is enough to mitigate by itself the overheating risk. Combining both strategies, natural ventilation and shading systems, a reduction of indoor temperature has been achieved in the three studied typologies, reaching PH limitations. Nevertheless, high airflow rates are much higher than ASHRAE determines to attain users' comfort, as a result, it must be controlled.

Regarding flat typologies, the corner-oriented and crossed-oriented typologies work better than the single-oriented, due to their capacity to produce more air changes per hour. However, it is necessary to regulate the opening of the windows and doors to prevent high airflow velocity. Other variables to be considered in ventilation strategies are the wind factor, the floor height, the windows size and the opening percentage which also influence on the airspeed.

The current study has been able to incorporate a general idea about the behaviour of different factors that affect overheating on residential buildings under the PH standard. Allowing to quantify the decrease of indoor temperature depending on the used strategy. However, it is considered necessary to present new studies and future investigations to support and complete the current research. It would be interesting to reproduce the same simulations in the same location but with other weather files in order to analyse the impact over the obtained results. In addition, to attend the climate change predictions, the warm season should be extended in the simulations, expanding it from May to October. Other investigations can be performed considering each opening and solar protection with different conditions that enable individual control; allowing to reach thermal comfort on the inside and to control those periods of high temperatures and airspeed. It must be researched the influence of the behaviours of the users on indoor comfort according to post-occupancy evaluations (POE). Lately, the current study should be compared to results based on adaptive analysis that take into account all the variables that have an impact on thermal comfort (relative humidity, air velocity, clothes thermal resistance, activity level, dry temperature and radiant temperature). The purpose is to define the maximum indoor temperatures that can be reached to achieve thermal comfort.

CRediT authorship contribution statement

Anna Figueroa-Lopez: Methodology, Validation, Formal analysis, Data curation, Writing – original draft. **Alba Arias:** Methodology, Validation, Formal analysis, Data curation, Writing – original draft. **Xabat Oregi:** Conceptualization, Supervision, Resources. **Iñigo Rodríguez:** Conceptualization, Supervision, Resources.

Declaration of competing interest

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

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