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Developing the Prototype of the Climate-Responsive Building Form: Merging Passive and Active Space Cooling Strategies

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Abstract

This article presents the considered capabilities to improve space cooling energy efficiency in the Mediterranean climate ambience by merging and optimizing selected natural ventilative techniques. The first part of the analysis defines a set of control strategies with a multilevel design approach based on a specific configuration of cross ventilation and fan-assisted advanced natural ventilation (ANV) centre-in, edge-out (C-E) form. The objective is to take advantage of principally lower nocturnal temperature ranges and to reflect such a potential on the reduction of the day-time cooling energy loads. The second part of this paper examines the integration of defined control strategies into a climate responsive building form of a mid-rise office-type building positioned in the city of Barcelona (Spain). In the last part of the study, the building model is exposed to present weather conditions in the building performance simulation environment while the general control and adjustments of established indoor airflow patterns are done by computational fluid dynamics (CFD) analyses. Performed simulations achieves the yearly reduction of space cooling energy loads by 65.3%. The night-time operation takes the large part of 50.5%, using lower nocturnal outdoor temperatures due to being less affected by current climate change effects. Based on the use of the renewable energy source, the designed climate responsive building form, named D-Fence model, represents the bioclimatic approach with the examined capabilities in cutting cooling energy demands in the Mediterranean climate ambiance.

Keywords: Natural ventilation; passive and active cooling; hybrid mode; climate responsive building

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Desarrollo del Prototipo de la Forma del Edificio Sensible al Clima: Fusión de Estrategias de Refrigeración Pasivas y Activas

Resumen

Este artículo presenta las capacidades consideradas para mejorar la eficiencia energética de la refrigeración de espacios en el ambiente de clima mediterráneo mediante la fusión y optimización de técnicas de ventilación natural seleccionadas. La primera parte del análisis define un conjunto de estrategias de control con un enfoque de diseño multinivel basado en una configuración específica de ventilación cruzada y ventilación natural avanzada asistida por ventiladores (ANV) en forma de centro hacia adentro, borde hacia afuera (C-E). El objetivo es aprovechar los rangos de temperatura nocturna principalmente más bajos y reflejar dicho potencial en la reducción de las cargas de energía de enfriamiento durante el día. La segunda parte de este documento examina la integración de estrategias de control definidas en una forma de edificio sensible al clima de un edificio de oficinas de mediana altura ubicado en la ciudad de Barcelona (España). En la última parte del estudio, el modelo del edificio se expone a las condiciones climáticas presentes en el entorno de simulación del rendimiento del edificio, mientras que el control general y los ajustes de los patrones de flujo de aire interior establecidos se realizan mediante análisis de dinámica de fluidos computacional (CFD). Las simulaciones realizadas logran la reducción anual de las cargas de energía de refrigeración de espacios en un 65,3 %. La operación nocturna se lleva la mayor parte del 50,5%, utilizando temperaturas exteriores nocturnas más bajas al estar menos afectado por los efectos del cambio climático actual. Basado en el uso de la fuente de energía renovable, la forma de construcción sensible al clima diseñada, denominada modelo D-Fence, representa el enfoque bioclimático con las capacidades examinadas para reducir la demanda de energía de enfriamiento en el ambiente climático mediterráneo.

Palabras clave: Ventilación natural; refrigeración pasiva y activa; modo híbrido; edificio sensible al clima

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1. Introduction

Building techniques based on natural ventilation (NV) played a vital role in the Mediterranean vernacular architecture. During the last decades, a group of fundamental ventilative strategies is reconsidered in the contemporary building design as an energy efficient approach with a potential to reduce building cooling energy loads to a certain level. Contrary to buildings enclosed with common mechanical ventilation—considered as the *sealed*-type and disconnected from its surroundings, another advantages of NV systems are provided healthier indoor environments with an established level of human thermal comfort indoors conditions.

On this basis, such formed microclimate ambiances can be further exploited and explored, regarded as a climate responsive or *breathing architecture* (Stavridou, 2015). This approach towards sustainable design takes a part in a general tendency for the *recovery of natural environments* (Short, 2018).

This study is focused on the Mediterranean coastal region of Catalonia, where weather data recordings indicate a disproportion between the rise of average night and day temperatures in the last 70 years, reflected in the ratio of 1:1.6 (Servei Meteorològic de Catalunya—METEOCAT, 2019a). In that respect, the objective of this research is to explore possibilities to increase climate responsive level, i.e., correlating from one side traditional or basic NV principles in an adequate building form, and on the other side, a range of advanced control strategies. The general aim is to take advantage of principally lower ranges of regional night-time air temperatures that are less affected with current climate anomalies. Thereby, the design concept is considered as an *open* natural ventilative system—directly exposed to favourable night-time weather conditions. On the other side, the day-time configuration is defined as a *closed* system, accordingly, with an established higher level of climate resilience.

2. Regional climate configuration

For this study is selected one of the most populated areas on the Western Mediterranean coast—the geographical location of the city of Barcelona, the capital of the autonomous community Catalonia of Spain. According to Köppen-Geiger world climate classification and published high resolution map and data (Kottek *et al*., 2006; Climate Change & Infectious Diseases Group, 2017), Barcelona is located a common climate zone along the Northern Mediterranean defined as the hot summer Mediterranean climate or *Csa* type. This region is characterized with mild weather conditions with yearly average air temperatures in the range between 14.1 °C and 20.9 °C (Table 1).

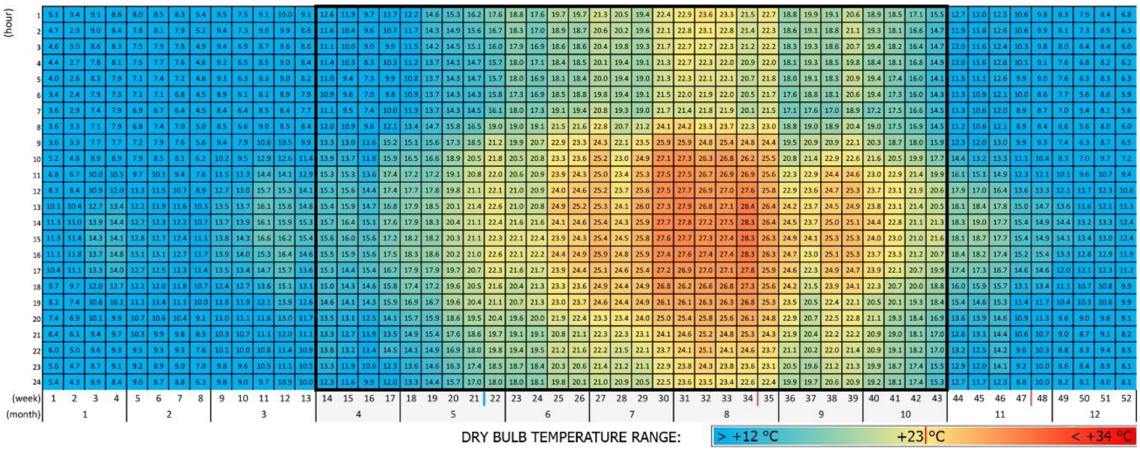
Table 1. **Average yearly and seasonal climate data for the city of Barcelona, Catalonia, Spain (Servei Meteorològic de Catalunya, 2019b)**

Climate zone	Meters above sea level	Dry bulb temperature [°C]			Relative humidity [%]	Wind speed [m/s]				Wind direction [°]			
		low	average	high		Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Csa	6	14.1	17.4	20.9	70	3.2	3.1	3.2	3.9	175	176	173	247

Source: by author, 2020.

Regarding average hourly dry bulb temperatures (DBT) (NREL, 2019) sorted by each week during a year, the commonly considered building cooling period is May–October with the highest ranges of outdoor temperatures principally between the second half of July and the end of August (Figure 1). On the other side, this Mediterranean climate area is marked with typically lower temperatures during late nights and early mornings, apart from broadly higher DBT throughout August.

Figure 1. **Average dry bulb temperatures (DBT) in Barcelona; *x-axis*: weeks/months, *y-axis*: hours; considered regional space cooling period May–October (outlined)**



(hour) \ (week)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	5.1	3.4	9.1	8.6	8.0	8.5	8.3	5.4	9.5	7.5	9.1	10.0	9.1	12.6	11.9	9.7	11.7	12.2	14.6	15.3	16.2	17.6	18.8	17.6	19.7	19.7
2	4.7	2.9	9.0	8.4	7.8	8.1	7.9	5.2	9.4	7.3	9.0	9.9	8.6	11.6	10.4	9.6	10.7	11.7	14.3	14.9	15.6	16.7	18.3	17.0	18.9	18.7
3	4.6	3.0	8.6	8.3	7.5	7.9	7.8	4.9	9.4	6.9	8.7	9.6	8.6	11.1	10.0	9.0	9.9	11.5	14.2	14.5	15.1	16.0	17.9	16.9	18.6	18.6
4	4.4	2.7	7.8	8.1	7.5	7.7	7.6	4.6	9.2	6.5	8.5	9.0	8.4	11.4	10.3	8.3	10.3	11.2	13.7	14.1	14.7	15.7	18.0	17.1	18.4	18.5
5	4.0	2.6	8.3	7.9	7.1	7.4	7.2	4.6	9.1	6.3	8.3	9.0	8.2	11.0	9.4	7.3	9.9	10.8	13.7	14.3	14.7	15.7	18.0	16.9	18.1	18.4
6	3.4	2.4	7.9	7.3	7.1	7.1	6.8	4.5	8.9	6.1	8.1	8.9	7.9	10.9	9.6	7.0	9.8	10.9	13.7	14.3	14.3	15.8	17.3	16.9	18.5	18.8
7	3.6	2.9	7.4	7.9	6.9	6.7	6.4	4.5	8.4	6.4	8.5	8.4	7.7	11.1	9.5	7.4	10.0	11.3	13.7	14.3	14.5	16.1	18.0	17.3	19.1	19.4
8	3.6	3.3	7.1	7.9	6.8	7.4	7.0	5.0	8.5	6.6	9.0	8.5	8.4	12.0	10.9	9.6	12.1	13.4	14.7	15.8	16.5	19.0	19.0	19.1	21.5	21.6
9	3.6	3.3	7.7	7.7	7.2	7.9	7.6	5.6	9.4	7.9	10.6	10.5	9.9	13.3	13.0	11.6	15.2	15.1	15.6	17.3	18.5	21.2	19.9	20.7	22.9	23.3
10	5.2	4.8	8.9	8.9	7.9	8.5	8.1	6.2	10.2	9.5	12.9	12.6	11.4	13.9	13.7	11.8	15.9	16.5	16.6	18.9	20.5	21.8	20.5	20.8	23.3	23.6
11	6.8	6.7	10.0	10.5	9.7	10.1	9.4	7.6	11.5	11.3	14.4	14.1	12.9	15.3	15.3	13.6	17.4	17.2	17.2	19.1	20.8	22.0	20.6	20.9	23.9	24.3
12	8.3	8.4	10.9	12.0	11.3	11.5	10.7	8.9	12.7	13.0	15.7	15.3	14.1	15.3	15.6	14.4	17.4	17.7	17.8	19.8	21.1	22.1	21.0	20.9	24.0	24.6
13	10.1	10.4	12.7	13.4	12.2	11.9	11.6	10.3	13.5	13.7	16.1	15.6	14.8	15.4	15.9	14.7	16.8	17.9	18.5	20.1	21.4	22.6	21.0	20.8	24.9	25.2
14	11.3	11.0	13.9	14.4	12.7	12.3	12.2	10.7	13.7	13.9	16.1	15.9	15.3	15.7	16.4	15.1	17.6	17.9	18.3	20.4	21.1	22.4	21.6	21.6	24.1	24.6
15	11.3	11.4	14.3	14.1	12.8	12.7	12.4	11.1	13.8	14.3	16.6	16.2	15.4	15.6	16.0	15.6	17.2	18.2	18.2	20.3	21.1	22.3	22.1	22.4	23.9	24.3
16	11.1	11.8	13.7	14.8	13.1	13.1	12.7	11.7	13.9	14.0	15.3	16.4	14.6	15.5	15.9	15.6	17.5	18.3	18.6	20.2	21.0	22.6	22.1	22.2	24.4	24.9
17	10.4	11.1	13.3	14.0	12.7	12.5	12.3	11.4	13.5	13.4	14.7	15.7	13.6	15.3	14.4	15.4	16.7	17.9	17.9	19.7	20.7	22.3	21.6	21.7	23.9	24.4
18	9.7	9.7	12.0	12.7	12.1	12.0	11.8	10.7	12.4	12.7	13.6	15.1	13.1	15.0	14.3	14.6	15.8	17.4	17.2	19.6	20.5	21.6	20.4	21.3	23.3	23.6
19	8.2	7.4	10.6	10.1	11.1	11.4	11.1	10.0	11.8	11.9	12.1	13.9	12.6	14.6	14.1	14.3	15.9	16.9	16.7	19.6	20.4	21.1	20.7	21.3	23.0	23.7
20	7.4	6.9	10.1	9.9	10.7	10.6	10.4	9.1	11.0	11.1	11.6	13.0	11.7	13.5	13.1	12.5	14.1	15.7	15.9	18.6	19.5	20.4	19.6	20.0	21.9	22.4
21	6.4	6.1	9.4	9.7	10.3	9.9	9.8	8.3	10.3	10.7	11.1	12.0	11.1	13.3	12.7	11.9	13.5	14.9	15.4	17.6	18.6	19.7	19.1	19.1	20.8	21.1
22	6.0	5.0	9.6	9.3	9.5	9.3	9.3	7.6	10.1	10.0	10.8	11.4	10.9	13.8	13.2	11.4	14.5	14.1	14.9	16.9	18.0	19.8	19.4	19.5	21.2	21.6
23	5.6	4.7	8.7	9.1	9.2	8.9	9.0	7.0	9.8	9.6	10.5	11.1	10.5	13.3	11.9	10.6	12.3	13.6	14.6	16.3	17.4	18.5	18.7	18.4	20.3	20.6
24	5.4	4.3	8.9	8.4	9.0	8.7	8.8	6.3	9.8	9.0	9.7	10.9	10.0	12.3	11.6	9.9	12.0	13.3	14.4	15.7	17.0	18.0	18.0	18.1	19.8	20.1
(month)	1				2				3					4				5					6			

(hour) \ (week)	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
1	21.3	20.5	19.4	22.4	22.9	23.6	23.3	21.5	22.7	18.8	19.9	19.1	20.6	18.9	18.5	17.1	15.5	12.7	12.0	12.5	10.6	9.8	8.3	7.9	8.4	6.8
2	20.6	20.2	19.6	22.1	22.8	23.1	22.8	21.4	22.3	18.6	19.1	18.8	21.1	19.3	18.1	16.6	14.7	11.9	11.8	12.6	10.6	9.9	8.1	7.3	8.9	6.3
3	20.4	19.8	19.3	21.7	22.7	22.7	22.3	21.2	22.2	18.3	19.3	18.6	20.7	19.4	18.2	16.4	14.7	12.0	11.6	12.4	10.3	9.8	8.0	6.4	8.4	6.0
4	20.1	19.4	19.1	21.3	22.7	22.3	22.0	20.9	22.0	18.1	19.3	18.5	19.8	18.4	18.1	16.8	14.9	12.0	11.6	12.6	10.1	9.1	7.6	6.8	8.2	6.2
5	20.0	19.4	19.0	21.3	22.3	22.1	22.1	20.7	21.8	18.0	19.1	18.3	20.9	19.4	17.4	16.0	14.1	11.5	11.1	12.6	9.9	9.0	7.6	6.3	8.3	6.3
6	19.8	19.4	19.1	21.5	22.0	21.9	22.0	20.5	21.7	17.6	18.8	18.1	20.6	19.4	17.3	16.0	14.3	11.3	10.9	12.1	10.0	8.6	7.7	5.6	8.6	5.9
7	20.8	19.3	19.0	21.7	21.4	21.8	21.9	20.1	21.5	17.1	17.6	17.0	18.9	17.2	17.5	16.6	14.5	11.3	10.6	12.0	8.9	8.7	7.0	5.4	8.1	5.6
8	22.8	20.7	21.2	24.1	24.2	23.3	23.7	22.3	23.0	18.8	19.0	18.9	20.4	19.0	17.5	16.9	14.5	11.2	10.6	12.1	8.9	8.4	6.6	5.6	8.0	6.0
9	24.3	22.1	23.5	25.9	25.9	24.8	25.4	24.8	24.4	19.5	20.9	20.9	22.1	20.3	18.7	18.0	15.9	12.3	12.0	13.0	9.9	9.3	7.4	6.3	8.7	6.5
10	25.2	23.0	24.9	27.1	27.3	26.3	26.8	26.2	25.5	20.8	21.4	22.9	22.6	21.6	20.5	19.9	17.7	14.4	13.2	13.3	11.1	10.4	8.3	7.0	9.7	7.2
11	25.0	23.4	25.3	27.5	27.5	26.7	26.9	26.9	25.6	22.3	22.9	24.4	24.6	23.0	22.9	21.4	19.9	16.1	15.1	14.9	12.3	12.1	10.1	9.6	10.7	9.4
12	25.2	23.7	25.6	27.5	27.7	26.9	27.0	27.6	25.8	22.9	23.6	24.7	25.3	23.7	23.1	21.9	20.6	17.9	17.0	16.4	13.6	13.3	12.1	11.7	12.3	10.6
13	25.3	24.1	26.0	27.3	27.9	26.8	27.1	28.4	26.4	24.2	23.7	24.5	24.9	23.8	23.1	21.4	20.5	18.1	18.4	17.8	15.0	14.7	13.6	11.6	12.1	11.3
14	25.4	24.3	25.9	27.7	27.8	27.2	27.5	28.3	26.4	24.5	23.7	25.0	25.1	24.4	22.8	21.1	21.3	18.3	19.0	17.7	15.4	14.9	14.4	13.2	13.3	12.4
15	25.4	24.5	25.8	27.6	27.7	27.3	27.4	28.3	26.3	24.9	24.1	25.3	25.3	24.0	23.0	21.0	21.6	18.1	18.7	17.7	15.4	14.9	14.1	13.4	13.0	12.4
16	25.9	24.8	25.9	27.4	27.6	27.4	27.4	28.3	26.3	24.7	23.0	25.1	25.3	23.7	23.3	21.2	20.7	18.4	18.2	17.4	15.2	15.4	13.3	12.8	12.9	11.9
17	25.1	24.6	25.4	27.2	26.9	27.0	27.1	27.8	25.9	24.6	22.3	24.9	24.7	23.9	22.1	20.7	19.9	17.4	17.3	16.7	14.6	14.6	12.0	12.1	12.3	11.2
18	24.9	24.4	24.9	26.8	26.2	26.6	26.8	27.3	25.6	24.2	21.5	23.9	24.1	22.3	20.7	20.0	18.8	16.0	15.9	15.7	13.1	13.4	11.1	10.7	10.8	9.9
19	24.6	24.4	24.9	26.1	26.1	26.3	26.3	26.8	25.3	23.5	20.5	22.4	22.1	20.5	20.1	19.3	18.4	15.4	14.6	15.3	11.4	11.7	10.4	10.3	10.6	9.9
20	23.3	23.4	24.0	25.0	25.4	25.8	25.6	26.1	24.8	22.9	20.7	22.5	22.8	21.1	19.3	18.4	16.9	13.6	13.9	14.6	10.9	11.3	9.6	9.0	9.6	9.1
21	22.3	22.3	23.1	24.1	24.6	25.2	24.8	25.3	24.3	21.9	20.4	22.2	22.2	20.9	19.0	18.1	17.0	12.6	13.1	14.4	10.6	10.7	9.0	8.7	9.1	8.2
22	22.2	21.5	22.1	23.7	24.1	25.1	24.1	24.6	23.7	21.1	20.2	22.0	21.4	20.9	19.1	18.2	17.0	13.2	12.5	14.2	9.6	10.3	8.8	8.3	9.4	8.5
23	21.4	21.2	21.1	22.9	23.8	24.3	23.8	23.6	23.1	20.5	19.6	21.2	21.3	19.9	18.7	17.4	15.5	12.9	12.0	14.1	9.2	10.0	8.6	8.4	8.9	8.1
24	21.0	20.9	20.5	22.5	23.6	23.5	23.4	22.6	22.4	19.9	19.7	20.6	20.9	19.2	18.1	17.4	15.3	12.7	11.7	12.3	8.8	10.0	8.2	8.1	8.0	8.1
(month)	7				8					9				10				11					12			

Source: weather dataset (National Renewable Energy Laboratory—NREL, 2019); arranged by author, 2020, 2022.

3. State-of-the-art

The Mediterranean region is the subject of a transversal line of contemporary studies and evaluations of climatic potential for NV. From a global scale, Chen *et al.* (2017) established *NV hour* as an indicator for natural ventilative potential, while Chiesa and Grosso (2015, 2017), among two conducted analyses, defined *cooling degree-hour (CDH)*. Causone (2016) developed the methodology and the index called *climate potential for natural ventilation (CPNV)* for calculating a hypothetical availability of NV, both for ventilation and cooling purposes. On a building level, a series of different type of structures were evaluated through case studies—from a residential-type building located in Valencia, done by Mora-Pérez *et al.* (2016), across analyses for an office-type building conducted by Pesic *et al.* (2018a, 2018b), up to an environment of vernacular architecture at the opposite side of the Mediterranean Basin, in Cyprus, carried-out by Michael *et al* (2017).

The aspect of adaptability to estimated climate change effects has been recently analysed by Shen *et al.* (2020) as a case study in Rome, while Moghtadernejad *et al.* (2020) presented a line of design strategies for high-performance facades facing estimated climate change threats. In the same domain of building envelopes Bonato *et al.* (2020) developed a model of façade low-consumption ventilation as an autonomous system, reducing in that way cooling energy loads. Another line of very recent studies explored new tendencies in energy management in buildings, where Sánchez Ramos *et al.* (2019) demonstrated that buildings could act as *active elements*—combining selected control strategies and thermal mass properties in locations across Spain, while Mhuireach *et al.* (2020) analysed the integration of *night ventilation of mass* approach in mixed-mode systems.

Soon, a certain level of energy poverty could be increased along the decarbonisation route proportionally with a rise of energy prices. These aspects could induce a large-scale impact on a built environment and on a general managing policy of remaining energy sources, affecting in that way complexly interrelated sector (Santamouris, 2019). Considering these facts and if no adequate preventive measures are taken on a large scale, the EU could suffer a level of high physical and economic impacts by the end of the 21st century (Ciscar;, J. C *et al.*, 2018). The building sector is broadly presumed to play an important part in the current energy transition regarding the reduction of overall energy demands (Intergovernmental Panel on Climate Change, 2015), where office-type buildings are evaluated as the second largest energy consumer in non-residential group (EU, 2016).

In the field of the EU's overall building sector, it is still difficult to identify accurately cooling energy demands on a large scale due to a complex character of interweaving building systems and equipment (JRC, 2012).

However, looking at cooling energy demands by each EU's member state, and zoning on regional climate configurations, the Southern Europe is the most exposed in that terms, where Spain has among the highest cooling energy loads in the EU's building service sector (EU, 2016; Jakubcionis and Carlsson, 2018). Parallel with overall tendencies for an improvement of the energy efficiency in buildings, another benefit from a local point of view, is that buildings with incorporated low-energy strategies are certainly more valued on the market than buildings without (López-Jiménez *et al.*, 2016). Contemporary large scale and urban design processes should also incorporate specific patterns of behaviour of citizens and their mobility factors—as components that prove to be more important than particular improvements of building energy performance (Martyniuk-Pęczek, J. *et al.,* 2022). In addition, such a multidisciplinary approach could expand as well to the level of *citizen initiatives,* seen as innovative practices at different levels of today's society (Berigüete, F. *et al.,* 2022).

4. Merging ventilative techniques

The objective of this study is to take advantage of corresponding NV strategies, CV and ANV principles, for the following series of assessments incorporating them into an adequate new building form that will be experimentally evaluated through a series of performed BPS. The purpose is to make the most in the aspect of CV and ANV favourable performances and to integrate both techniques into a single operative ventilative system, regarded primarily as a more climate *responsive* or climate *sensitive* building form. In that respect, a spatial organization should be adequately formed considering airflow patterns for each of these techniques, for the purpose to generate efficiently corresponding types of air circulations for both techniques—CV and ANV. Key-issues of CV and ANV techniques are displayed as a comparative overview of advantages and disadvantages (Table 2).

Table 2. **Comparative overview of key-aspects between cross ventilation (CV) and advanced natural ventilation (ANV) space cooling strategies**

Key-aspect of design strategy	Cross ventilation (CV)	Advanced natural ventilation (ANV)
Principal generating force	wind	thermal buoyancy
Façade type	open	sealed
Level of exposure to outdoor conditions (weather, pollution, etc.)	high	low
Fresh air delivery method	directly via window	indirectly via atrium
Indoor zone airflow pattern	simple	complex
Main air circulation direction	window-to-window	air-shaft-to-chimney
Building floor-type (footprint)	narrow	mid-narrow/deep

Source: by author, 2020.

An existing potential for merging ANV and CV strategies into a more complex operative system, and in that respect, a new building model is founded on the following list of design premises:

- Merging two principal ventilative techniques: ANV and CV.
- Merging two types of floor plans—for ANV is adequate the *deep-plan* floor configuration, and CV technique is based on *narrow-plan* shapes.
- Combining two examined techniques into one system implies merging two typical operation schedules into one continuous operation period—more specifically, mixing day- and night-time operations through different cycles, but continuously ventilating same building enclosure—stated also as: *same space-different times* principle.

- ANV system can be additionally supported with compatible assisted techniques, forming in that manner a complex ventilative form. From one side, ANV is already defined as a *mixed-mode change-over* type of ventilation, and in this scenario, ANV is additionally supported with exhaust fans. In those terms the system is defined as: *day-time fan-assisted mixed-mode change-over advanced natural ventilation (ANV)*—seen as a *hybrid* ventilative form.

Considering previously listed premises and related possibilities, the new formed ventilative cooling system can be defined considering the following aspects (Table 3):

Table 3. **Established ventilative system: comparative overview of key-properties**

Key-aspect of design strategy	Cross ventilation (CV)	Advanced natural ventilation (ANV)
Aimed operation time	night	day
Office floor type	narrow plan	deep plan
Airflow direction	window-to-window	air-shaft-to-chimney
Fresh air delivery method	directly via window	indirectly via airshaft
Limitation of generated air speeds	principally no (Nocturnal operation time)	yes (Diurnal occupation time)
Mixed-mode cooling system part	no	yes
↳ if yes: which type?	-	fan coil units (FCU)
↳ if yes: which mode?	-	change-over
Applied assisted technique(s)	no	yes
↳ if yes: which type?	-	exhaust fans (fan-assisted)
↳ if yes: continuous or periodic?	-	periodic
General categorization of established ventilative system:	**night-time passive cross ventilation (CV)**	**day-time fan-assisted mixed-mode change-over advanced natural ventilation (ANV)**

Source: by author, 2020.

Regarding the ventilated office zone, in addition to previously outlined features, the application of both here presented strategies also implies that will not be a collision between planned operation periods—regarded as two split ventilative cycles: diurnal and nocturnal.

In other words, CV is planned for operation during night-time when the office space is unoccupied and when are theoretically the highest cooling capacities related to local wind speeds from one side, and from the other, when are primarily lower nocturnal air temperatures ranges. At the same time, during an occupancy schedule, ANV provides diurnal comfort cooling interrelated with AC equipment, all seen as the *mixed-mode change-over* concept. In addition, ANV is supported with exhaust fans, forming in that way a specifically designed fan-assisted *hybrid* ventilative system.

5. Building model design

Summarizing previously defined principles (Table 3), the observed configuration of the office-type floor plan for the new building model is defined as follows:

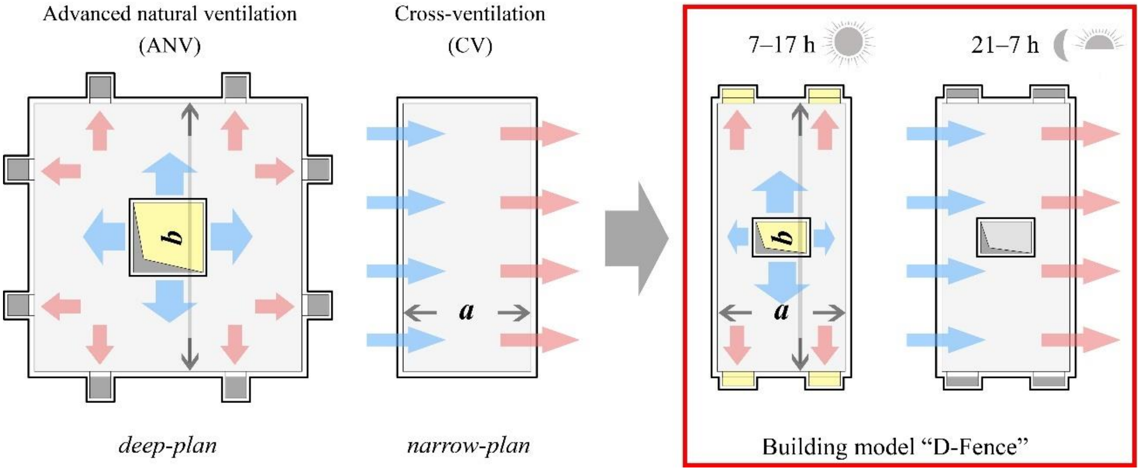
- Combination of deep- and narrow-plans results in a rectangular footprint in ratio 1:2.
- A centrally positioned atrium or an airshaft with a rectangular shape.
- Provided ribbon windows (linear windows) on opposite wider façades, aimed for a proper function of CV induced by dominant local winds.
- Provided exhaust shafts or chimneys on a building's perimeter for a proper ANV operation, positioned on narrow parallel façades—perpendicular to window-to-window air flow.

- Lower ceiling height as ANV airflow inside an office zone is fan-assisted, i.e., does not rely on additional thermal buoyancy-effect of high ceilings as it was the case in the concept of the basic building model with ANV (without fan assisted techniques).

ANV function is based on a configuration of centrally positioned atrium in a deep-plan floor type. The recommended maximal distance for establishing horizontal airflow paths is about 5 floor-to-ceiling heights (Irving *et al.*, 2005).

With respect to a theoretical building model volume named *The Fence* by Van Den Dobbelsteen *et al.* (2008), and regarding the objective of this study—raising the overall building's level of resilience against unfavourable climate effects—the outcome of this investigation is a developed climate responsive building prototype named *D-Fence* ®.

Figure 2. **Schematic concept of building model *D-Fence* with merged natural ventilation (NV) strategies: (a) advanced natural ventilation (ANV), centre-in, edge-out (C-E) form; (b) cross ventilation (CV); (c) combination of ANV and CV strategies, operative schedules: 7–17 h; (d) 21–7 h**



(a) (b) (c) (d)

Source: by author, 2020, 2022.

ANV system advanced natural ventilation (ANV), centre-in, edge-out (C-E) form forms a double atrium-to-chimney direction, shaping in that way a *deep-plan* floor type of roughly suggested 10 floor-to-ceiling heights (Lomas, 2007) (Figure 2a). On the other side, with respect to the main CV principle, the common building shape for conducting wind-driven NV is planned as a *narrow-plan* building where the window-to-window airflow direction is seen as the same single recommended building width, that is to say, no more than 5 floor-to-ceiling heights (Irving *et al.*, 2005) (Figure 2b).

Applying both these design concepts into a single building form, the new building concept examined for this part of research is defined as a combination of both these principles as it is presented in Figure 2c, d. From the point of CV approach, it is seen as a *narrow-plan* floor shape, while ANV direction of air circulation, perpendicular to CV airflow, forms the *deep-plan*, adequate for the atrium-to-chimney airflow direction.

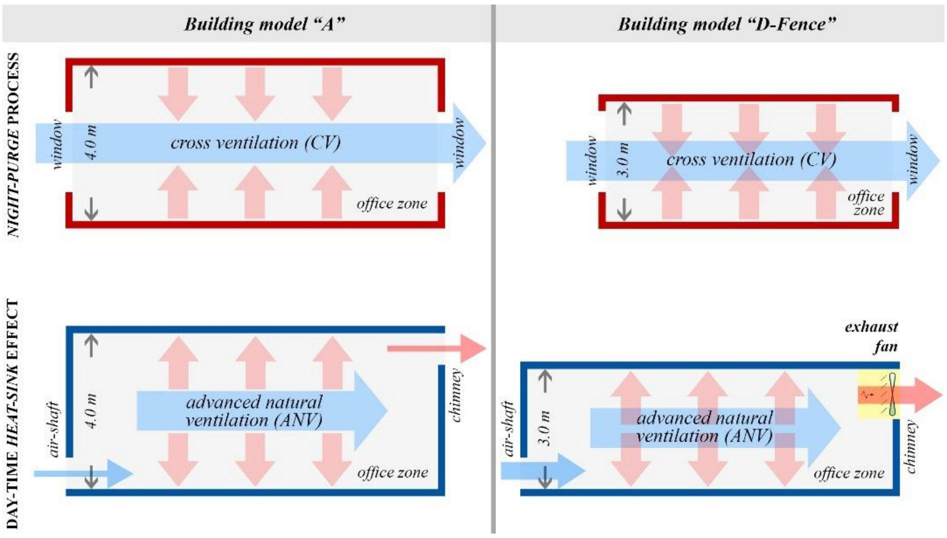
In order that CV principle could be adequately generated along an office zone, ribbon windows (linear windows) are positioned on wider parallel façades—forming the window-to-window direction of air circulation aimed for the night-time CV operation 21–7 h.

Perpendicularly to this established airflow pattern, the longer axis of the building plan is considered as direction for generating ANV-based airflow pattern, receiving in that manner the outdoor fresh air via a light-well or an airshaft, which is an architectural element whose size and configuration depend on the final building design concept and calculated ventilative capacities. Contrasting the previously defined night-time CV operation, ANV is conceived as a diurnal cooling system, operating 7–17 h.

It is important to underline that atrium or a light-well is an architectural element considered also for introducing the natural light, particularly regarding design concepts of office buildings in the perspective of deeper floor plans. However, with reference to the previously determined design premises, atrium is not a distributor of natural light since the building plan is narrow in this developed design concept. In that respect, an atrium or a centrally positioned roofed element is defined as an airshaft and its unique purpose in this specific building configuration is to conduct and deliver the fresh air into each of connected floors. In that respect, airshaft can be divided in order that each building floor could receive individually conducted fresh air, as one optional design possibility.

In this case, ANV is defined as a fan-assisted space cooling concept, and one of the advantages of a corresponding established design is that a ceiling height in the office zone can be reduced, comparing with a basic ANV system without the fan assistance.

Figure 3. **Schematic presentation: ceiling height and illustrated generated the *night-purge* and *heat-sink* effects—cross-sections: (a) basic ANV building model; (b) building model *D-Fence***



(a) (b)

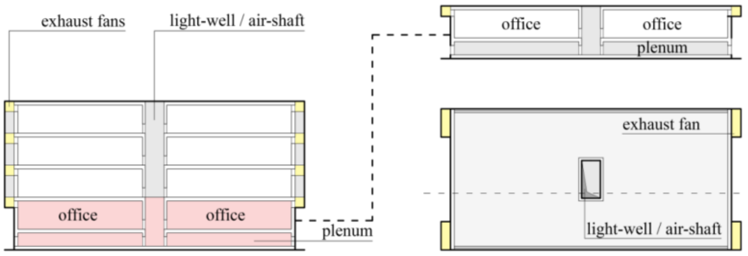
Source: by author, 2020, 2022.

Such new design method, based on the introduction of a lower ceiling height, raised following new design premises (Figure 3):

- Lower ceiling height induces a higher level of efficiency of dynamic heat storage as the distance between exposed high-thermal mass concrete slabs is reduced.
- Reduced floor volume implicates a lower level of cooling energy loads for AC system and accordingly, a higher level of energy efficiency for NV-based systems.
- More effective CV airflow in the window-to-window direction in relation to possible generated air velocities of the delivered fresh air through provided linear windows.
- More effective *flushing* process regarding the performance of dynamic heat storage.

As a result of these observed aspects, the floor-to-ceiling height is set at h = 3.0 m, principally lower than in basic ANV function based on the passive stack-effect as the air circulation line was established from a base of an atrium, through office spaces, up to exhaust roof-top outlets. This design method may prove to be beneficial in terms of final achieved energy efficient calculations regarding that day-time air circulations generated by fan-assisted ANV will be better thermally threated, or otherwise stated, effects of the diurnal *heat-sink* and night and early morning *flushing* cycles could have a higher level of efficiency during CV operations.

Figure 4. **Schematic presentation—concept of building model *D-Fence*—fan-assisted advanced atural ventilation (ANV): (a) longitudinal section; (b) extrapolated typical office floor with a ground-floor plenum: longitudinal section (above) and floor plan (below)**

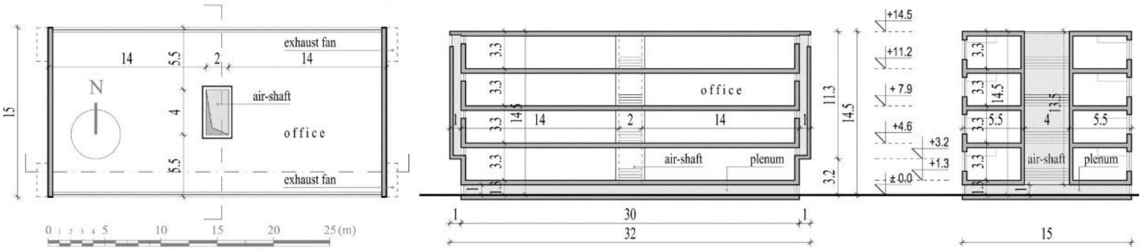


(a) (b)

Source: by author, 2020.

After a conducted series of preliminary designed shapes, the final building form for *DesignBuilder* computer software (DesignBuilder Software Ltd., 2019) BPS stays in the frame of research objectives as a mid-rise office building of 3 to 5 floors (Figure 4a). For a conducted series of analyses, the building model *D-Fence* is represented as one of office floors extrapolated from a hypothetical building—seen as a single, stand-alone model for *DesignBuilder*'s modelling environment (Figure 5a).

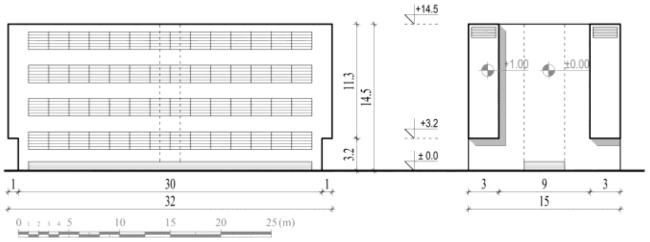
Figure 5. **Building model *D-Fence*: (a) floor plan, (b) longitudinal section; (c) transverse section**



(a) (b) (c)

Source: by author, 2020.

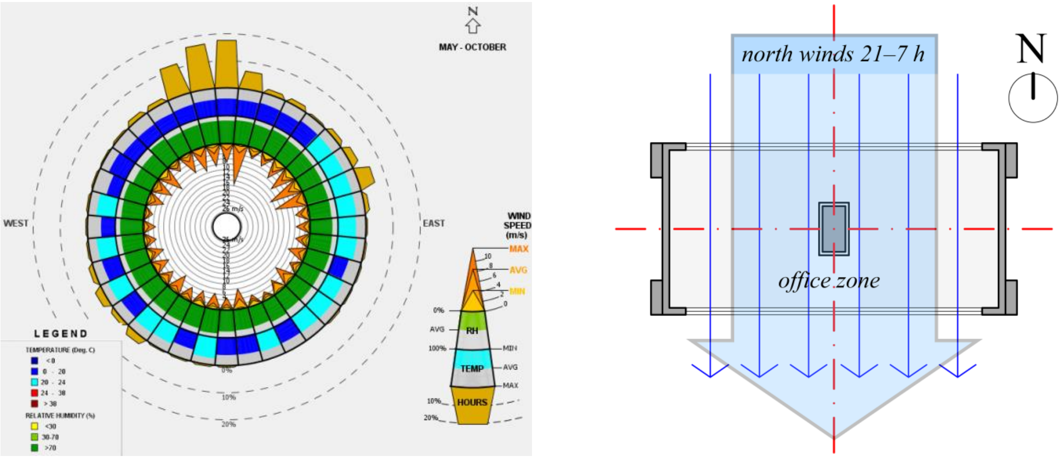
Figure 6. **Concept of building model *D-Fence*: (a) south façade elevation; (b) lateral facades**



(a) (b)

Source: by author, 2020

Figure 7. **Wind aspects in building design: (a) *wind wheel*—average wind parameters in Barcelona, May–October, 21–7 h; (b) orientation principle of building model—longer west-east axis perpendicular to dominant north winds**



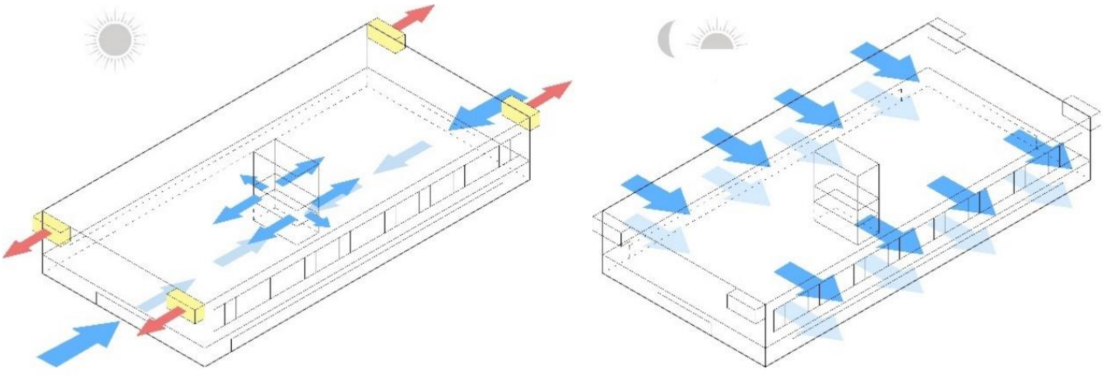
(a) (b)

Source: (a) data image generated by *Climate Consultant* [computer software] (UCLA, 2019); (b) by author, 2020.

Considered local winds are filtered from weather data for the specific 6-month period May–October, as a defined regional space cooling season, and additionally, only is filtered data when CV is operative, as the programmed time-frame 21–7 h (Figure 7a). According to these results, and in order to achieve theoretically the highest level of cooling efficiency by CV means, the building's model longer axis is oriented perpendicularly to dominant north winds in order to fully exploit the potential of wind-generated CV for the night-time and early morning *flushing* process (Figure 7b).

The floor organization is seen as an *open-plan* or *office landscape* type of work environment, in other words, without any partitions, and in the centre is positioned the rectangular airshaft 4.0 × 2.0 m (in relation to the calculated ventilative capacities according to the modelled isolated typical office floor in this case). Its primary function is to deliver vertically the drawn-in fresh air from the ground-floor plenum, as a part of an established ANV airflow pattern.

Figure 8. **Axonometric view: building model *D-Fence*—the hypothetical office floor-type with illustrated ventilative strategies: (a) day-time fan-assisted hybrid advanced natural ventilation (ANV) operation 7–17 h; (b) night-time and early morning cross ventilation (CV) operation 21–7 h**



(a) (b)

Source: by author, 2020.

The rectangular building shape represents a common segment of a linear or a narrow office building (Figure 8). Footprint dimensions are 30.0 × 15.0 m and the *plenum floor-to-ceiling height* (D_p) = 1.0 m. The central light-well is oriented perpendicularly to the longer building's east-west axis, in order that a transverse direction of CV airflow (directions of dominant north winds) is less obstructed during the *flushing* process. In this respect, parallel north and south façades are with provided *continuous ribbon* or *linear* windows with the aim to maximize the efficiency of CV.

Figure 9. ***DesignBuilder*'s 3D visualization of building model *D-Fence*—the office-type floor**

Source: *DesignBuilder* software (DesignBuilder Software Ltd, 2019); user interface adopted by author, 2020

The envelope of the building model is insulated according to one of Passivhaus recommendations (Passive House Institute. 2015, 2016) for the warm temperate climate zone, which includes the region of Catalonia's coastline. In that respect, the maximum considered values for the heat transfer coefficient (U) for the building's model envelope—façade walls and roof, is set at 0.3 W/(m² K) and for the vertical glazing is 1.05 W/(m² K).

To minimize the level of solar radiation, windowpanes are additionally improved with an exterior layer of coated glass with the high level of solar reflectance.

Along the south façade is applied a sun protection system in a form of mounted horizontal fixed *louvres*, while in the interior are installed high-reflective window blinds, programmed according to the indoor air temperature (Table 4).

Table 4. **Overview on a part of main parameters for *DesignBuilder*'s [computer software] (DesignBuilder Software Ltd, 2019) building model *D-Fence***

Footprint dimensions:	30.0 × 15.0 m	Heat transfer coefficient (U) [W/m² K]:		Exterior sunshade system:	louvres
Floor-to-ceiling height:	h = 3.0 m	Envelope (façade walls, roof):	0.3	Interior sunshade system:	blades
Plenum ceiling: height:	h = 1.0 m	Exterior glazing:	1.05	Exterior layer of glazing:	coated glass
Floor area (office):	405 m²	High-density concrete:	2,000 kg/m³	Infiltration rate:	0.3 ac/h

Source: by author, 2020.

All building's zones are defined with a constant 24 h infiltration rate at 0.3 ac/h. The building's high-thermal mass is concrete with *volumetric mass density* (ρ) = 2,000 kg/m³, considered as an entirely exposed material positioned in key-locations along NV airflow lines: in the plenum (ceiling and the ground-floor slabs, the interior layer of façade walls) and in the office zone (ceiling and floor slabs).

6. Control Strategies Setup

The HVAC system is designed in *DesignBuilder* software with activated advanced functions: *calculated natural ventilation* and *detailed HVAC*. The office open-plan zone is equipped with the common fan coil unit (FCU) system supplied with air-cooled chillers. Chillers' coefficient of performance (CoP) is set at 3.5 and the mechanical ventilation is delivering constantly 7–17 h the minimum rate of fresh air set at 10 l/person (Table 5).

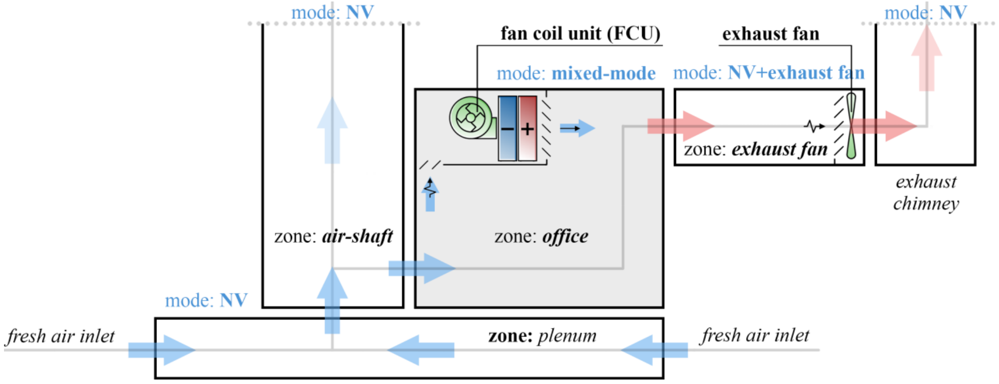
Table 5. **Main heating, ventilation, and air conditioning (HVAC) parameters for the builing model *D-Fence* designed in *DesignBuilder* [computer software] (DesignBuilder Software Ltd, 2019)**

CoP	3.5	Economizer:	Off	Occupancy:	8:00–17:00 h
Cooling temp.:	+24.0 °C	Humidifier:	Off	ANV + AC:	7:00–17:00 h
CV min temp.:	+20.5 °C	Dehumidifier:	Off	CV:	21:00–7:00 h
ANV min temp:	+20.5 °C	Exhaust fan supply:	45 W	Exhaust fan capacity:	0.3 m^3/s

Source: by author, 2020.

AC cooling temperature is set at +24.0 °C, while NV cooling (lower) temperature is set at +20.5 °C, controlling ANV day-time operation and CV *night-purge* process. The control of minimum outside temperatures is set at +14.0 °C, below which one all windows and vents are closed, as a prevention against the overcooling effect during night-time CV operation.

Figure 10. **Schematic diagram: *DesignBuilder*'s concept of applied advanced natural ventilation (ANV) airflow pattern principle; fan coil unit (FCU), air cooled chiller and exhaust fan**



Source: by author, 2020.

According to *DesignBuilder's* modelling environment, applied exhaust fans are defined as independent elements without any connection to the main HVAC loop (Figure 10). To assist and maintain stable ANV airflows, each of four exhaust fans is defined with the flow rate of 0.3 m^3/s, the power supply of 45 W, the efficiency is set at 0.75 and the fan pressure is 125 Pa. The office zone equipment (e.g., computers, lighting, etc.) is considered with a high-level of energy efficiency so that all equipment's heat gains are set in a lower range, at 10 W/m^2.

To reach the maximum possible cooling energy efficiency, this research is based on the *adaptive model* of thermal comfort conditions according to ASHRAE Standard 55-2017 and the chosen model of 80% acceptability limits (ANSI/ASHRAE Standard 55-2017, 2017). *DesignBuilder* provides a simulation report including several hours during a defined timeframe in case when thermal comfort parameters fall below the acceptance level for the *adaptive model* of 80%, and as well the model of 90%.

In this study, *DesignBuilder* calculates total time when indoor conditions did not meet the selected adaptive comfort model of 80% during a defined occupancy schedule: in the office zone 8–17 h, on working days and during the established 6-month building cooling season 1st May–31st October.

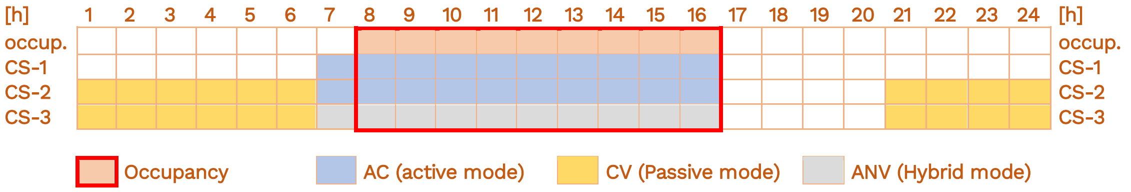
The design approach regarding indoor levels of relative humidity (RH) and the effectiveness of ANV is that humidifiers or dehumidifiers are not activated for threating additionally the indoor air.

For experimental comparative analyses of achieved levels of energy efficiency, the same building form is programmed with three different zone cooling *control strategies* (CS), whose ventilative operations are programmed differently for the purpose of BPS in *DesignBuilder* modelling environment.

This study considers that ANV C-E type is planned for the day-time operation as fan-supported its airflow is forced by the effect of negative pressure difference produced by exhaust fans. On the other side, the use of CV is aimed for the night and early morning *purge* or the *flushing* process of building's high-thermal mass. Also, it should be indicated that CV can be partially defined as *comfort cooling* approach, since the purpose of this technique is to cool down unoccupied space by taking advantage of outside air temperatures, which are in some cases below established thermal comfort benchmarks it could be inacceptable in case of an occupied zone.

Summarizing chosen ventilative strategies for this analysis, fan-assisted ANV C–E system runs during an occupancy schedule as a *hybrid* or *mixed-mode* approach (with the support of AC equipment), while CV operates as the nocturnal and completely *passive* cooling system. For comparative analyses of achieved levels of energy efficiency, the same building form is programmed with three different space cooling control strategies: CS-1, CS-2, and CS-3.

Table 6. **Occupancy schedule and comfort cooling ventilation control strategies (CS) during the 24 h period: CS-1, CS-2 and CS-3**



[h]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	[h]
occup.								🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧									occup.
CS-1							🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦									CS-1
CS-2	🟨	🟨	🟨	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					🟨	🟨	🟨	🟨	CS-2
CS-3	🟨	🟨	🟨	🟨	🟨	🟨	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒					🟨	🟨	🟨	🟨	CS-3

🟧 Occupancy 🟦 AC (active mode) 🟨 CV (Passive mode) ▒ ANV (Hybrid mode)

Source: by author, 2020.

The complete cooling system is programmed as a 20 h continuous ventilation period, 21–17 h (next day), including the Sunday night function 21–7 h (Table 6). The occupancy schedule is defined 8–17 h, while all mechanical ventilative systems operate 7–17h. An overview of such defined control strategies is given along the following lines:

- *Control strategy "1" (CS-1)—AC (air-conditioning):* The building model is entirely equipped with AC system and is planned for reference cooling energy loads. AC system operates 7–17 h, i.e., starting the cooling process one hour before the occupancy determined schedule 8–17 h. The cooling system is seen as an *active* comfort cooling approach.
- *Control strategy "2" (CS-2): AC + CV (air-conditioning and cross ventilation):* AC system operates 7–17 h, while CV strategy is active during the night-time and early morning schedule 21–7 h (next day) when are mostly lower ranges of outdoor temperatures. The system is planned for the nocturnal and early morning *flushing* process of building's high-thermal mass and is defined as a combination of day-time *active* (AC) and night-time *passive* (CV) comfort cooling approach.

- *Control strategy "3" (CS-3): CV + ANV (cross ventilation and advanced natural ventilation):* The previous model CS-2 is further upgraded in the aspect that 7–17 h ANV and AC are programmed as a *hybrid* or *mixed-mode* ventilation type, with an applied *change-over* function: both systems operating in *same space, different times.* On the other side, CV keeps running 21–7 h, as the night-time completely passive comfort cooling ventilative approach.

7. Computational Fluid Dynamics (CFD) Analyses—Barcelona: Present

The general system validation in terms of established airflow patterns for applied control strategies CS-2 and CS-3 (Table 6) is controlled and adjusted in a series of performed computational fluid dynamics (CFD) analyses. Performances of ANV and CV operations are displayed as comparative time-slices, visualised through selected CFD sectional planes (Table 7 and Figure 11).

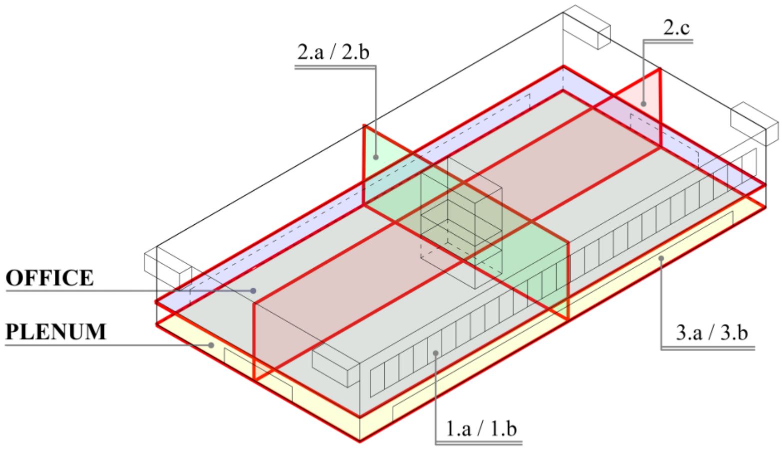
Their typical operations are demonstrated during periods of favourable weather conditions in the summer cooling season as following examples (time-slices): the day-time performance of ANV system on 12th June at 14 h, and the early morning CV function on 8th July at 5 h.

Table 7. **Structure of presented sectional planes for computational fluid dynamics (CFD) analyses**

Office floor plan	(on page 14)	Office and plenum cross-section	(on page 15)	Plenum floor plan	(on page 16)
1.a ANV operation	(Figure 12)	2.a ANV operation	(Figure 14)	3.a ANV operation	(Figure 17a)
1.b CV operation	(Figure 13)	2.b CV operation	(Figure 15)	3.b CV operation	(Figure 17b)
		2.c ANV operation	(Figure 16)		

Source: by author, 2020.

Figure 11. **Schematic presentation: axonometric view of the building model *D-Fence* with outlined sectional planes for visualisation of computational fluid dynamics (CDF) analyses**



Source: by author, 2020.

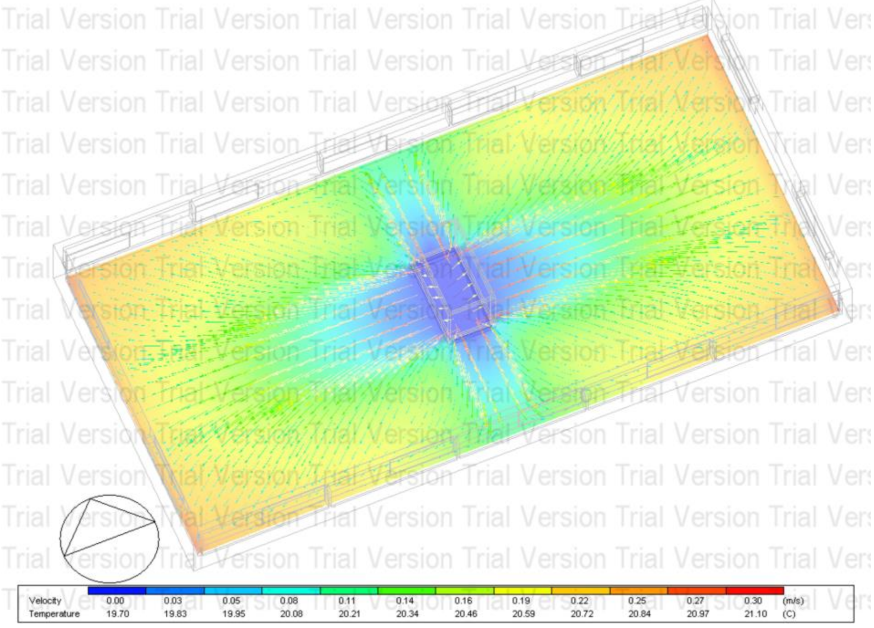
CV does not operate when windows are closed due to lower or higher than acceptable ranges of outdoor air-temperatures, extreme wind-speeds, storms, etc.

CFD analyses present both programmed strategies as previously defined:

- CS-2: cross ventilation (CV) night-time operation 21–7 h.
- CS-3: fan-assisted advanced natural ventilation (ANV) day-time operation 7–17 h

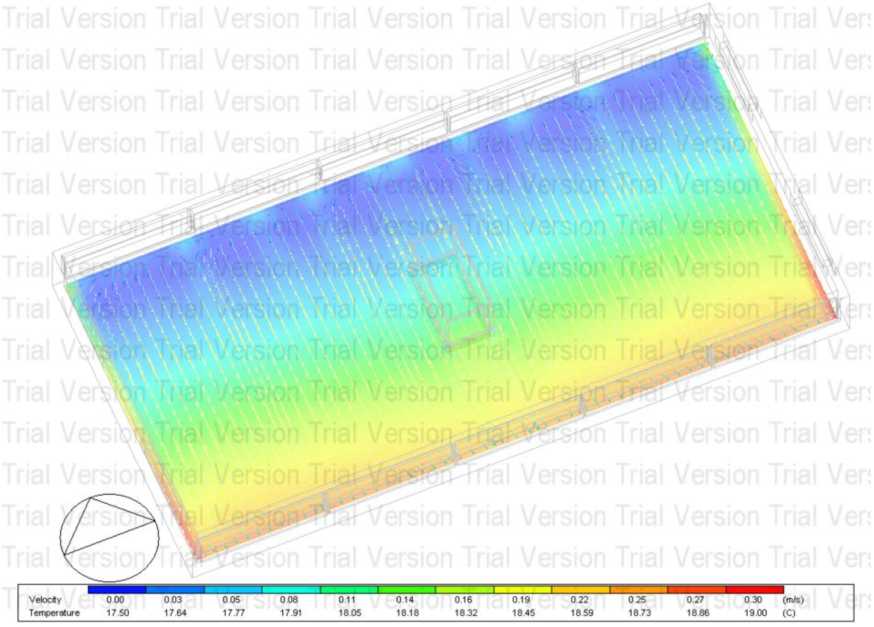
7.1. *Office space—floor plan: "1.a" and "1.b"*

Figure 12. **Sectional plane visualisation 1.a: Computational fluid dynamics (CFD) analysis of applied natural ventilative space cooling technique; axonometric view—office floor plan; example of advanced natural ventilation (ANV) operation, summer period; 12th June at 15 h**



Source: image dataset generated by software simulation engine *DesignBuilder*.

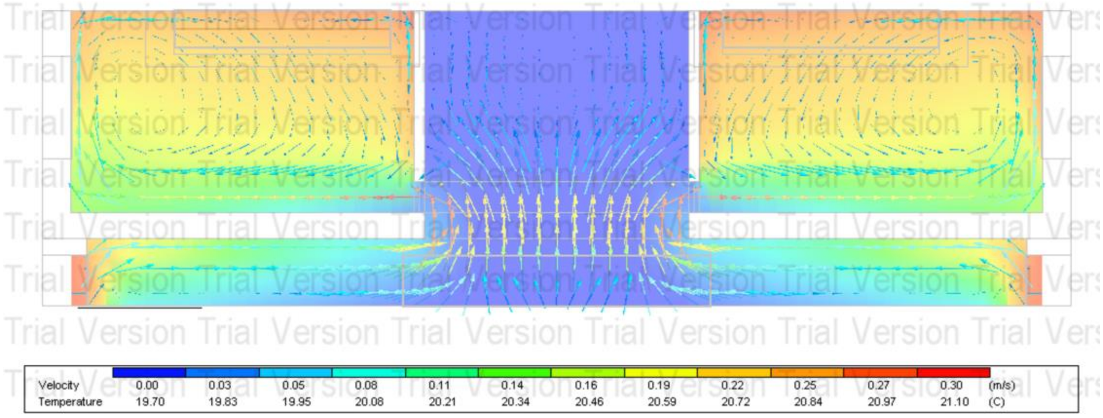
Figure 13. **Sectional plane visualisation 1.b: computational fluid dynamics (CFD) analysis of applied natural ventilative space cooling technique; axonometric view—office floor plan; example of cross ventilation (CV) operation—*flushing* process of high-thermal mass; 8th July at 5 h; north wind**



Source: image dataset generated by software simulation engine *DesignBuilder*.

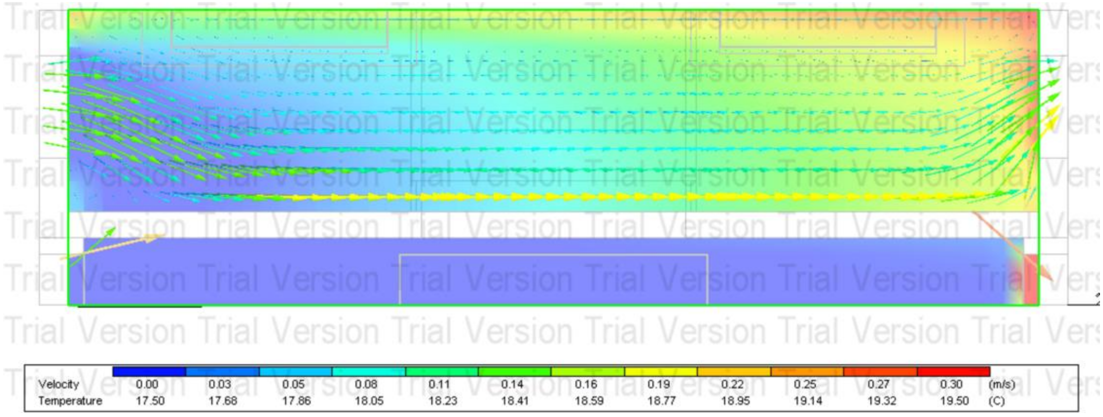
7.2. *Office space and plenum—cross-sections: "2.a", "2.b" and "2.c"*

Figure 14. **Sectional plane visualisation 2.a: computational fluid dynamics (CFD) analysis of applied natural ventilative space cooling technique; transverse section; example of advanced natural ventilation (ANV) operation, summer period; 12th June at 15 h**



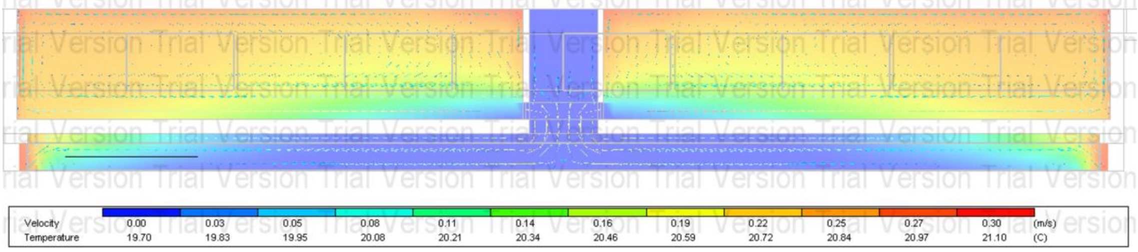
Source: image dataset generated by software simulation engine *DesignBuilder*.

Figure 15. Sectional plane visualisation 2.b: computational fluid dynamics (CFD) analysis of applied natural ventilative space cooling technique; transverse section; example of cross ventilation (CV) operation—*flushing* process of building high-thermal mass; 8th July at 5 h; north wind direction



Source: image dataset generated by software simulation engine *DesignBuilder*.

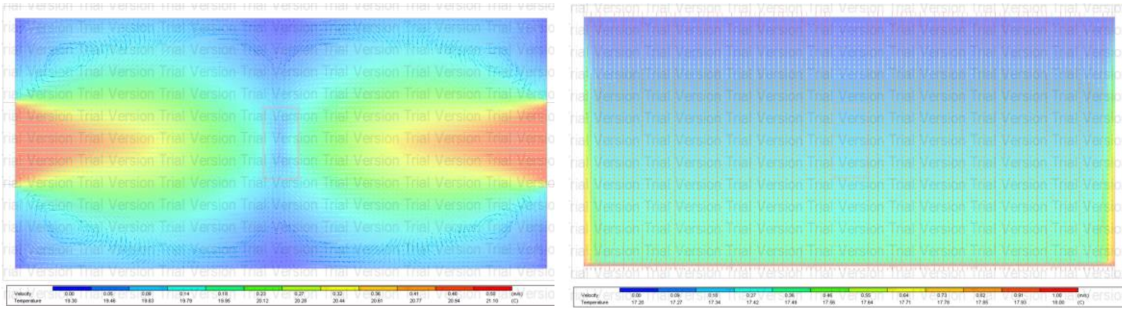
Figure 16. **Sectional plane visualisation 2.c: computational fluid dynamics (CFD) analysis of applied natural ventilative space cooling technique; longitudinal section; example of advanced natural ventilation (ANV) operation, summer period; 12th June at 15 h**



Source: image dataset generated by software simulation engine *DesignBuilder*.

7.3. *Plenum—floor plans: "3.a" and "3.b"*

Figure 17. **Sectional plane visualisation 3.a: computational fluid dynamics (CFD) analysis of applied natural ventilative space cooling technique, summer period; plenum floor plan; (a) example of advanced natural ventilation (ANV) operation, 12th June at 15 h; (b) example of cross ventilation (CV) operation, 8th July at 5 h, north wind**



(a) (b)

Source: image dataset generated by software simulation engine *DesignBuilder*.

CFD analyses visualize ANV and CV operations and consequently produced cooling effects of both techniques during two chosen summer days, considered as two time-slices of their typical performances (Figure 12–Figure 17).

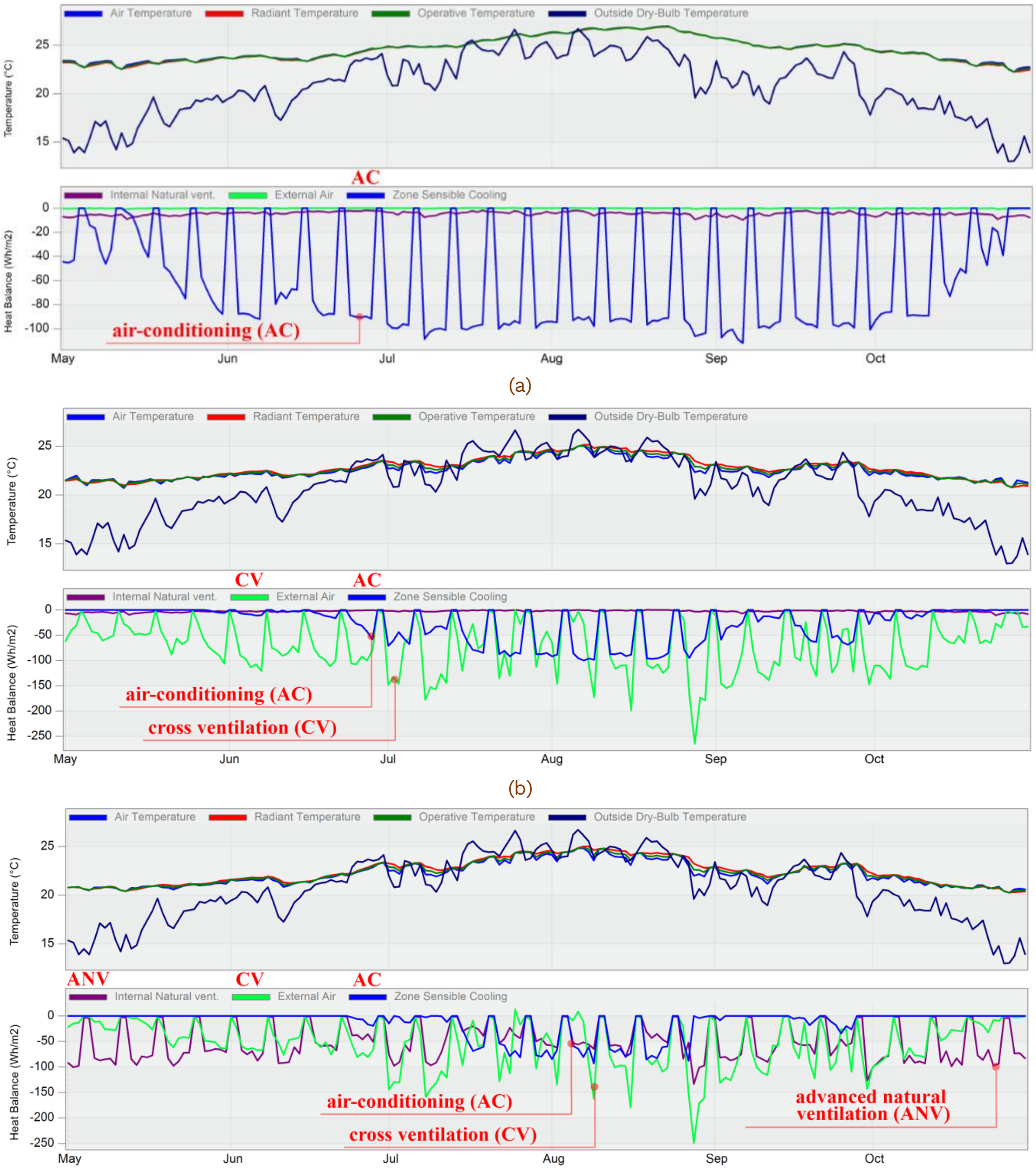
The day-time operation of ANV shows the pre-cooling effect of high-thermal mass positioned in the ground-floor plenum, where the temperature of the warmer outside fresh air is reduced prior to be delivered into the office zone: the fresh air enters the plenum at +21 °C, where its temperature is reduced to an average of +17.5 °C before entering the airshaft, and at the end of this ventilation segment is distributed into the office space at average temperature at +19.5 °C (Figure 14, Figure 16 and Figure 17a). This simulation also displays the period when the function of changeover mixed-mode is taken completely by ANV function, in other words, AC system is in the stand-by regime at that time. Generated air velocities in the office zone at the exit of air-shaft's supply vents are at a maximum range of around 0.3 m/s and then are gradually reduced throughout office space, to average air speeds between 0.05 m/s and 0.15 m/s (Figure 14 and Figure 16).

On the other side, the early morning operation of CV demonstrates how the colder outdoor fresh air, induced by morning north winds, is flushing progressively the interior high-thermal mass with accumulated heat from the previous day (Figure 13, Figure 15 and Figure 17b). As a passive cooling method, while flushing the heavy-weight exposed concrete slabs and lowering gradually its temperature, in this example it is demonstrated the process when high-density mass is thermally being preparing in that manner for generating the *heat-sink* effect, whose function is aimed for the next part of the day, during the occupancy schedule.

8. Building Performance Simulations

Generated outputs of performed BPS are displayed as graphical representations of ventilative performances for each defined control strategy (CS-1, CS-2, and CS-3) operating 1st May—31st October. CS-1 (AC system—reference cooling loads) can be progressively substituted with performed operations of NV-based systems—firstly, with CS-2 (AC + CV), and afterwards with CS-3 (CV + ANV).

Figure 18. **Graphical representation of data: temperature and heat balance overview; cooling period: May–October; office space: (a) control strategy “1” (CS-1): air-condition (AC) operation 7–17 h; (b) control strategy “2” (CS-2): air-condition (AC) operation 7–17 h, cross ventilation (CV); (c) ; control strategy “3” (CS-3): air-condition (AC) operation 7–17 h, advanced natural ventilation (ANV) 7–17 h, cross ventilation (CV) 21–7 h**



(a)

(b)

(c)

Source: image dataset generated by software engine *DesignBuilder*, post-processed image by author, 2020.

Comparing the reference air-conditioning (AC) control strategy CS-1 with cross ventilation (CV)-based CS-2 (Figure 18a,b), heat balance results display that cooling capacities of CV operations are gradually increased from the beginning of May and the end of October towards June and September (Figure 18 b).

In these two periods CV nocturnal operation can efficiently minimize the reference AC Day-time cooling loads, while during July and August AC still stands as the primary building cooling system. Displayed periodical high oscillations in CV heat balance overview are the result of variable local wind speeds, which can be controlled with a more detailed programming of windows, particularly on the most exposed north façade, considering dominant regional north winds.

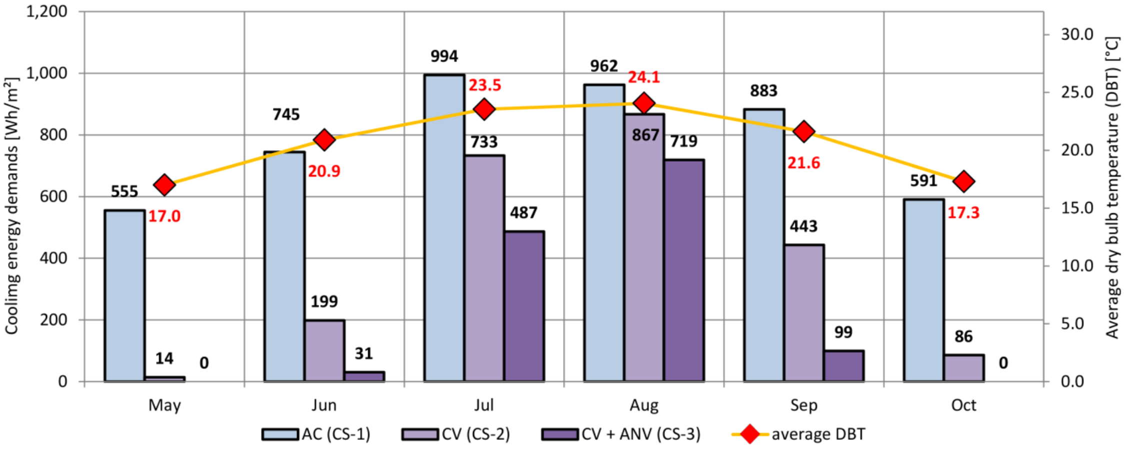
The next comparison between CS-2 and CS-3 (Figure 18b,c) shows how the additional introduced advance natural ventilation (ANV) system provides supplemental capacities in the decrease of overall AC cooling demands, in which case, AC operation is now narrowed principally to the period between the end of July and the end of September.

Another observed effects in that sort of determined indoor environments are that AC system alone, as SC-1, operates in August at the edge of upper boundary conditions for human thermal comfort when exist general risks for the *overheating* effect of office zone (Figure 18a).

On contrary, both NV-based systems, CS-2 and CS-3, operate with risks of *overcooling* the same building's space during the first half of May and the second half of October—mostly considered as transitional intervals between building cooling and heating seasons, in this case indicated with lower morning outdoor air temperatures (Figure 18b,c). However, both these risks could be minimized with a more detailed setup of CS operations or with an additional energy consumption for comfort cooling (CS-1 in August) and heating (CS-2 and CS-3 during certain periods in May and October).

Following building performance simulations (BPS) outputs present total achieved yearly cooling energy efficiency levels for each applied ventilative system, as the principal monthly and yearly comparison overview, in this case, during re-established regional cooling season for this series of analyses, which is May–October (Figure 19 and Figure 20a,b, on next page).

Figure 19. **Graphical representation of data: monthly cooling energy demands [Wh/m²] by each cooling strategy: air-conditioning (AC), cross ventilation (CV), cross ventilation and advanced natural ventilation (CV + ANV); average monthly outdoor dry-bulb temperatures (DBT) [°C] in Barcelona; cooling period: May–October**

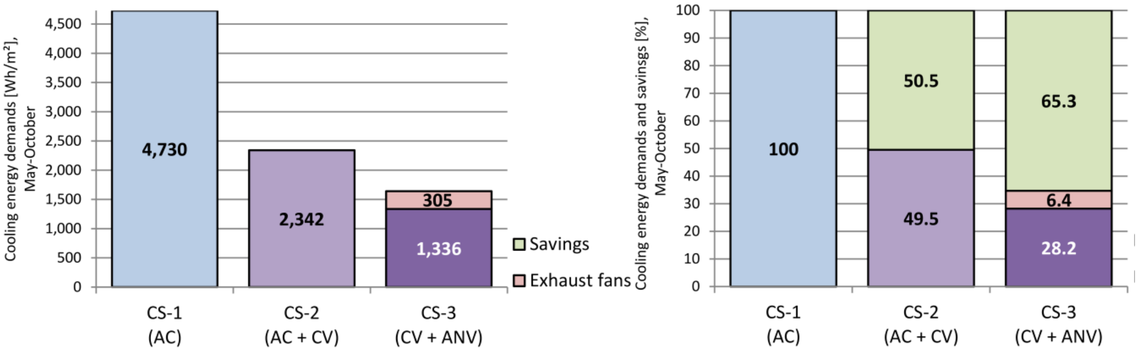


Source: output edited by author, 2020.

August keeps the most unfavourable weather conditions for generating CV and ANV cooling performances, displaying evidently the lowest level in cutting cooling loads of AC system (Figure 19). July is represented with a considered level of reductions, 26% for CV and 51% for the dual operation of CV and ANV systems.

The first part of July should be considered as a partly favourable for NV performances while the second half of the month, along with August, forms the central period with the highest yearly temperatures. Such a weather configuration, with very limited favourable conditions for comfort cooling, allows CV and ANV to provide sporadic and principally ventilative or non-cooling operations.

Figure 20. **Graphical representation of data: comparative overview between control strategies; cooling period: May–October; (a) total cooling energy demands [Wh/m²]; (b) proportion between total cooling energy demands and cooling energy efficiency [%]**



(a) (b)

Source: output edited by author, 2020.

BPS outputs display total cooling demands by each applied strategy comparing with the full AC system—defined for reference values (Figure 19 on previous page and Figure 20a). On the yearly basis, the applied CV technique reduces cooling demands by 50% and in a combination with ANV, the total cut of building cooling demands is achieved at 65% (Figure 20b).

Applied exhaust fans have variable activation periods during its support operations for maintaining stable ANV airflows. It is assumed that the total energy consumption of all four installed exhaust fans during the 6-months cooling period, May–October, is 125 kWh or 305 Wh/m² (Figure 20a), which represents 6.4% in a comparison with the total AC cooling loads (4,730 Wh/m²), or it takes part of 23% in CV + ANV (CS-3) cooling energy consumption (Figure 20b)—or seen from the other angle that the efficiency of CS-3 is reduced by that range.

However, this parameter in praxis predominantly depends on a type of installed fans—e.g., type of engine, blades, supporting control system, etc. (Schild and Mysen, 2009). This value is also additionally related to a specific building's floor position where are installed exhaust fans (i.e., differences between performances comparing for instance 1st and 4th storey), and to variable outdoor conditions impacting steady airflows of a produced thermal buoyancy-effect inside the building—in that way continuously activating and deactivating the fan-support system.

8.1. *Aspects of Thermal Comfort*

The results of energy simulations of control strategies CS-2 and CS-3 show that with the applied *adaptive model* of 80% acceptability limits (ASHRAE Standard 55-2017, 2017), the average mean air temperature in office zone is lower between 1.1 °C and 1.9 °C comparing to CS-1 value (Table 8, on next page).

Table 8. **Main *DesignBuilder*'s output for the office space zone related to thermal comfort, by each control strategy: CS-1, CS-2, and CS-3**

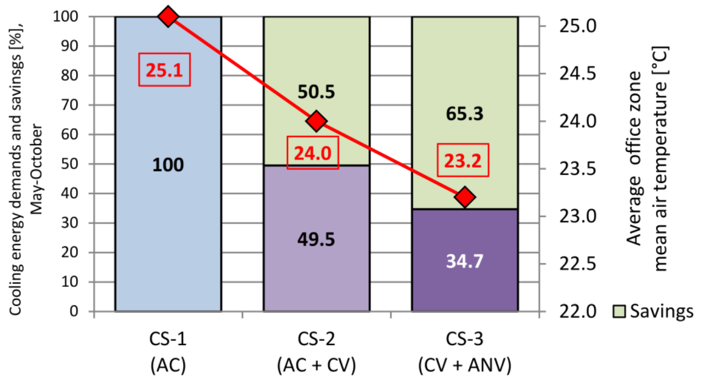
Control strategy (CS)	Adaptive Thermal comfort: model 80%, deviations [h] April–October	Average office zone mean air temperature [°C]			Average office zone relative humidity (RH) [%]		
		low (monthly)	April–October	high (monthly)	low (monthly)	April–October	high (monthly)
CS-1	0	22.2	25.1	27.5	63.3	66.1	69.2
CS-2	0	20.8	24.0	25.8	69.5	73.2	79.0
CS-3	1.8	20.3	23.2	25.6	60.9	70.2	73.9

Source: by author, 2020.

These values are reflected in the applied boundary condition for a minimum number of discomfort hours for occupants where only during CS-3 operation a minimum of thermal comfort anomalies appeared during defined yearly cooling period. Such an effect is manifested in the morning just after a completed CV operation because of the radiation effect of overcooled interior building's elements.

Regarding these temperature related issues, with applied AC system exist potential risks for the *overheating* effect of the office zone, and on the other side, exists a possibility for the space *overcooling* during NV operations. In that context, control strategy CS-1, as AC-based system, reached the scale of upper acceptable temperature boundary conditions for the human thermal comfort with the space *overheating* risk, accordingly to higher outdoor air temperatures in August (Figure 18a). On the other side, CS-2 and CS-3 with applied NV-based strategies reached a lower scale of acceptable indoor temperatures, mainly during morning periods 8–10 h. This effect is the result of overcooled interior building's components after the completed CV night and early morning *flushing* process. In those terms, the high-thermal mass continues radiating and cooling down the indoor air. In addition, critical periods for rapid thermal comfort oscillations are short intervals during hybrid-mode's switching processes when ANV takes function over AC and vice versa.

Figure 21. **Graphical representation of data: correlation between total space cooling energy savings [%] and average mean air temperature in office zone [°C]; cooling period: May–October; applied *adaptive model* of thermal comfort for 80% occupant acceptability**



Source: output edited by author, 2020.

The correlation of these inverse thermal risks can also be observed in Figure 21 regarding levels of calculated total annual proportions of cooling energy demands, versus average mean air temperatures in the office zone. CS-1, as a *sealed* system, displays lower levels of interior RH (Table 8) because of the constantly recirculated indoor air through FCU equipment, so that during specific periods it could be considered the activation of humidifier HVAC equipment, which would be reflected as an additional energy consumption.

9. Summary

The conducted experimental building performance simulations (BMS), with applied three different comfort cooling control strategies (CS-1, CS-2 and CS-3), display achieved levels of reduction of cooling energy demands under present-time weather conditions in Barcelona—50% for the defined CS-2 based on cross ventilation (CV), and 65% for CS-3 conceived on a combination of CV and advanced natural ventilation (ANV) (Figure 20b).

In both examples is demonstrated that CV is an efficient and completely passive technique for night-time space cooling operations relying on a configuration of local wind velocities and a principally lower ranges of nocturnal and early mornings' outdoor temperatures in Barcelona.

On the other side, ANV as a more complex hybrid system can be applied during daytime, having a more resilient level for both ventilation and comfort cooling purposes. In addition, ANV has a more stable airflow patterns, maintaining in that manner a controllable level of thermal comfort during the occupancy period with accordingly a lower level of energy efficiency.

However, as ANV is the fan-supported system, around ¼ of its gross generated energy efficiency is reduced regarding the power consumption of dedicated exhaust fans. Nevertheless, system provides a healthier working environment than an office space equipped exclusively with a *sealed* AC system. The applied *adaptive model* of thermal comfort for 80% occupant acceptability establishes limits for nocturnal cross ventilation application in case when interior high-thermal mass elements could be overcooled, which afterwards, by a radiation effect could reduce indoor air temperatures during critical morning hours in these terms, mainly 8–9 h.

However, these sorts of thermal comfort anomalies could be corrected with a more detailed programming and optimization of cooling operations, or simply by activating heating system in early April and late October, which would be reflected in additional building energy consumption.

From the thermic point of view, a vulnerable part of the building, which is reflected in overall cooling energy demands and regardless the applied cooling strategy, stands the south facing façade. It should be considered a higher level of protection against solar radiation by using additional exterior elements, bioclimatic techniques or perhaps, an additional envelope insulation, which would be an irrational method from the point of view of today's building standards.

Conflict of interest: Authors declare that there is no conflict of interests.

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