Natural ventilation strategies for indoor thermal comfort in Mediterranean apartments

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Natural ventilation strategies as effective low energy refurbishment solutions are identified within this research study, for an existing urban multi-storey apartment building in Athens, representative of over four-million Greek urban residential buildings. Retrofit strategies were evaluated using occupant comfort criteria and the existing ventilation strategy, for a single apartment using dynamic thermal simulations. These strategies included individual day and night ventilation, a wind-catcher and a dynamic façade. Suitable openings operation in response to environmental parameters provided sufficient day and night ventilation and occupant comfort. The inclusion of a wind-catcher yielded very little improvement to the ventilation performance. However, the combined operation of the wind-catcher and the dynamic façade delivered operative temperature reductions of up to 7^{o}C below the base-case strategy, and acceptable ventilation rates for up to 65% of the cooling period. The successful performance of the proposed strategies highlights the potential for reducing energy consumption and improving thermal comfort in a large number of buildings in hot climates.

Keywords: ventilation; thermal comfort; wind-catcher; dynamic façade;dynamic modeling

1. Introduction

Natural ventilation is the most common passive cooling technique evident in vernacular architecture throughout the Mediterranean region. However, currently the use of air-conditioning in southern European countries is increasing (Kapsomenakis et al. 2013). The domestic sector in Greece, which comprises 79% of the existing building stock, has the highest energy consumption in Europe (Asimakopoulos et al. 2012; Theodoridou et al. 2011) and accounts for 24% of the country's energy consumption (Eurostat 2016). It has been predicted that up to 70% of the houses operate air-conditioning systems during summertime (Drakou et al. 2011). The energy required for cooling in hot climates is higher than the energy required for heating (Yun and Steemers 2011), while concerns over fuel poverty in more than 20% of Greek households clearly highlight the need for low energy solutions to ventilation and cooling (Santamouris et al. 2007b).

Despite the EU 20-20-20 targets (i.e. to achieve by 2020 in Europe: 20% increase in energy efficiency; 20% reduction of CO_2 emissions; and 20% increase of renewables in final energy consumption), the implementation of the legislation in Greece has coincided with an economic recession. This has influenced the building construction sector, leading to a sharp decline in new build and low building retrofitting rates (Papamanolis 2015). However, the use of renewables in buildings has increased, demonstrating a cultural understanding of the value of improving the energy efficiency of buildings (Papamanolis 2015), which could also facilitate low energy building refurbishments for natural ventilation.

Natural ventilation can provide healthy indoor environments, occupant thermal comfort and contribute to sustainable development (CIBSE 2005; Prajongsan and Sharples 2012). The Mediterranean sub-climate of Greece (typically warm and dry during the cooling period) is well suited to natural ventilation, with the highest winds and hours of clear skies in the Mediterranean (Psomas et al. 2014). Despite this, natural ventilation is often insufficient in urban environments due to the urban density that contributes to lower ventilation rates relative to undisturbed sites and due to the current ventilation practices (most commonly single-sided ventilation) that contribute to low ventilation rates (Georgakis and Santamouris 2006). The influence of urban atmospheric pollution on indoor comfort typically discourages natural ventilation practices. Although indoor air quality (IAQ) measurements in 50 Athenian households predicted high levels of indoor pollution, this was principally attributed to low ventilation rates (Santamouris et al. 2007a).

Previous studies in warm climates have explored the performance of natural ventilation solutions in buildings, as well as the energy behaviour of Greek domestic buildings (Calautit et al. 2012; Santamouris et al. 2010; Theodoridou et al. 2011). However, there is a lack of information available on the performance of natural ventilation systems implemented in the most common residential building type in Greece with potential applications throughout the Mediterranean. The aim of the work reported here was to use modelling to evaluate passive cooling and ventilation strategies for low energy renovations of residential buildings in the most representative apartment building type in Greece. By predicting the ventilation and cooling performance of natural ventilation strategies implemented in a representative existing building, valuable guidance for future low energy refurbishment projects could be provided.

The research was conducted by considering an individual apartment in an urban multi-storey apartment building in the city of Athens. The apartment block is a representative example of the urban architectural typologies in Greece for its design, year and construction type, according to building classification studies (Papadopoulos et al. 2008; Theodoridou et al. 2011). Modelling this type of apartment has relevance to a significant volume of existing buildings in Athens and Greece in general as there are up to four million multi-storey apartment buildings in Greece (EL.STAT. 2014).

2. Method

Dynamic thermal simulation modelling was carried out in a typical apartment building in Greece and the ventilation performance of the following natural ventilation strategies was explored: individual and combined day and night ventilation through a ventilation shaft; use of a wind-catcher; use of internal openings and use of a dynamic façade. The impact on natural ventilation of the existing ventilation openings was first evaluated (base-case) and was then improved with controlled day and night cross ventilation (Part A). The implementation of vernacular strategies including a wind-catcher and a dynamic façade of shading systems was then evaluated (Part B). The analyses were performed for a single apartment during the cooling period (15th of May until 15th of September (Androutsopoulos et al. 2012)).

The case-study building used for this work was an existing five-storey apartment building located in an urban zone north of the centre of Athens, constructed in the 1970s (Figure 1), with a repeated floor layout. The building occupies the total length of the site, the main façade is southwest. The building is adjacent to surrounding apartment buildings from both the northeast and the southwest sides and has a 4m setback from both the main road (southeast) and the rear (northwest). Opposite buildings from the southeast are located at a 15-metre distance. Direct access to daylight and outdoor air is restricted to the bedrooms' external openings (patio doors towards the balcony) due to the building design. Three airshafts mainly designed as light wells, with cross-section area 2.5m^2 and height equal to the building height, allow the escape of stale air from the core spaces when the openings connecting the apartment to the airshaft are open. The top of the airshafts is protected from precipitation by a suspended lightweight roof allowing air to enter the shaft from the sides. The surrounding buildings (nine urban blocks were surveyed for the purpose of this study) were predominantly multi-storey apartment buildings of up to eight storeys. Also adjacent on two sides, they created open rectangular spaces, at the rear of the buildings (centre of the urban blocks), which are typical of the urban Greek architecture (Papamanolis, 2000).

A residential unit located on the first floor, facing southeast, was selected for the purpose of this study (Figure 2), with a total floor area of $53m^2$ and floor to ceiling height of 2.7m. Due to the unfavourable facade orientation of the buildng (southeast) caused by the intensity of the solar gains, this makes the apartment studied a worst case scenario. An extended description of the apartment studied is included in Spentzou (2015). The building geometry was created in the simulation as a multi-zone 3D model based on the original building drawings provided by the local municipality. The simulation model includes the detailed building design and the surrounding buildings. Despite the focus of this study being a specific apartment, all floors and partitions were included in the simulations in order to compare the ventilation performance of the apartment to the other apartments. Even though the study focused on a single apartment, often, exploring the properties of a single phenomenon under specific conditions provides better understanding of the whole. The simulations were based on several assumptions/parameters (e.g. heat gains, openings, thermal mass) that were kept consistent for each of the strategies examined. Therefore, the relative performance between the natural ventilation strategies that were determined from this modelling campaign is representative of real behaviour trends.

Dynamic thermal modelling was performed to predict hourly, space-averaged values of indoor air temperatures, ventilation rates, CO_2 emissions and levels of relative humidity for the cooling period. Simulations were performed using IES VE (IESVE 2012). IES VE has been highly rated by users for its usability and graphical visualization of its interface, and template driven approach (Attia et al., 2009). Simulation results using IES VE have been shown to be in good agreement with experimental results (Hamza, 2008). For the evaluation of natural ventilation, the software incorporates empirical wind pressure coefficients, buoyancy effects, flow characteristics of large openings and cracks, two-way flows and Rayleigh instability. In IES VE MacroFlo, wind pressures are estimated using wind pressure coefficients that have been derived from wind tunnel experiments. The software uses the adapted meteorological wind speed given by Equation 4.5 in CIBSE Guide A (CIBSE, 2006), which is the free stream wind speed defined by the building height and the urban morphology (IES VE, n.d.). IES VE offers three types of terrain coefficients for wind speed corrections (country, suburbs and city) and CIBSE Guide A offers four (open country, country with scattered wind breaks, urban and city). The case-study building is located in an 'urban' area (CIBSE, 2006), although due to lack of a respective type within the IESVE, the building was modelled in the category 'suburbs' that falls between the 'urban' and the 'country with scattered wind breaks' in CIBSE Guide A. For each opening an exposure type was selected (i.e. exposed, semi-exposed and sheltered) according to the degree of sheltering of the opening by surrounding obstacles, and the geometrical aspects of the surface (e.g. vertical surfaces, pitched roofs).

The performance of the proposed natural ventilation strategies was evaluated relative to the base-case ventilation of the apartment, their expected performance as reported by others in similar studies (Calautit et al. 2012; Geros et al. 1999; Niachou et al. 2005; Santamouris et al. 2007) and according to a set of acceptable values for IAQ (defined in the next paragraph). The hours during which thermal conditions fall within the thermal comfort ranges defined by standards, and the energy saving potential of the most efficient strategy, were predicted.

Peak temperatures of 28^{o}C in living spaces and 26^{o}C in bedrooms are recommended in free-running buildings; these should not be exceeded for more than 1% of the occupied time in order to avoid overheating (CIBSE 2006; Androutsopoulos et al. 2012). British Standards (BS EN15251 CEN 2007) recommend a minimum operative temperature of 22^{o}C for existing buildings during summer and 18^{o}C during winter; in this study, 18^{o}C will be considered as the minimum threshold for summer ventilation. Studies in free-running buildings in hot climates show that occupants' perceived comfortable operative temperatures substantially exceed these thresholds, particularly when combined with high air speeds for direct physiological cooling (Cândido et al. 2011; Sakka et al. 2010). For example, indoor temperatures exceeding 25^{o}C could be balanced with increased air speed (BS EN15251 CEN 2007); adaptive control algorithms were considered for this purpose. Poor IAQ can be improved with as low as 1ach^{-1} (CIBSE 2006), however higher values (5 to 10ach^{-1}) can deliver comfort cooling by ventilation (CIBSE 2005). Up to 5ach^{-1} have been measured in Greek residential buildings during wintertime (Santamouris et al. 2007a), while values as high as 80ach^{-1} have been measured in existing Greek buildings (Geros et al. 1999; Niachou et al. 2005). Relative humidity should be approximately 45% for indoor air temperatures of 26^{o}C (Androutsopoulos et al. 2012) and should be for no more than 70% for prolonged periods (CIBSE 2005). Acceptable CO_2 concentrations are considered to be values below 1000ppm and preferably below 800ppm (ASHRAE 2013; CIBSE 2005).

Three adaptive control algorithms were considered for this research: the CIBSE 2005, one developed specifically for the climate of Greece (McCartney and Nicol 2002) and one provided by the British standard EN15251 (BS EN15251 CEN 2007) that is applicable to Europe. The EN15251 was considered the most appropriate for this study according to a comparison study by Nicol and Humphreys (2010) and because it permitted adaptation in higher operative temperatures than the one developed for Greece. The EN15251 provided bands within which comfortable conditions have been identified to lie in response to the running mean temperatures for the specific building site; within these bands of indoor temperatures, people readily adapt.

In Greek houses, individual split A/C units installed per occupied space (Drakou et al. 2011) are typical. These operate by recirculating and cooling the indoor air, while ventilation is not provided during their operation. In order to evaluate the energy saving potential of the natural ventilation strategies examined, a hybrid cooling and ventilation strategy was developed to represent the current building operation. The building was assumed to be in free-running mode for in total seven hours each day. The set point temperature was 26^{o}C (Androutsopoulos et al. 2012). The mechanical system selected was an energy efficient mini-split system (energy class A^{++}) that supplied chilled air to the bedrooms (two-units) (coefficient of performance: 4.38), which represents the best-case scenario.

2.1. Ventilation strategies and model description

2.1.1. Part A scenarios: Ventilation via existing openings (base-case and new proposed strategies)

For the base-case ventilation strategy ([base-case]), survey data were used from published work to represent occupants' interaction with the openings and the building (e.g. occupancy). This ventilation scenario was designed conservatively in order to meet the expected low IAQ reported in published work by others, showing CO_2 concentrations exceeding the maximum acceptable threshold for comfort in houses (Santamouris et al. 2007a). Consequently, openings were modelled according to the expected individual operation by occupants (i.e. number of times per day, time of the day and duration) with regard to comfort and activities (e.g. house cleaning, cooking, occupants' presence) (Mavrogianni et al. 2014; Papakostas and Sotiropoulos 1997). Night ventilation was not provided in the [base-case] strategy and the infiltration rates were set for wooden frame single glazed openings. The internal windows (connecting to the airshaft) were operated during cooking periods (Papakostas and Sotiropoulos 1997) and the external windows were scheduled to open three times per day during the hours shown in Table 1 (Drakou et al. 2011).

Daytime Ventilation [DV] was achieved using the external building openings and the ventilation shaft connected to the kitchen via internal openings, providing both single-sided and cross ventilation. Day ventilation was provided according to the indoor and outdoor air properties required for occupants' comfort, as well as the number of occupants and their activities, as shown in Table 1. This ventilation strategy took place between 6am and 10pm; during the rest of the day, the ventilation strategy used was the [base-case]. Givoni (1994) describes how comfort ventilation can be achieved for ambient temperatures below 28-32°C for indoor air speeds of 1.5-2m/s. Although the indoor air velocity was not evaluated in this study, the high values of air speed would be reflected in the considerably high values of air changes that could ensure thermal comfort during high ambient temperatures. Such ambient temperatures were identified for up to 75% of the cooling period for the site under investigation and thus [DV] was considered suitable for the climate studied.

Nigh-time ventilation [NV] was provided for the hours of the day between 10pm and 6am throughout the cooling season, while the [base-case] scenario was used during the rest of the day (Table 1). [NV] was considered an appropriate strategy for the climate studied as the diurnal temperature difference (average of 7-8^{o}C) of the site under investigation was sufficient to deliver adequate temperature reductions, supported by the literature (Givoni 1994). [NV] was expected to provide comfort when the number of occupants would be high, and delay the peak temperatures of the following day. Throughout the night, the internal openings were fully open and the internal doors open by 20% to ensure privacy while providing ventilation.

The combined day and night ventilation [DV & NV] strategy fully replaces the base-case ventilation strategy and provides control of openings in response to thermal comfort throughout the day. This was expected to be the suitable ventilation scenario relative to the [base-case] and the two individual strategies ([NV] and [DV]). The control conditions of the ventilation strategies are shown in Table 1.

2.1.2. Part B scenarios: Low energy interventions

Three natural ventilation strategies using low energy interventions were identified in the literature and implemented in the case-study building, considering limitations imposed by the building layout and operation. These were added to the [DV & NV] ventilation strategy.

1. Four-directional wind-catcher [WC]

Capturing air above a building's roofline can improve the building's ventilation performance, by avoiding polluted air with lower velocities in the urban canyons (Georgakis and Santamouris 2006). Wind-catchers are also ideally suited to the local strong winds (above 10m/s). These were expected to outperform the existing airshaft/light well (used in Part A scenarios) because wind-driven systems could provide 76% higher ventilation rates than buoyancy-driven systems, as shown by Calautit et al. (2012).

A four-sided wind-catcher [WC] with cross-sectioned area of 2.64m^2 and internally divided into four zones, was added to the top of the existing airshaft, which is connected to the case-study apartment. The total area of the wind-catcher's openings was designed to be twice the area of the internal opening connecting the kitchen to the shaft. The wind-catcher is 1.5m above the roof of the penthouse, which is in compliance with the Greek general construction regulation (GOK, 1985). Cross-partitions on 'X' arrangement (5m length) facilitate simultaneous inflow and upwards escape of stale air. A four-sided wind-catcher design with a top horizontal covering surface (see Figure 3), was favoured because it could utilise all available wind directions and mitigate against any negative impact of the surrounding buildings on the ventilation performance of the wind-catcher (Spentzou et al., 2017).

Based on the work by Spentzou et al. (2017), exploratory thermal modelling simulations performed identified the most suitable wind-catcher design and operation of its openings. Wind-catcher tower height increments of 0.5m and up to 2m above and below were investigated; the taller towers delivered higher ventilation rates, although to a small degree. It was observed that when the leeward and windward openings operated simultaneously the ventilation rates in the spaces were increased for the hours of the day with the highest wind speeds (between 12pm and 8pm), as one opening assisted the outflow and the other assisted the inflow; for the rest of the day, openings would remain fully open. Lastly, at the lower part of the internal partitions, automatically controlled dampers were modelled to operate simultaneously with the top wind-catcher openings and thus obstruct air circulations in those channels that the top openings were closed. The opening operation of the top wind-catcher openings is summarised in Table 2a, showing the operation of the internal openings and doors for specific hours, the operation of the external openings (patio doors) under conditions 1 and 2, and the operation of the top wind-catcher openings under conditions 3 and 4.

2. Internal openings [InOp]

Alternative indoor airflow paths were anticipated to assist the cross ventilation of the apartment when all the internal doors remained closed. The ancillary space located above the false ceiling of the bathroom, which is a typical element of the multi-storey apartment buildings in Greece, was utilised for this purpose. This was proposed to be connected to the existing light well using an additional internal opening (with free area $0.3m^2$) and to the hallway via an opening of free area $0.6m^2$. The ventilation air could flow in and out of the living spaces through the hallway and the purpose-provided openings, designed above the party walls of the hallway. The hallway was used as a distribution space (Figure 3). The new internal openings were proposed to operate during the night, when the bedroom doors would be closed. This ventilation strategy [InOp], was combined with the [DV & NV] strategy (Table 2a) and the wind-catcher.

3. Lightweight dynamic façade [DF & WC]

Shading devices coupled with automated openings could provide comfort for up to 52% of the daylight hours for the cooling season and the site under investigation, as it was predicted via the software ClimateConsultant (2014) in Spentzou (2015). The performance of façade relief techniques, including wing walls and an external layer of horizontal shading systems, were evaluated.

The dynamic façade was designed to include three sets of louvres that provide operation flexibility, uniformity and aesthetic contribution to the existing building façade. This strategy was expected to combine the benefits of natural ventilation and solar gain reductions. New partition walls (proposed to be composed of glass brick) were added perpendicular to the two façades between all apartments. Each zone enclosed the balcony area and the two balcony doors of each apartment, reducing the risk of air circulation between the different ownerships. The louvres (21cm width, centre pivoted) were designed for east orientations (i.e. the number of louvers multiplied by their width is equal to the opening height) according to Palmero-Marrero and Oliveira (2010), at the edge of the balcony; this complied with the Greek general construction regulation, which defines 40cm to be the maximum allowable width of façade elements (GOK 1985).

One of the limitations of the dynamic thermal simulation software used was its inability to model custom-designed louvres and operation in response to environmental parameters. This was overcome through simplifications in the design. The façade was modelled as a second layer of three external horizontal openings that incorporated vertically operating blinds. The louvres would operate in response to the amount of solar radiation and the time of the day. The upper and lower sets of louvres operated simultaneously; they remained closed (fully shaded) for horizontal solar radiation above 550W/m^2, which occurred for 30% of the hours with direct radiation. The middle groups of louvres remained closed for horizontal solar radiation levels above 200W/m^2, which occurred for 45% of the hours and was the average value of solar radiation for the cooling period of Athens (Argiriou et al. 2010). This ventilation strategy was evaluated in combination with the wind-catcher design (Table 2b) as exploratory simulations demonstrated that the combined operation of these two strategies [DF & WC] delivered higher ventilation rates than for the dynamic façade strategy alone (Figure 4).

2.2. Description of building properties and modelling input parameters

2.2.1. Building properties

Limited information regarding the building properties was available, which is common for buildings constructed before the thermal insulation law implementation in Greece (in 1980). A brief description of the building properties was provided by the design team of the building (Spentzou 2013, pers. comm.). This information was validated and supplemented with information included in Androutsopoulos et al. (2012) for buildings constructed prior to 1979. Briefly, the exterior walls are non-insulated double brick and the internal partitions are single brick. The supporting building structure, the roof and floor slabs are made with cast in situ reinforced concrete. All operating windows and balcony doors were single-glazed, wooden framed, with external shutters. For the provision of cooling, individual split air-conditioning units (system not specified) are installed per building space according to occupants' needs and preferences; these were considered inactive during all ventilation strategies modelled. Further details of all construction elements of the building and U-values are included in Spentzou (2015).

2.2.2. Building occupancy: a daily profile

The building was considered occupied at all times in this study, with varied occupancy throughout the day, which was defined according to published work (Mavrogianni et al. 2014; Papakostas and Sotiropoulos 1997). An occupancy profile was created for the typical 24-hours that represent the current operation of the case-study building. Internal heat gains due to lighting and equipment were defined according to published work (Papadopoulos et al. 2008; Papakostas and Sotiropoulos 1997) and corresponded to the occupants' activities. The energy source and the number of internal heat gains were obtained from Androutsopoulos et al. (2012) (Table 3).

2.2.3. Climate data

Natural ventilation was evaluated for the cooling period, which is defined as the period between 15th of May and 15th of September (Androutsopoulos et al. 2012). Due to lack of climate data for the specific area, these were generated in Meteonorm software (Meteonorm 7 2012) for the period of 1961-1990. In addition, climate data of a two-year period were collected at a private weather station (Koukousianos 2011) with close proximity to the site. Although the Meteonorm climate file suggested lower DBTs by approximately 9% and higher wind speeds by 25% than the two-year dataset, as these were not normalised over a large period, the Meteonorm climate data were considered representative of a longer period and were thus used for the purpose of this study (Spentzou, 2015).

The apartment under investigation is located on the first floor and it was thus expected that the lower wind speed typical in urban canyons would impact on the natural ventilation (Georgakis and Santamouris 2006). For the climate studied, throughout the cooling period, wind speeds varied significantly during the day, typically reaching higher values in the afternoon and evening (4m/s on average) and lower values during the late morning hours (2.5m/s on average). The hourly variations of the ambient temperatures were repeated daily in a pattern during the cooling period. Accordingly, four daily sub-groups were observed with similar values of ambient temperatures, between 1am-6am, 6pm-12am, 12pm-6pm and 6pm-12am (Figure 5). These daily six-hour groups could be used to evaluate thermal comfort and IAQ more efficiently than using averaged daily values, as shown by others (Prajongsan and Sharples 2012; Spentzou et al., 2013).

2.2.4. Surrounding buildings and solar gains

The building site and the surrounding area were surveyed to obtain the number, use, location and dimensions of the surrounding buildings (Figure 6). These were modelled as blocks, contributing to the shading and wind analysis. During the four-month period, the building façade was unobstructed for up to 5½ hours, from 6am or 7am; additional shading would be required during these hours (predicted using SunCast IES VE). The apartment studied has direct access to sunlight for a shorter period than the rest because it is located on the first floor and thus, the performance of shading was expected to be less efficient relative to the rest of the building.

3. Results: Natural ventilation and cooling performance

3.1. Part A scenarios: Ventilation via existing openings

The [base-case] strategy, predicted operative temperatures were clustered around the recommended value for comfort of 26°C for the milder days of the cooling period. However, for most of the cooling period, operative temperatures exceeded the comfort threshold and the ambient temperature (Figure 7). Even when the openings remained closed, indoor air temperatures closely followed the fluctuations and peaks of the ambient temperature. During the late afternoon/early evening hours (Figure 8), the external openings were fully open in response to occupancy, coinciding with the high ambient temperatures, resulting in high air changes (up to 21ach^{-1}), and high indoor temperatures (29°C on average). For the hours of the day that the openings operated, ventilation is principally wind driven although there are values of ventilation rates due to temperature gradient (when wind speeds are close to zero, Figure 9). Predicted CO_2

levels exceeded the upper comfort limit of 1000ppm. These predictions agree with measured CO_2 values in Greek residential buildings with low ventilation rates (Santamouris et al. 2007a) and they represent business as usual for this representative residential building.

The new [DV] strategy that controlled the openings between 6am-10pm, significantly reduced the indoor temperatures (1.6^{o}C on average) during the night by preconditioning of the spaces in the evening. The proposed [NV] strategy reduced the indoor temperatures during the morning (on average by 2.4^{o}C) and the peak temperatures throughout the day by 3^{o}C, relative to the [base-case]; this performance was consistent with the expected benefits of night ventilation as reported by others (Geros et al. 1999). In particular, CO_2 levels in the bedrooms during the night time (about 433ppm) were predicted to be lower than both [base-case] and [DV] due to the large patio door opening which led to high air change rates (19.2ach^{-1} on average) as expected.

The combined day and night ventilation strategy [DV & NV] resulted in up to 7^{o}C temperature reductions relative to the [base-case]. Operative temperatures were predicted lower than ambient for 60% of the cooling period, exceeding the ambient by only 1^{o}C on average. These were up to 8^{o}C lower than the ambient during the peak hours of the day, which could ensure indoor comfort by the lower indoor temperatures (Figure 10). Humidity levels remained close to the comfort range (defined in literature by Androutsopoulos et al. (2012); CIBSE (2005)), with relative humidity of approximately 50%. The ventilation rates were found to be lowest between the hours 12pm to 7pm (Figure 8), in contrast to the [base-case] strategy. This was because the openings remained closed for longer periods due to the higher ambient temperatures. The ventilation rates were thus independent of the wind speeds that remained variable throughout the day (Figure 11). For 31% of the ventilation hours, wind-driven ventilation was achieved, as derived by the correlation of wind speed and ventilation rates shown in Figure 11. The automatic opening operation during day and night achieved high ventilation rates during low wind speeds, which was not evident during the [base-case]. The [DV & NV] strategy significantly reduced the hours during the cooling period for which the CO_2 levels exceeded the upper acceptable limit for IAQ relative to the [base-case] strategy (29% of the time exceeded 1000ppm), to as little as 1%. This is significant considering the reported concerns in the literature regarding high CO_2 values in residential buildings, particularly in mechanically ventilated spaces (Santamouris et al. 2007a).

3.2. Part B scenarios: Low energy interventions

The implementation of a wind-catcher was expected to result in higher ventilation rates and temperature reductions as shown in literature (Elmualim 2006), than was predicted. There is a common concern over the accuracy of the pressure coefficients used in building energy simulation tools (Cóstola et al. 2009). However, the intention of this research was not to assess the design of wind-catchers but their ventilation potential in a typical apartment building; further study addressing the detailed performance of the wind-catcher is presented in Spentzou et al. (2017) using CFD. For wind speeds above 3m/s, the [WC] strategy delivered ventilation rates exceeding 280l/s for 24% of the ventilation hours (16% of the cooling period), due to wind driven ventilation. Sufficient ventilation rates (above 140l/s) were achieved due to temperature differences alone during 53% of the ventilation hours (36% of the cooling period) as wind speeds remained below 3m/s. The overall relationship trend between wind speeds and ventilation rates is comparable to measured values in an existing building with a wind-catcher (Elmualim 2006).

The new internal openings and airflow paths [InOp] strategy was able to deliver sufficient ventilation rates (Figure 12), ensure privacy within the apartment spaces (fully closed internal doors), and provide comfort relative to the [base-case] strategy. However, due to the small cross-sectional area of the hallway openings, the strategy was unable to improve the natural ventilation of the apartment. All proposed ventilation strategies explored were more efficient than this strategy. Further work would be required to optimise the performance of this strategy by exploring different design configurations and openings operations.

The new [DF & WC] strategy provided further temperature reductions and reduced the daily temperature fluctuations relative to the rest of the ventilation strategies. For high ambient temperatures exceeding 30^{o}C, up to 8^{o}C to be lower internal air temperatures were predicted. Operative temperatures were predicted lower than the ambient for 81% of the time (49% for the [base-case]). Average operative temperatures were predicted to be lower than with the [base-case] by 3.6^{o}C, and with reduced variability (smaller standard deviation).

4. Summary and discussion

4.1. Overall ventilation and cooling performance of the proposed strategies

For a sample 7-day period (Figure 13), operative temperatures followed the fluctuations of the external temperatures due to the frequent operation of the openings in the new strategies, which ensured acceptable IAQ. The high air changes during Groups C and D appear to have a small contribution in the indoor temperatures (Figure 13). It is evident that the [DF & WC] strategy led to further temperature reductions than the [DV & NV] by up to 0.5^{o}C, however, with little difference on average throughout the cooling period (i.e. 0.2^{o}C), which is reflected in the comparable values of air change rates (Figure 13). This little difference between the [DF & WC] and the [DV & NV] is also shown by the comparable values of standard deviation (2.5 for the proposed strategies and 2.7 for the [base-case]) predicted for all six natural ventilation strategies. Both [DV & NV] and [DF & WC] strategies were able to maintain indoor air temperatures lower than the ambient (by up to 8^{o}C) during the late hours of the day with the highest occupancy levels (Group C-D), and delivered lower operative temperatures by up to 4^{o}C on average relative to the [base-case]. Lower operative temperatures were achieved during the first two groups of the day (Group A-B) for the [DF & WC] due to the large diurnal temperature difference and particularly the wind-catcher design; this performance was consistent with work by others (Elmualim 2006).

With the [base-case], ventilation rates were predicted higher between noon and midnight, with peak values between 12-6pm during which the building is mostly unoccupied. With the proposed strategies (particularly the [DV & NV] and [WC & DF]), ventilation rates fell to their minimum during the warmer hours of the day (noon-6pm), while they remained similar to the [base-case] values between 6pm and midnight. This was due to the low occupancy that led to low CO_2 levels and due to the ambient temperature being higher than the internal temperature, which led to the external openings being mostly closed during this time. The new strategies exploited the high wind speeds and the diurnal temperature difference, and delivered the highest rates between midnight and noon (Group A-B) when the building is mostly fully occupied. The proposed strategies delivered air change rates with smaller standard deviations than the [base-case] by up to $7ach^{-1}$ ensuring less variation in indoor comfort conditions. As shown in Figure 12, the proposed strategies provided air changes above $1ach^{-1}$ for longer periods (only 27% of the cooling period below $1ach^{-1}$ in [DF & WC]), which thus exceeded the minimum acceptable value for comfort for (CIBSE 2006). During 65% of the cooling period, the [DF & WC] strategies led to air change rates between one and $20ach^{-1}$ that is considered as the highest of typical measured in existing buildings; these agree with measurements in residential urban buildings in Greece (Geros et al. 1999; Niachou et al. 2005). In addition, the CO_2 levels that were predicted during the [base-case] exceeded the upper limit of 1000ppm for 30% of the cooling period; this was reduced to just 1% using the [DV & NV] and [DF & WC] strategies. These strategies maintained CO_2 levels below 500ppm during 55% of the cooling period (from 19% in the [base-case]), which are within accepted indoor air quality norms (Elmualim 2006).

4.2. Comfort evaluation

The predicted operative temperatures for all ventilation strategies were evaluated against the overheating thresholds of 26^{o}C (bedrooms) and 28^{o}C (other rooms) defined by Guide A (CIBSE 2006). The least hours above the 26/28^{o}C thresholds were predicted during the period 6am-noon, which was the period with the lowest number of occupants. The combined [DF & WC] strategy resulted in the fewest overheating hours (47% of the cooling period above 26^{o}C, and 17% above 28^{o}C) relative to the other six ventilation strategies, but still exceeded the recommended overheating thresholds. During 50% of the cooling period of the [base-case] simulation, indoor temperatures exceeded 30^{o}C (Figure 14). This performance is consistent with measurements in free-running residential buildings in Athens studied by Sakka et al. (2010), predicting mean indoor temperatures during summer of 30^{o}C for up to 70% of the period. Although during the [DV & NV] and [DF & WC] strategies the 30^{o}C threshold was exceeded for no more than 7% and 4.4% of the time respectively, these metrics do not reflect occupants' adaptation. In free running spaces, occupants' response to discomfort and their adaptation levels should be considered.

Operative temperatures were thus plotted against the acceptable levels for comfort defined by the EN15251 adaptive control algorithm (BS EN15251 CEN 2007). For this research, only the first, T_I, high level of expectations and the third bands, T_{III}, moderate expectations that is suitable for existing buildings, were selected. These define a range of acceptable upper and lower limits (BS EN15251 CEN 2007) within which operative temperatures are defined, in order to achieve comfort. Operative temperatures at the [base-case] exceeded the upper limit (Figure 15) of the first band (T_{Imax}) for almost 50% of the time and for 10% of the time exceeded the upper limit of the third band (T_{IIImax}). As the T_{III} is suited for existing buildings, the predicted performance of the [base-case] strategy was as expected and provided confidence in the simulation results. Up to

52% of the predicted daily operative temperatures for the [DV & NV] lie within the narrowest (T_I) band of upper and lower limits, which is the optimum comfort range. This has been evident for all interventions ([WC], [DF], [DF & WC] and [InOp]). Particularly, for the [DF & WC], operative temperatures exceeded the TI max for only 1% of the cooling period, achieving low indoor temperatures. During up to 48% of the cooling period, operative temperatures were below the T_{Imin} for the [DF & WC] strategy; however, these were above the minimum temperature for comfort (18^{o}C) and below 22^{o}C for only 6% of the time. These values were predicted to be lower than the indoor temperatures in residential buildings in Athens, typically characterised by a mean temperature of 30^{o}C for 70% of the time (Sakka et al. 2010). Using the [DV & WC] strategy, operative temperatures previously ([base-case]) clustered around the T_{IIImax}, were able to shift closer to the T_{IIImin}, evidently providing significant temperature reductions. Operative temperatures were predicted within the acceptable comfort limits for high level of expectations (up to 70% for the six-hour groups) and for moderate expectations (up to 98%), therefore, occupants' comfort was achieved. Alternative strategies could be employed such as provision of mechanical cooling by A/C units, to eliminate the hours of the day with operative temperatures outside the comfort limits

Using the [DV & NV] strategy, the least hours within the narrowest comfort band (T_I) were predicted for Group B (Figure 16), which is the group with the lowest occupancy. Operative temperatures were below the top limit of the narrowest band (T_{Imax}), which was exceeded for only 5% during Group D. The most hours within the narrowest comfort band were predicted during Groups C and D of the cooling period (up to 68%), which represent the periods with the highest occupancy; the [DV & NV] strategy would thus ensure occupant comfort.

The ventilation performance of the interventions is specific for the case-study apartment and the results of this comfort study would be expected to vary even throughout the same building.

The total average daily operative temperatures for the other building apartments connected to the same airshaft (8 in total), varied by up to 0.5^{o}C above the average daily temperatures of the case-study apartment. Indoor air temperatures gradually increased from the case-study apartment (1st floor) towards the top of the building (4th floor) (Figure 17), reaching up to 1^{o}C temperature difference. This was due to the higher number of hours with direct solar radiation on the top floors, the reduced length of the wind-catcher shaft during buoyancy-driven flows, the influence of thermal mass and insufficient roof insulation.

4.3. Quantification of the potential energy savings

To ensure indoor comfort, mechanical cooling would need to operate for 40% of the cooling period during the [base-case] scenario, resulting in total energy consumption of up to 1135.3kWh (approximately 23kWh/m^2), as it was predicted. The A/C system evaluated during this strategy (the [hybrid]) was very energy efficient and less representative of the vast majority of systems currently installed and operated in residential buildings in Greece, particularly if fuel poverty and the cost of systems' replacement are considered. Energy consumption in multi-storey apartments for both heating and cooling can be up to 220kWh/m^2/year (Papamanolis 2015), which is significantly higher than the predicted value, especially considering that the energy for cooling is higher than the energy for heating (Yun and Steemers 2011). The energy consumption could significantly increase if a less energy efficient A/C unit was in operation; thus, the predicted value can only be indicative of the performance of the system. The actual performance would depend on external parameters such as the systems' installation, maintenance, exposure to direct solar gains and urban heat island that has not been taken into account in this study (up to 25% coefficient of performance reduction was predicted in Athens due to UHI (Santamouris et al. 2001)). Therefore, by utilising the proposed natural ventilation strategies, and by considering the occupants' adaptation to higher indoor air temperatures, significant energy savings could be achieved.

During the [hybrid] strategy, operative temperatures were predicted to have small fluctuations during the warmer days of the cooling period (i.e. average DBT exceeding 24^{o}C). These exceeded the threshold of 26^{o}C for 72% of the cooling period and never exceeded the threshold of 28^{o}C, which are particularly low relative to the [DF & WC] strategy (47% and 16% respectively) (Figure 18). However, the operation of the A/C units resulted in poor IAQ due to the insufficient provision of fresh air and removal of the stale air. In particular, CO_2 in the spaces was predicted to be up to 1300ppm. This performance was consistent with measurements in existing buildings in Greece with low ventilation rates (Santamouris et al. 2007a). Additionally, during the [hybrid] strategy, operative temperatures were found to be up to 60% higher than when the [DF & WC] strategy was used, which is when the [DF & WC] was benefited by the low ambient temperatures and the high wind speeds.

If mechanical cooling was used in combination with, and only during the hours that the [DF & WC] strategy could not provide sufficient cooling, then potentially the energy consumption could reduce by two-thirds of the previously predicted consumption with the [base-case] strategy. Work by others has similarly reported that free-running buildings consume 50% less energy than air-conditioned buildings (O'Sullivan and Kolokotroni 2014).

5. Conclusions

This study investigated the potential of a series of natural ventilation strategies and interventions to provide occupant comfort, adequate ventilation rates and improved IAQ in residential buildings in Greece. Using energy performance modelling it was predicted that day and night cross ventilation resulted in up to 7^{o}C temperature reductions and reduced the hours during the cooling period for which the CO_2 levels exceeded the upper acceptable limit for comfort to a marginal 1%, relative to the base-case strategy. The cooling performance of the combined day and night ventilation was comparable to the performance of the proposed interventions (e.g. wind-catcher) due to the limitations of the modelling technique to effectively evaluate wind-driven natural ventilation.

The new ventilation strategies reduced the hours during the cooling period with ventilation rates below the minimum acceptable limit for comfort (just 27% of the cooling period), and provided less variability within the day. CO_2 levels predicted during the base-case exceeded the acceptable upper limit of 1000ppm during 30% of the cooling period, which was reduced to just 1% with the new ventilation strategies. Simulation results show that day and night natural ventilation, and the implementation of a wind-catcher and a dynamic façade could ensure occupant comfort for a certain period. These strategies could be supplemented with mechanical cooling only when they do not provide sufficient performance.

The successful performance of the proposed strategies implemented on a representative residential building in Greece, highlighted the potential for reducing energy consumption and improving thermal comfort in a large number of buildings in hot climates. This research will continue with the investigation of the cost-effectiveness of the proposed intervention strategies implemented on other case-study building and microclimates.

References

Androutsopoulos A, Aravantinos D, Gaglia A, Giannakidis C, Gidaki C, Dimoudis A, Droutsa K, Efthimiadis A, Zacharias P, Iliadis C, Theodosiou T, Kalliakoudi K, Katsimihas S, Kteniadakis M, Ladopoulos C, Lampropoulou L, Laskos K, Malahias C, Mantas D, Maris A, Maris T, Balaras K, Polychronia E, Sagia G, Sofronis H, Tsagkrasoulis A, Tsikaloudaki K, Chasapis D (2012). Technical Directive T.O.T.E.E. 20701-1/2010. Detailed national requirements of parameters for calculating the energy performance of buildings and issuing the energy performance certificate [in Greek], Athens, Greece: Ministry of Environment, Energy and Climate Change-YPEKA, Technical Chamber of Greece TEE, 2nd Ed.

Argiriou A, Gaglia A, Daskalaki E, Zaharias P, Katsanos D, Kontogiannidis S, Ladopoulos G, Ladopoulos I (2010). Technical Directive T.O.T.E.E. 20701-3/2010 Climate data of Greek Cities [In Greek]. Ministry of Environment, Energy and Climate Change-YPEKA, Technical Chamber of Greece TEE, Athens.

ASHRAE (2013). *ANSI/ASHRAE Standard 62.1*-2013. Ventilation for Acceptable Indoor Air Quality, Atlanta: American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

Asimakopoulos DA, Santamouris M, Farrou I, Laskari M, Saliari M, Zanis G, Giannakidis G, Tigas K, Kapsomenakis J, Douvis C, Zerefos SC, Antonakaki T, Giannakopoulos C (2012). Modelling the energy demand projection of the building sector in Greece in the 21st century. Energy and Buildings 49: 488–498.

Attia S, Beltrán L, Herde AD, Hensen J (2009). Architect Friendly: a comparison of ten different building performance simulation tools. In: Building Simulation 2009. Glasgow, Scotland, Eleventh International IBPSA Conference, 204–211.

BS EN15251 CEN (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. British Standards Institute (BSI), London, UK.

Calautit JK, Hughes BR, Ghani SA (2012). A numerical investigation into the feasibility of integrating green building technologies into row houses in the Middle East. Architectural Science Review 1–18.

Cândido C, Lamberts R, de Dear R, Bittencourt L, de Vecchi R (2011). Towards a Brazilian standard for naturally ventilated buildings: guidelines for thermal and air movement acceptability. Building Research & Information, 39(2): 145-153.

CIBSE (2005). *CIBSE Guide B*. Heating, ventilating, air conditioning and refrigeration London UK.

CIBSE (2006). *CIBSE Guide A*. Environmental design. London UK, doi:10.1016/B978-0-240-81224-3.00016-9.

ClimateConsultant (2014). Climate Consultant. software version 5.5 (build 5), free licence, Department of Architecture and Urban Design University of California, Los Angeles.

Drakou A, Tsangrassoulis A, Roetzel A (2011). Occupant interaction with the interior environment in Greek dwellings during summer. In: Proceedings of the 27th Conference on Passive and Low Energy Architecture (Plea 2011), Presses universitaires de Louvain, Louvain-la-Neuve Belgium, 475–480.

EL.STAT. 2014 “Statistical Database”, Hellenic Statistical Authority (EL.STAT.), available at: www.statistics.gr.

Elmualim AA (2006). Verification of design calculations of a wind catcher/tower natural ventilation system with performance testing in a real building. International Journal of Ventilation 4(4): 393–404.

Eurostat (2016). Eurostat - Your key to European statistics. Europian Commission, available at: http://ec.europa.eu/eurostat/web/energy/data/main-tables. Accessed 16 June 2016.

Georgakis C, Santamouris M (2006). Experimental investigation of air flow and temperature distribution in deep urban canyons for natural ventilation purposes. Energy and Buildings 38(4): 367–376.

Geros V, Santamouris M, Tsangrasoulis A, Guarracino G (1999). Experimental evaluation of night ventilation phenomena. Energy and Buildings, 29(2): 141–154.

Givoni B (1994). Passive and Low Energy Cooling of Buildings. Van Nostrand Reinhold, USA 1stEd.

GOK (1985). General Construction Regulation of Greece Article 11 and 16 [in Greek], available at portal.tee.gr.

Hamza N (2008). Double versus single skin facades in hot arid areas. Energy and Buildings 40(3): 240–248

IESVE (2012). Virtual Environment, software, version 6.4.0.11, student licence. Integrated Environmental Solutions Ltd available at: www.iesve.com.

IES VE (n.d.) MacroFlo Opening Types User Guide [Internet]. Available from: www.iesve.com/downloads/help/Thermal/MacroFloOpeningTypes.pdf.

Kapsomenakis J, Kolokotsa D, Nikolaou T, Santamouris M, Zerefos SC (2013). Forty years increase of the air ambient temperature in Greece: The impact on buildings. Energy Conversion and Management 74: 353–365.

Koukousianos S (2011). Meteorological Station of Galatsi. Available at: http://galatsi.meteoclub.gr. Accessed 11 Jan 2013.

Mavrogianni A, Davies M, Taylor J, Chalabi Z, Biddulph P, Oikonomou E, Das P, Jones B, (2014). The impact of occupancy patterns, occupant-controlled ventilation and shading on indoor overheating risk in domestic environments. Building and Environment 78: 183–198.

McCartney KJ, Fergus Nicol J (2002). Developing an adaptive control algorithm for Europe. Energy and Buildings 34(6): 623–635.

Meteonorm 7 (2012). Software, version 7”, (Meteotest), Bern Switzerland.

Niachou K, Hassid S, Santamouris M, Livada I (2005). Comparative monitoring of natural, hybrid and mechanical ventilation systems in urban canyons. Energy and Buildings 37: 503–513.

Nicol F, Humphreys M (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. Building and Environment 45(1): 11–17.

O'Sullivan PD, Kolokotroni M (2014). Time-averaged single sided ventilation rates and thermal environment in cooling mode for a low energy retrofit envelope. International Journal of Ventilation 13(2): 153–168.

Palmero-Marrero AI, Oliveira AC (2010). Effect of louver shading devices on building energy requirements. Applied Energy 87(6): 2040–2049.

Papadopoulos AM, Oxizidis S, Papathanasiou L (2008). Developing a new library of materials and structural elements for the simulative evaluation of buildings' energy performance. Building and Environment 43(5): 710–719.

Papakostas KT, Sotiropoulos BA (1997). Occupational and energy behaviour patterns in Greek residences. Energy and Buildings 26(2): 207–213.

Papamanolis N (2015). The first indications of the effects of the new legislation concerning the energy performance of buildings on renewable energy applications in buildings in Greece. International Journal of Sustainable Built Environment 4(2): 391–399.

Papamanolis N (2000). Natural ventilation as a design factor in buildings in Greece. Architectural Science Review 43(4):175-182.

Prajongsan P, Sharples S (2012). Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts. Building and Environment 50: 104–113.

Psomas T, Holzer P, Santamouris M (2014). A naturally ventilated efficient residential building under the impact of climate change. International Journal of Ventilation 13(2): 169–178.

Sakka A, Wagner A, Santamouris M (2010). Thermal comfort and occupant satisfaction in residential buildings – Results of field study in residential buildings in Athens during the summer period. Adapting to Change: New Thinking on Comfort, NCEUB, Network for Comfort and Energy Use in Buildings, Windsor UK.

Santamouris M, Argiroudis K, Georgiou M, Livada I, Doukas P, Assimakopoulos M, Sfakianaki A, Pavlou K, Geros V, Papaglastra M (2007a). Indoor air quality in fifty residences in Athens. International Journal of Ventilation 5(4): 367–80.

Santamouris M, Kapsis K, Korres D, Livada I, Pavlou C, Assimakopoulos M (2007b). On the relation between the energy and social characteristics of the residential sector. Energy and Buildings 39(8): 893–905.

Santamouris M, Papanikolaou N, Livada I (2001). On the impact of urban climate on the energy consumption of buildings. Solar Energy 70(3): 201–216.

Santamouris M, Sfakianaki A, Pavlou K (2010). On the efficiency of night ventilation techniques applied to residential buildings. Energy and Buildings 42(8): 1309–1313.

Spentzou E (2015). Refurbishment of apartment buildings in the Mediterranean Region for natural ventilation: implications for building design (PhD thesis). Loughborough University Loughborough UK, https://dspace.lboro.ac.uk/2134/18592.

Spentzou E, Cook JM, Emmitt S (2013). Enhancing indoor comfort in existing apartment buildings in Athens using natural ventilation. In: 13th Conference of International Building Performance Simulation Association. 25-28 August, IBPSA Chambéry France 1168–1175.

Spentzou E, Cook JM, Emmitt S (2017). Modelling natural ventilation for summer thermal comfort in Mediterranean dwellings. International Journal of Ventilation, DOI: 10.1080/14733315.2017.1302658

Theodoridou I, Papadopoulos AM, Hegger M (2011). A typological classification of the Greek residential building stock. Energy and Buildings 43(10): 2779–2787.

Yun GY, Steemers K (2011). Behavioural, physical and socio-economic factors in household cooling energy consumption. Applied Energy 88(6): 2191–2200.

Table 1. Control conditions of four ventilation strategies

<table>
<tr><th></th><th colspan="3">Base-case</th><th colspan="5">Night Ventilation</th><th colspan="7">Day Ventilation</th><th colspan="7">Day and Night Ventilation</th></tr>
<tr><th rowspan="2">Condition-Time</th><th rowspan="2">Int Op</th><th rowspan="2">Int Do</th><th rowspan="2">Ext Op</th><th rowspan="2">Int Op</th><th rowspan="2">Int Do</th><th colspan="2">Conditions for the Ext Op</th><th rowspan="2">Ext Op</th><th rowspan="2">Int Op</th><th rowspan="2">Int Do</th><th colspan="4">Conditions for the Ext Op</th><th rowspan="2">Ext Op</th><th rowspan="2">Int Op</th><th rowspan="2">Int Do</th><th colspan="4">Conditions for the Ext Op</th><th rowspan="2">Ext Op</th></tr>
<tr><th colspan="2">Condition-1</th><th colspan="2">Condition-1</th><th colspan="2">Condition-2</th><th colspan="2">Condition-1</th><th colspan="2">Condition-2</th></tr>
<tr><td rowspan="2">00:00-06:00</td><td rowspan="4">Closed</td><td rowspan="2">Closed</td><td rowspan="2">Closed</td><td rowspan="2">Open</td><td rowspan="2">20% Open</td><td rowspan="2">To>18°C and Ti>To</td><td>Y</td><td>Open</td><td colspan="2" rowspan="2">Closed</td><td colspan="4" rowspan="2"></td><td rowspan="2">Closed</td><td rowspan="2">Open</td><td rowspan="2">20% Open</td><td rowspan="11">To>18°C and Ti>To</td><td rowspan="5">Y</td><td colspan="2" rowspan="5"></td><td rowspan="7">Open</td></tr>
<tr><td>N</td><td>Closed</td></tr>
<tr><td>06:00-06:30</td><td rowspan="6">Open</td><td>Open</td><td rowspan="2">Closed</td><td rowspan="6">Open</td><td colspan="2" rowspan="7"></td><td>Open</td><td colspan="2" rowspan="7">Open</td><td rowspan="7">To>18°C and Ti>To</td><td rowspan="3">Y</td><td colspan="2" rowspan="3"></td><td rowspan="5">Open</td><td rowspan="7">Open</td><td rowspan="7">Open</td></tr>
<tr><td>06:30-12:00</td><td>Closed</td><td>Closed</td></tr>
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<tr><td>12:30-14:00</td><td>Closed</td><td>Closed</td><td rowspan="4">N</td><td rowspan="4">CO_2>1000 ppm and Ti>22°C</td><td rowspan="2">Y</td><td rowspan="6">N</td><td rowspan="6">CO_2>1000 ppm and Ti>22°C</td><td rowspan="2">Y</td></tr>
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<tr><td>N</td><td>Closed</td></tr>
</table>

Table Key	
Building elements	
Int Op	Internal openings (kitchen to airshaft)
Int Do	Internal doors
Ext Op	External openings (patio doors)
Environmental properties	
To	Ambient temperature (°C)
Ti	Indoor air temperature (°C)
CO_2	Carbon dioxide (ppm)

Table 2a. Control conditions for openings in the low energy interventions

<table>
<tr><th></th><th colspan="13">Wind Catcher</th><th colspan="8">Internal Openings</th></tr>
<tr><th rowspan="2">Condition-Time</th><th rowspan="2">Int Op</th><th rowspan="2">Int Do</th><th colspan="4">Conditions for the Ext Op</th><th rowspan="2">Ext Op</th><th colspan="2">Conditions for the WC Op</th><th rowspan="2">E+W WC Op</th><th colspan="2">Conditions for the WC Op</th><th rowspan="2">S+N WC Op</th><th rowspan="2">Int Op</th><th rowspan="2">Int Do</th><th rowspan="2">Bed Int Op</th><th colspan="4">Conditions for the Ext Op</th><th rowspan="2">Ext Op</th></tr>
<tr><th colspan="2">Condition-1</th><th colspan="2">Condition-2</th><th colspan="2">Condition-3</th><th colspan="2">Condition-4</th><th colspan="2">Condition-1</th><th colspan="2">Condition-2</th></tr>
<tr><td>00:00-06:00</td><td>Open</td><td>20% Open</td><td rowspan="9">To>18 °C and Ti>To</td><td rowspan="4">Y</td><td colspan="2" rowspan="4"></td><td rowspan="4">Open</td><td colspan="2" rowspan="3"></td><td rowspan="4">Open</td><td colspan="2" rowspan="3"></td><td rowspan="4">Open</td><td>50% Open</td><td>Close</td><td>Open</td><td rowspan="9">To>18 °C and Ti>To</td><td rowspan="4">Y</td><td colspan="2" rowspan="4"></td><td rowspan="6">Open</td></tr>
<tr><td>06:00-06:30</td><td rowspan="7">Open</td><td rowspan="7">Open</td><td rowspan="7">50% Open</td><td rowspan="7">Open</td><td rowspan="7">Close</td></tr>
<tr><td>06:30-12:00</td></tr>
<tr><td>12:00-12:30</td><td rowspan="3">74.999°<Wd< 164.99° or 254.999°<Wd< 344.99°</td><td>Y</td><td rowspan="3">164.999o <Wd< 254.99o or 349.999o <Wd< 74.99o</td><td>Y</td></tr>
<tr><td>12:30-14:00</td><td rowspan="5">N</td><td rowspan="5">CO_2>1000 ppm and Ti>22°C</td><td rowspan="2">Y</td><td rowspan="2"></td><td rowspan="2">N</td><td rowspan="2">Close</td><td rowspan="2">N</td><td rowspan="2">Close</td><td rowspan="5">N</td><td rowspan="5">CO_2>1000 ppm and Tin>22°C</td><td rowspan="2">Y</td></tr>
<tr><td>14:00-20:00</td></tr>
<tr><td>20:00-21:00</td><td rowspan="3">N</td><td rowspan="3">Close</td><td colspan="2" rowspan="3"></td><td rowspan="3">Open</td><td colspan="2" rowspan="3"></td><td rowspan="3">Open</td><td rowspan="3">N</td><td rowspan="3">Close</td></tr>
<tr><td>21:00-22:00</td></tr>
<tr><td>22:00-24:00</td><td>Open</td><td>20% Open</td><td>50% Open</td><td>Close</td><td>Open</td></tr>
</table>

Table Key

Building elements	
Int Op	Internal openings (kitchen to airshaft)
Int Do	Internal doors
Ext Op	External openings (patio doors)
Bed Int Op	Bedroom Opening
E+W WC Op	East and West facing wind-catcher openings
S+N WC Op	South and North facing wind-catcher openings
Environmental properties	
To	Ambient temperature (°C)
Ti	Indoor air temperature (°C)
CO_2	Carbon dioxide (ppm)
Wd	Wind direction (m/s)

Table 2b. Control conditions for openings in the low energy interventions

<table>
<tr><th></th><th colspan="19">Dynamic Facade</th></tr>
<tr><th rowspan="2">Condition-Time</th><th rowspan="2">Int Op</th><th rowspan="2">Int Do</th><th colspan="4">Conditions for the Ext Op</th><th rowspan="2">Ext Op</th><th colspan="2">Conditions for the WC Op</th><th rowspan="2">E+W WC Op</th><th colspan="2">Conditions for the WC Op</th><th rowspan="2">S+N WC Op</th><th rowspan="2" colspan="2">Condition -5</th><th rowspan="2" colspan="2">Condition-6</th><th rowspan="2">Mid Lv</th><th rowspan="2">Top & B Lv</th></tr>
<tr><th colspan="2">Condition-1</th><th colspan="2">Condition-2</th><th colspan="2">Condition-3</th><th colspan="2">Condition-4</th></tr>
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<tr><td>06:00-06:30</td><td rowspan="7">Open</td><td rowspan="7">Open</td></tr>
<tr><td>06:30-12:00</td></tr>
<tr><td>12:00-12:30</td><td rowspan="3">74.999o<Wd < 164.99o or 254.999o<Wd< 344.99o</td><td>Y</td><td rowspan="3">164.999°<Wd< 254.99° or 349.999°<Wd< 74.99°</td><td>Y</td><td rowspan="3">Dr> 550 W/m²</td><td>Y</td><td colspan="2"></td><td rowspan="2">Close</td><td>Close</td></tr>
<tr><td>12:30-14:00</td><td rowspan="5">N</td><td rowspan="5">CO_2>1000ppm and Ti>22°C</td><td rowspan="2">Y</td><td rowspan="2">N</td><td rowspan="2">Close</td><td rowspan="2">N</td><td rowspan="2">Close</td><td rowspan="2">N</td><td rowspan="2">Dr>200 W/m²</td><td>Y</td><td rowspan="5">Open</td></tr>
<tr><td>14:00-20:00</td><td>N</td><td>Open</td></tr>
<tr><td>20:00-21:00</td><td rowspan="3">N</td><td rowspan="3">Close</td><td rowspan="3" colspan="2"></td><td rowspan="3">Open</td><td rowspan="3" colspan="2"></td><td rowspan="3">Open</td><td rowspan="3" colspan="4"></td><td rowspan="3">20% Open</td></tr>
<tr><td>21:00-22:00</td></tr>
<tr><td>22:00-24:00</td><td>Open</td><td>20 % Open</td></tr>
</table>

Table Key

Building elements	
Int Op	Internal openings (kitchen to airshaft)
Int Do	Internal doors
Ext Op	External openings (patio doors)
E+W WC Op	East and West facing wind-catcher openings
S+N WC Op	South and North facing wind-catcher openings
Mid Lv	Middle louvres
Top& B Lv	Top and bottom louvres
Environmental properties	
To	Ambient temperature (°C)
Ti	Indoor air temperature (°C)
CO_2	Carbon dioxide (ppm)
Wd	Wind direction (m/s)
Dr	Direct solar radiation (W/m²)

Table 3. Sensible heat gain of the internal gains (after Androutsopoulos et al. 2012).

Source	Heat Gains	
Occupants	80 W/person	
Lighting	6.4 W/m²	200 lm/m² at a measuring level of 800 mm
Equipment	4 W/m²	average coefficient of operation 0.75

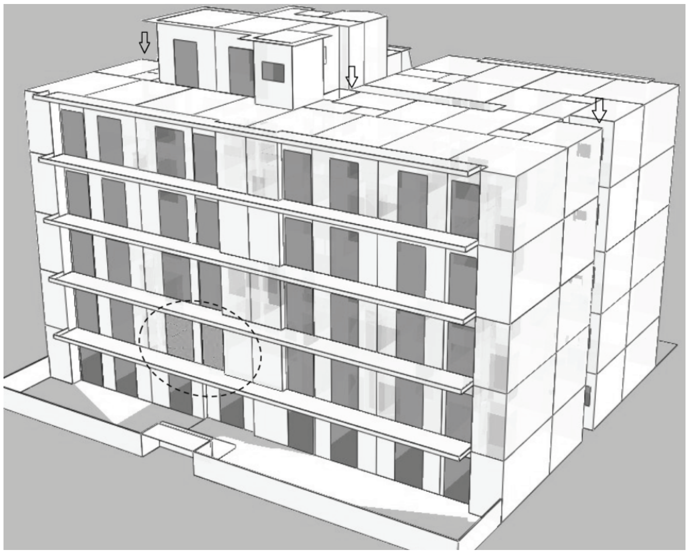


Figure 1. A 3D view of the IES VE model of the building, showing the selected apartment (two-patio door, light grey) and the location of the three airshaft

Figure 2. Floor layout of the case-study apartment (nts, dimensions in metres)

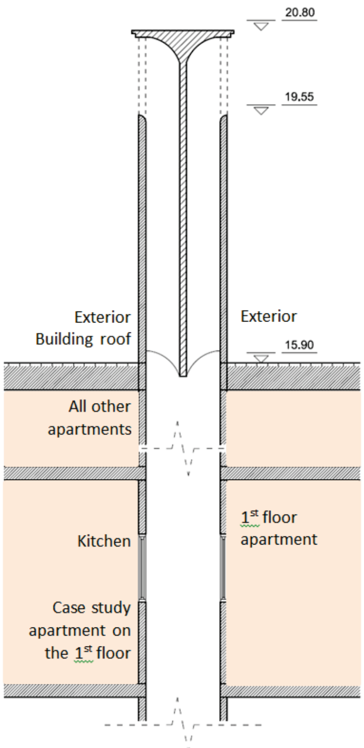


Figure 3. Schematic diagram of the wind-catcher design. Section showing the length of the partitions (meters).

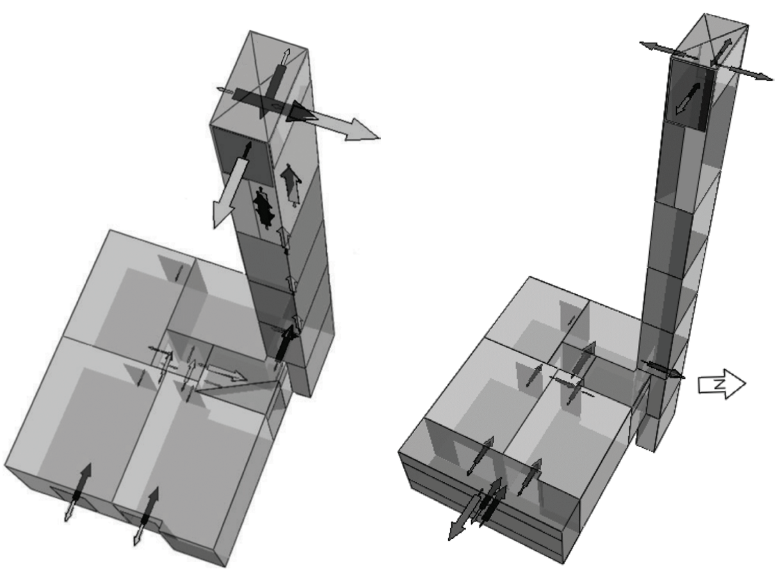


Figure 4. 3D-models of the [InOp] (left) and the [DF & WC] (right) strategies.

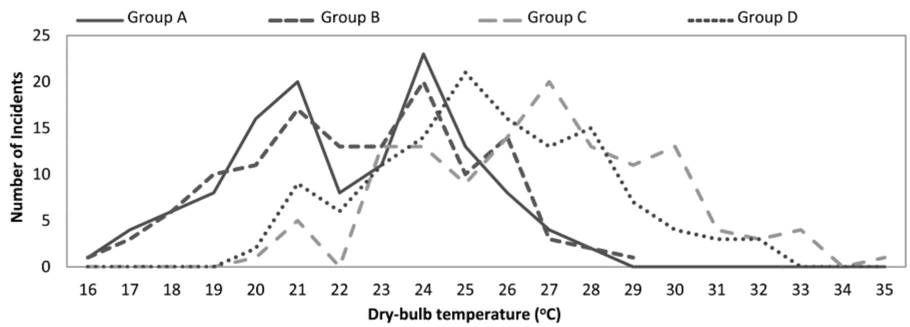


Figure 5. Average dry-bulb temperatures per 6-hour daily group (1am-6am, 6pm-12am, 12pm-6pm and 6pm-12am) for the cooling period (^oC).

Figure 6. Plan of the site showing building heights in metres and the case-study building centred (nts).

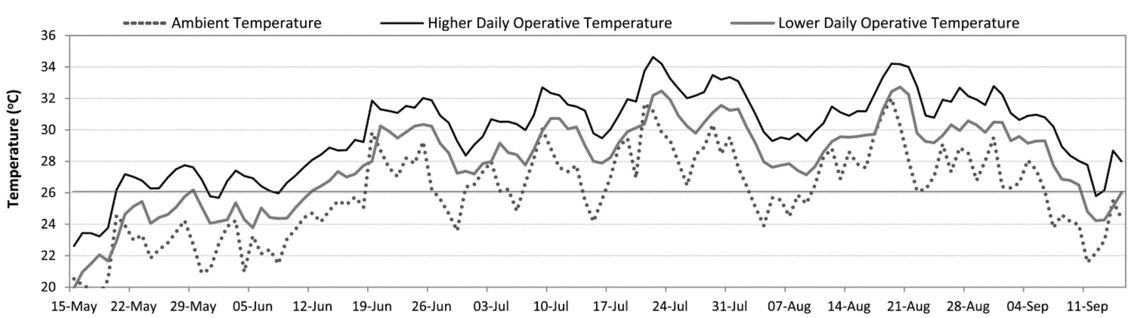


Figure 7. Average higher and lower daily operative temperatures for the apartmentd studied and ambient temperatures (^oC) for the cooling period, [base-case] strategy.

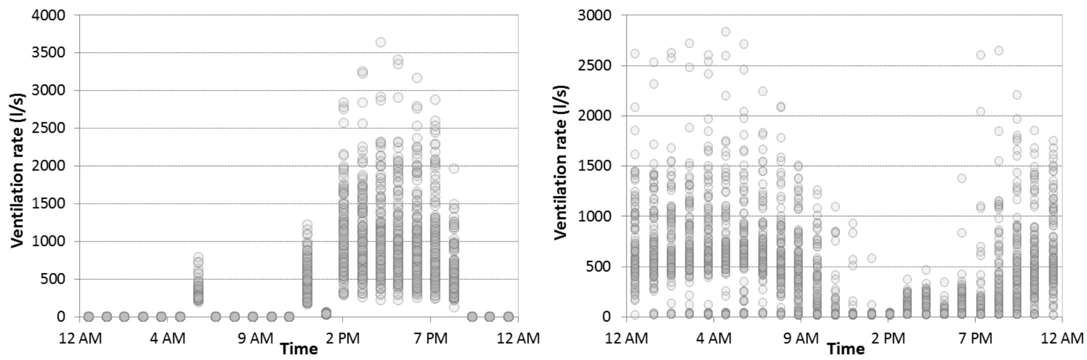


Figure 8. Daily distribution of ventilation rates for the cooling period, [base-case] (left) and [DV & NV] (right) strategies.

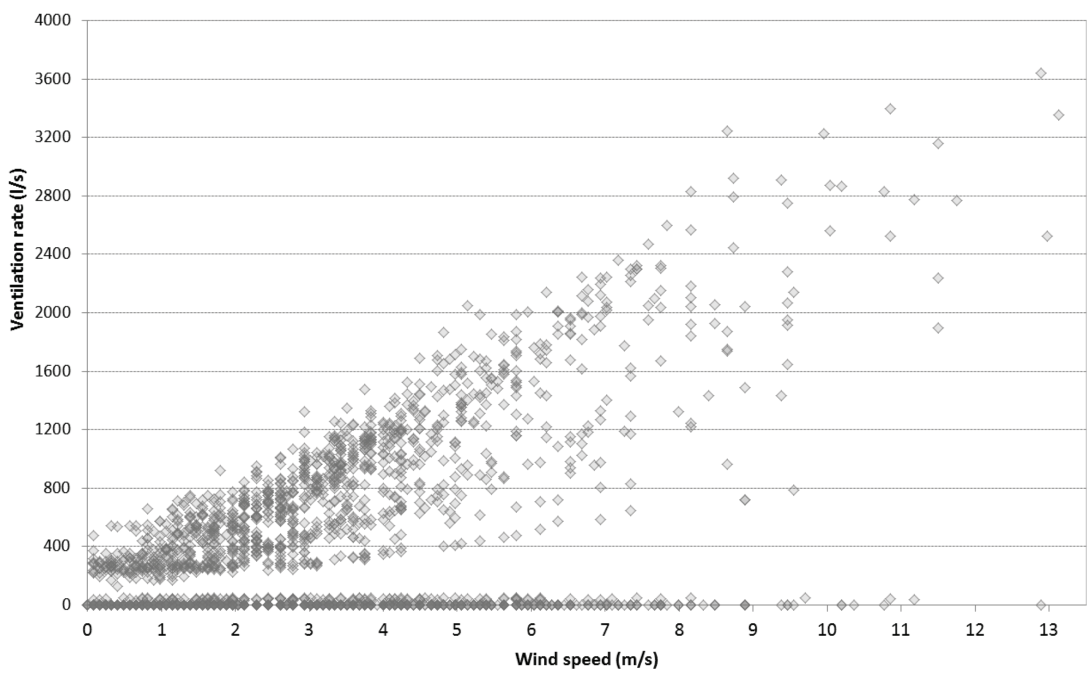


Figure 9. Wind speed and ventilation rates relationship, [base-case] strategy, showing ventilation rates close to zero when the openings remained mostly closed and a correlation between wind-speed and ventilation rates for higher wind speed values.

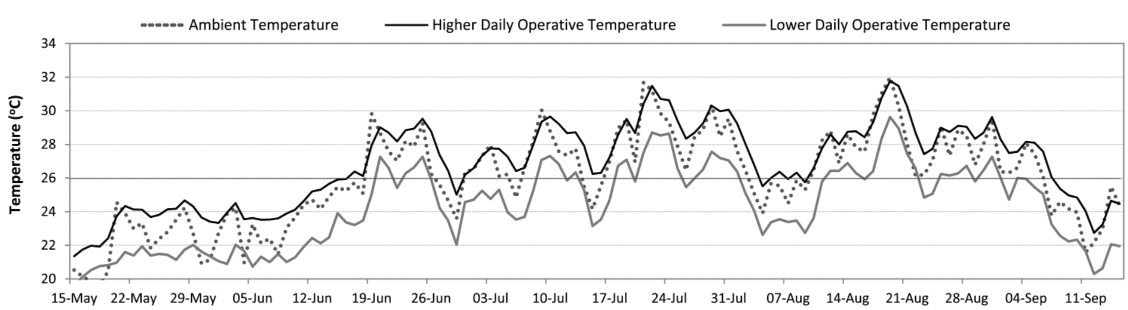


Figure 10. Average daily operative temperatures (high/low) and ambient temperatures (^oC) for the cooling period, [DV & NV] strategy.

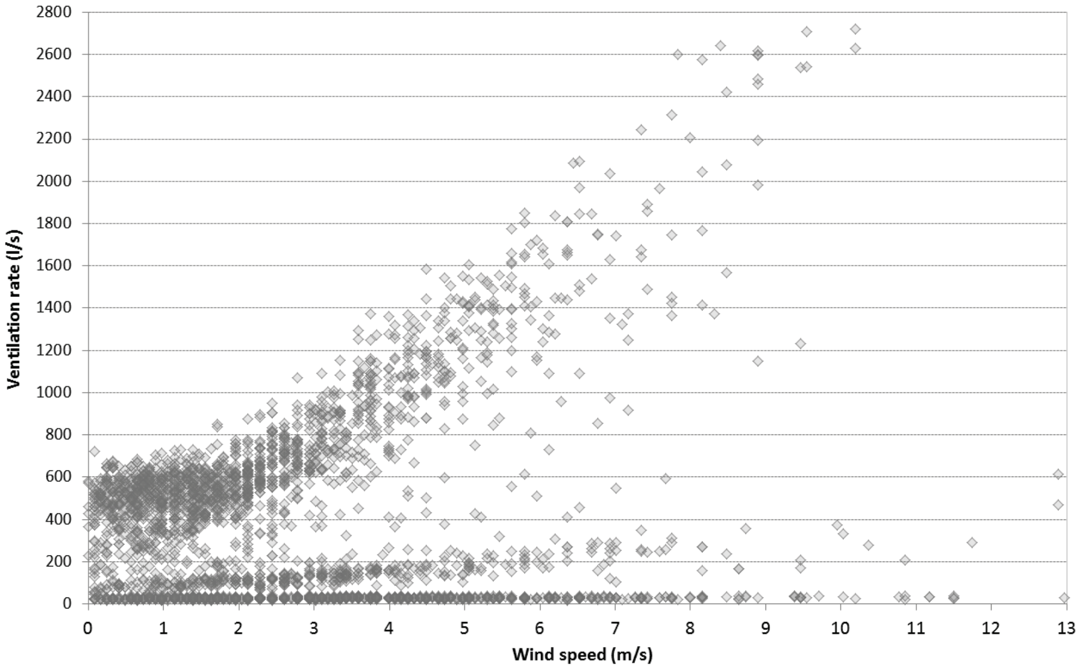


Figure 11. Wind speed and ventilation rates relationship, [DV & NV] strategy. Averaged values for the cooling period of the case study apartment.

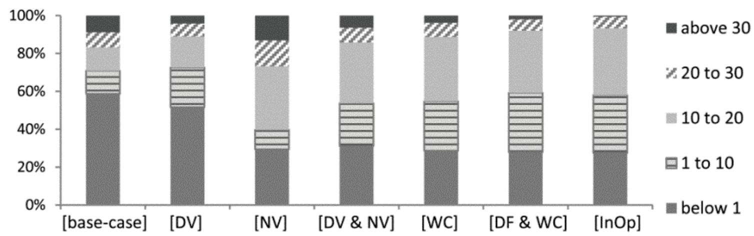
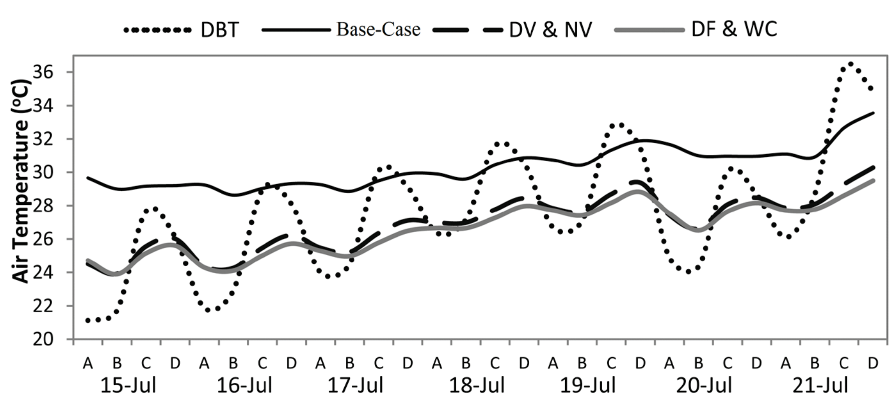


Figure 12. Predicted air change rate distribution (5) at five ranges (in ach^{-1}) during the cooling period, for seven natural ventilation strategies.



ach^{-1}	Base-case	Dv & NV	DF & WC
A	0	16	17
B	2	12	13
C	28	1	1
D	25	7	7

Figure 13. Average per 6-hour group predicted operative temperatures of three natural ventilation strategies and DBTs during an example 7-day period, and averaged air changes per hour for each 6-hour group and strategy for the same period.

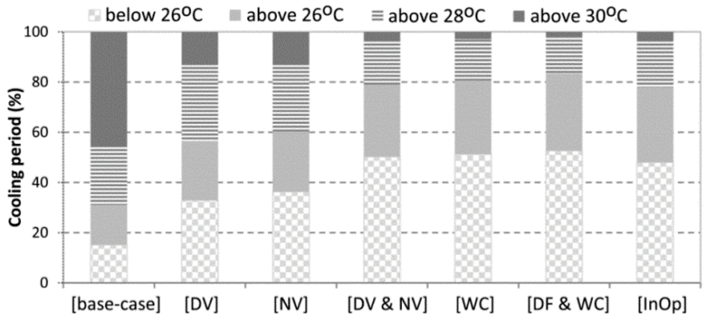


Figure 14. Percentage of hours exceeding four thresholds during the cooling period.

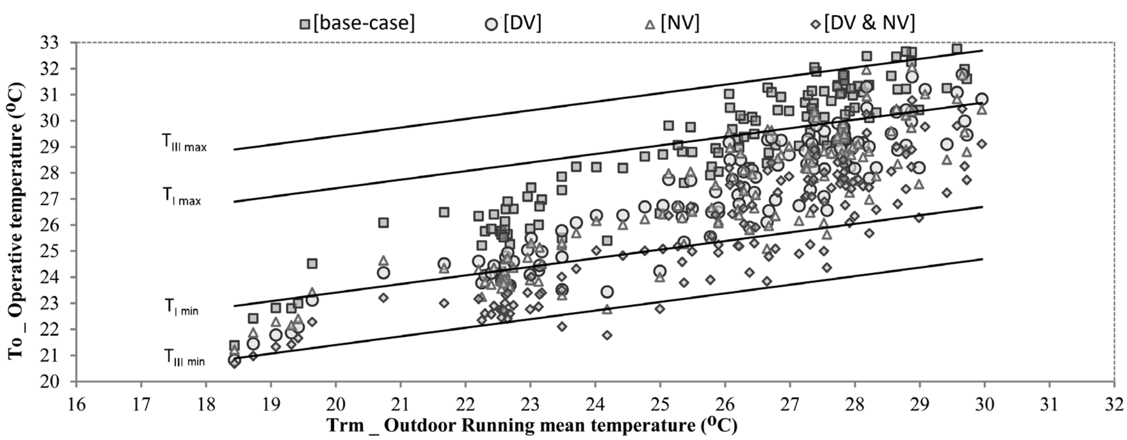


Figure 15. Relationship between outdoor running mean and operative temperatures for the [base-case], [DV], [NV] and [DV & NV] strategies.

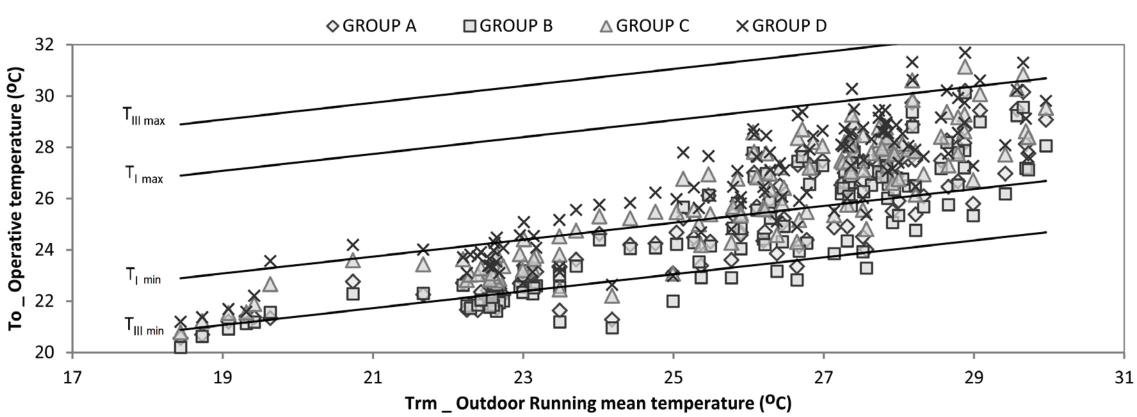


Figure 16. Relationship between outdoor running mean and average operative temperatures for the [DV & NV] ventilation strategy, showing the maximum and minimum acceptable levels according to BSEN15251 (Group A: midnight-6am, Group B: 6am-noon, Group C:noon-6pm, Group D: 6pm-midnight).

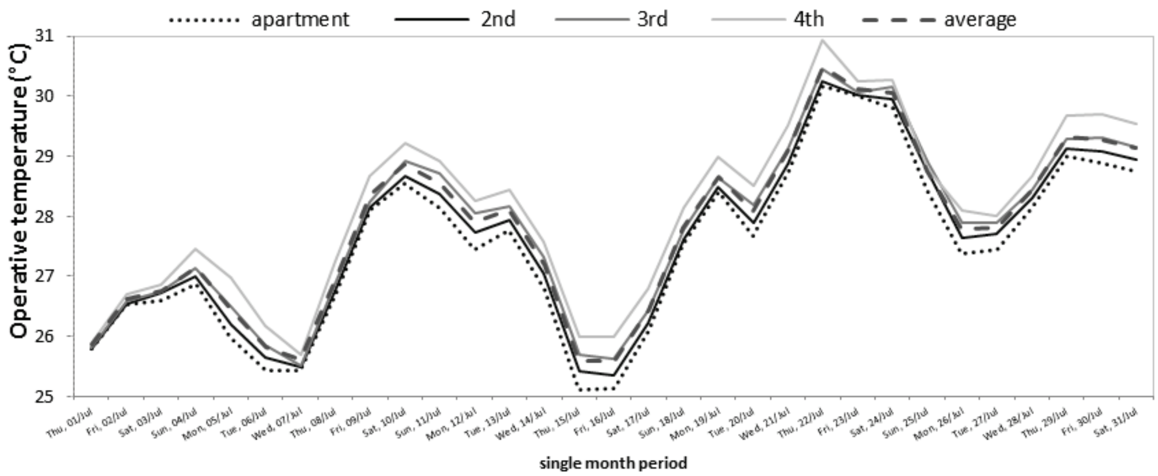


Figure 17. Predicted operative temperatures for the apartment studied, the three apartments above, and the average of the eight apartments connected to the wind-catcher for a period of a month.

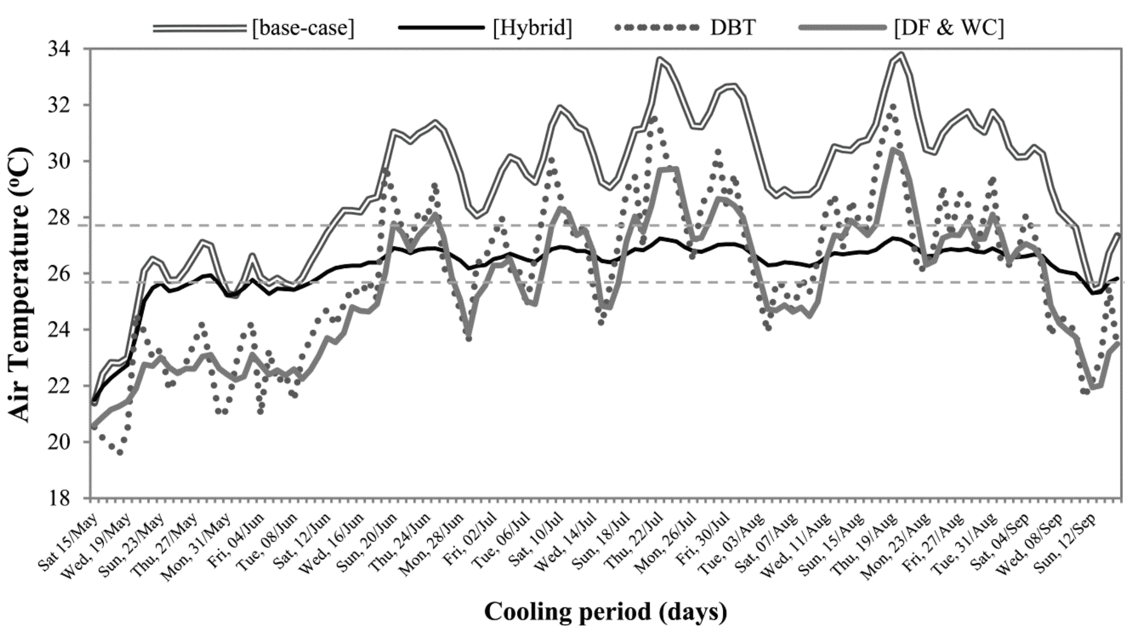


Figure 18. Predicted daily operative temperatures for mechanical and natural ventilation strategies during the cooling period.