ANALYSIS OF SOLAR PASSIVE TECHNIQUES AND NATURAL VENTILATION CONCEPTS IN A RESIDENTIAL BUILDING INCLUDING CFD SIMULATION

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ABSTRACT

The European residential building sector accounts for over 40% of final energy consumption in the European Union member states. Therefore, an improvement of buildings energy efficiency represents a great instrument to reduce CO_2 emissions. The first step to increase energy performance in buildings is to use passive strategies, such as orientation, natural ventilation or envelope optimisation.

This paper presents an analysis of solar passive techniques and natural ventilation concepts in a case study: La Clota residential building, located near Barcelona (Spain). It has been carried out a comparative analysis of La Clota building in order to evaluate its energy and environmental performance with respect to a conventional building and also with respect to another hypothetic building with improved performance with respect to La Clota. Main tools used are energy dynamic simulation and, when necessary, CFD analysis in order to go into the effect of specific measures in depth. Accordingly, conclusions about the most effective energy measures are drawn, not only for this particular building, but also for other Mediterranean climate locations.

1. INTRODUCTION AND OBJECTIVES

The European building sector accounts for over 40% of final energy consumption in the European Union (EU) member states, of which residential use represents 63% of total energy consumption in the whole sector (Balaras et al. 2007). In EU Mediterranean countries the energy needed for air conditioning (A/C) during summer time is indispensable as well is the energy needed for space heating in winter. Old buildings are energetically inefficient, while the new ones can reach an energy consumption about 50% lower. Eco-buildings have high energy performances and low environmental impact, with energy consumption for heating 5-10 times lower, from 10% to 20% of that used in traditional buildings (Meunier et al. 2007). Therefore, an improvement of building energy efficiency represents a great instrument to reduce the CO_2 emissions and, thus to comply with the requirements of the European Directive (EPBD 2002/91/EC) and its transposition in each EU country. The first step to increase energy performance in buildings is to use passive strategies, such as orientation, natural ventilation or envelope optimisation. A review of heating and cooling passive technologies for buildings can be found in Florides et al. (2002) and Hoy-Yen Chan et al. (2010).

This paper presents an analysis of solar passive techniques and natural ventilation concepts in a case study: La Clota residential building, which is located in Cerdanyola del Vallès, in the metropolitan area of Barcelona, Spain. The building has been developed in the frame of the European Commission POLYCITY project, which aims to improve energy performance of very large scale urban development projects in 3 European cities. The major issue for project success is to introduce innovative concepts for building demand reduction, so La Clota residential building represents a pilot building within this demonstration project.

The objective of the present work is to carry out a comparative analysis of La Clota residential building in order to determine and evaluate its energy and environmental performance with respect to a conventional building and also with respect to another hypothetic building better than La Clota one. Four types of measures are set in order to carry out the building analysis: passive solar heating, cooling through natural ventilation, envelope composition and use of shading devices. As a result of a crossed multi-parametric analysis, all different scenarios and their impact on the building energy consumption are evaluated. Accordingly, conclusions about the most effective energy measures are drawn, not only for this particular building, but also for other Mediterranean climate locations.

2. BRIEF DESCRIPTION OF THE BUILDING

La Clota residential building, located in Cerdanyola del Vallès (province of Barcelona, Spain), is a building promoted by the public company INCASOL as government subsidized housing and devoted to be rented to young people.

The building is composed by 2 blocks, A and B, which give a total of 112 dwellings (59 in block A and 53 in block B). Their plant view is shown in Figure 1. Only block B is included within POLYCITY project and financed by it. That is why this block B has been wider studied and its results are presented in this paper.

Block B has six floors and one underground parking. The total constructed area of 3935.78 m^2 is distributed as follows:

- Dwelling area: 2785.80 m^2 divided into 53 apartments, each of them with a useful area from 41 to 44 m^2.
- Underground parking: 650.70 m^2.
- Common zones (halls, stairs): 499,28 m^2.

Figure 1. Plant view of La Clota buildings

According to its shape and useful area, flats in block B can be classified into 4 types: B1, B1", B2 and B3. Figure 2 shows a schematic view of the building's plant, where the distribution of the different types of apartments is pointed out. The front entrances to the apartments are in an opened-shared corridor with north-east orientation. The balconies and clothesline are in the south-west façade.

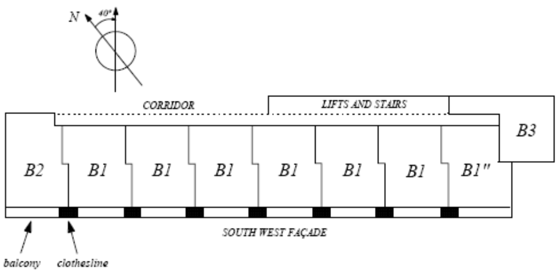

Figure 2. Schematic plant view of block B

The envelope of the building has an additional insulation thickness, which provides a thermal transmittance of the walls even lower than required by POLYCITY project (0.6 W/m^2K). Moreover, the ground floor (adjacent to the underground parking garage) includes a 0.09 m of layer of extruded polystyrene class 0.034. In the south-west façade, there is a glazed gallery. Balconies have double glass sliding windows with external blinds on the outside, and one double glass sliding door on the inside. This allows preheating in winter and solar protection in summer. The external and internal windows are double glazed (10mm + 8mm air + 10mm), with aluminium frame and cold bridge breaking. All apartments are designed to allow cross ventilation. The project of the building (Pastor and Toral 2006) plans two basic natural ventilation mechanisms: a stack-driven configuration, in which a chimney with operable openings induces airflow into the apartment, and a wind-driven option by having windows in both façades. The two mechanisms should provide an acceptable level of ventilation over the summertime when outdoor conditions are favorable.

3. MODELLING

Main tools used to perform this study are, on one hand, the energy dynamic simulation with a software programme which uses Energy Plus calculation engine (DesignBuilder 2010), and on the other hand, the Computational Fluid Dynamics techniques just to go into the effect of specific measures in depth (Crawley 2008).

3.1 Criteria for modelling and simulation

To measure the energy and environmental performance of La Clota residential building, going beyond the POLYCITY requirements verification (Polycity 2005), a comparative study has been carried out. This study is based on the development of two alternative models, besides the model corresponding to La Clota building (called **actual** model), that will be used to make the comparison.

The first alternative model, called **reference**, is a building designed according to the standards and the criteria used at the time which La Clota was projected. The second alternative model, called **improved**, explores a more rigorous application of passive design strategies than La Clota building. The following paragraphs describe the characteristics and parameters assigned to each model.

3.1.1 Scope of the analysis

At the beginning of the study it was decided not to develop simulations and analysis for the whole building, but just for a representative part of it. This decision aimed at:

a) Developing models that allow obtaining information as detailed as possible about energy and environmental performance, as well as about the operation of the building devices such as ventilation shafts, the glazed gallery and solar protections.

b) Considering the relative importance of each of the components of the model, in order to define the criteria to carry out further analysis with larger parts of the building or the entire building.

Therefore, it was set to develop the simulation model only for the most representative apartment of La Clota, since it shows the behaviour of the majority of the apartments. The selected apartment is a B1 type placed in a central position of the floor, and also located in an intermediate floor of the building, thus it has no exposed roof, floor or side walls.

Although this apartment is the most sheltered one, and therefore the thermal exchanges between the building and its surroundings are set aside, this case study may be assumed as suitable due to the comparative nature of the analysis.

In order to model the apartment B1 in a isolated way it has been assumed that the surfaces in contact with the neighbouring dwellings are adiabatic, thus heat exchanges between them are negligible since they all present similar thermal conditions. However, thermal mass properties of the construction elements have been considered in simulations, as well as other supplementary modelling elements such as the corridor slabs, which cast a shadow over the apartment.

3.1.2 Model simplification

Another important adjustment was the simplification of the apartment plant distribution with the purpose of avoiding non-convex areas. This is an Energy Plus requirement for using the "Full interior-exterior" option in the solar radiation calculation. This option allows to correctly calculating solar gains on the glazing located between the living room and the gallery. Anyway, the original area of each zone was maintained.

3.2 Geometric configuration

3.2.1 Actual model

The architectural configuration of the actual model has been defined according to the building project available information and following the simplification criteria mentioned above. The actual simulation model includes the zones described in Table 1. Images of the actual model are shown in Figure 3, Figure 4 and Figure 5.

The ventilation chimney has been modelled in three sections. The first one forms part of the dwelling block, the second one is part of an upper block and the third one is exposed on the roof of the building. The walls of the second section have been modelled as adiabatic, while the third one has been defined as black painted galvanized steel. The three sections of the chimney have been connected by holes and grouped as a single zone. The modelling of the ventilation chimney is completed with a ventilation grille placed in the bottom section, which connects the chimney with the living room, and also four grilles in the top section.

The orientation of the actual model has been defined according to the architectural project of the building (Pastor and Toral 2006), so that the glazed gallery faces the southwest (40º from North).

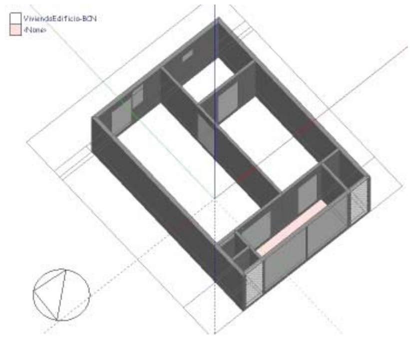

Figure 3. Zones composing the actual model

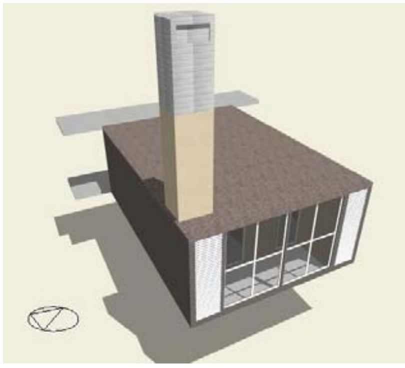

Figure 4. Actual model, southwest façade

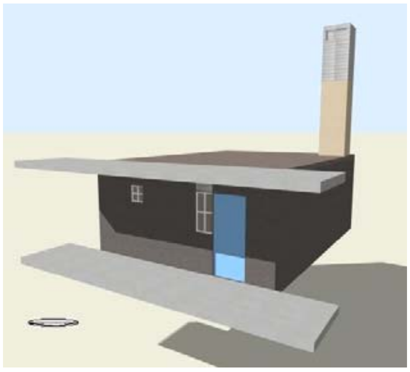

Figure 5. Actual model, northeast façade

Table 1. Zones included in the actual model

Zone number	Zone name	Zone type	Area (m^2)	Volume (m^3)
1	Living room	Standard	19.50	52.65
2	Bedroom	Standard	12.06	32.56
3	Bathroom	Standard	5.17	13.96
4	Gallery	Semi-exterior unconditioned	5.67	15.31
5	Ventilation chimney	Semi-exterior unconditioned	0.64	1.73
6	Closed	Semi-exterior unconditioned	0.48	1.30
7	Laundry	Semi-exterior unconditioned	1.12	3.02
		TOTAL	44.64	120.53

3.2.2 Reference model

The internal architectural configuration is the same taken for the actual model, but with three significant adjustments (see Table 2):

a) There is no ventilation chimney

b) The glazed gallery has been replaced with smaller conventional balconies, since most of the Spanish apartments are constructed in this way.

c) The shared access corridor is not considered opened, but as a central corridor that is part of a double bay building. This is a common feature in Spanish residential buildings and its greatest impact is the difficulty to achieve optimum cross ventilation.

In Figure 6 are shown the zones that compose the reference model.

The reference model is oriented to the west in order to consider an "average" orientation, in terms of energy performance. This parameter was defined by a preliminary study, which consisted in simulating the reference model facing each of the eight main cardinal points. Energy consumption for every 8 cases was obtained, and a consumption average value was calculated. Finally, it was found that the reference model oriented to the west has the closest consumption to this consumption average calculated value.

An image of the reference model is shown in Figure 7.

Figure 7. Reference model, west façade

3.2.3 Improved model

The internal architectural configuration is also the same taken for the actual model, as it is shown in Figure 8. But in this case significant adjustments have been made (see Table 3):

a) There is no ventilation chimney. Instead of it, it has been emphasized the natural cross ventilation.
b) In order to enhance cross ventilation, larger windows have been placed on the wall giving onto the central interior corridor.
c) 80 cm overhangs have been added on the south façade, with the intention to reduce the impact of solar radiation on it, mainly in summer (see Figure 9).

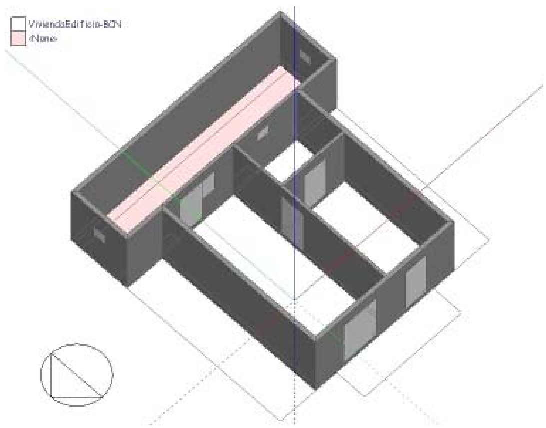

Figure 6. Zones composing the reference model

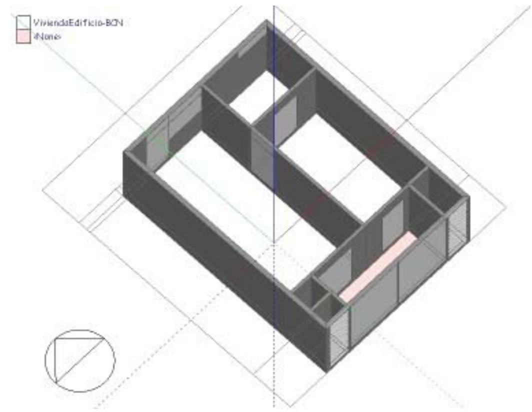

Figure 8. Zones composing the improved model

The improved model is exactly oriented to the south, which generally favours the use of solar radiation during the winter and an easier protection against it in summer.

Table 2. Zones included in the reference model

Zone number	Zone name	Zone type	Area (m^2)	Volume (m^3)
1	Living room	Standard	19.50	52.65
2	Bedroom	Standard	11.80	31.86
3	Bathroom	Standard	5.43	14.66
4	Corridor	Semi-exterior unconditioned	18.45	49.82
		TOTAL	55.18	148.99

Table 3. Zones included in the improved model

Zone number	Zone name	Zone type	Area (m^2)	Volume (m^3)
1	Living room	Standard	19.50	52.65
2	Bedroom	Standard	12.06	32.56
3	Bathroom	Standard	5.17	13.96
4	Gallery	Semi-exterior unconditioned	5.67	15.31
6	Closed	Semi-exterior unconditioned	0.48	1.30
7	Laundry	Semi-exterior unconditioned	1.12	3.02
		TOTAL	44.00	118.80

Figure 9. Improved model, south façade

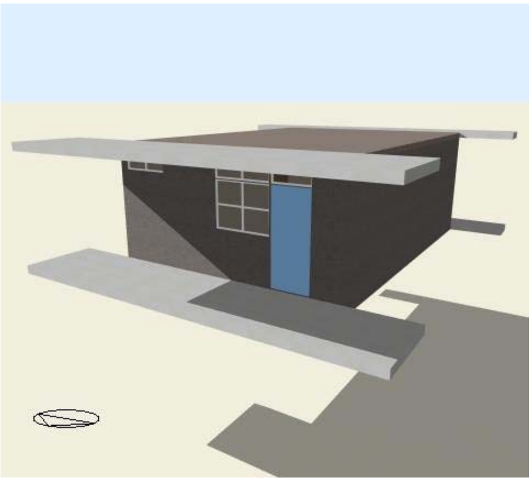

Figure 10. Improved model, north façade

In Table 4, a summary of the main features of the tree models is presented.

3.3 Data and parameters used

3.3.1 Weather data

In all three model simulations an hourly weather data file has been used. The data in this file corresponds to the city of Barcelona, which is the closest one to Cerdanyola del Vallès in climatic terms. The file was generated by Meteonorm from the available information in the nearby weather stations, and also using satellite information. It contains information from a full year, on an hourly profile, regarding parameters such as the dry bulb temperature and dew point, humidity, solar radiation (global horizontal, direct normal and diffuse horizontal) and wind conditions (direction and speed).

It is possible that climate data file does not fit exactly to the characteristics of Cerdanyola del Vallès, which is further from the coast and has mountains behind it. This is especially true with respect to wind conditions. However, given the comparative nature of the study, it was considered that data are reasonably adequate for this preliminary phase of the study. In Figure 11 main weather data of Barcelona are shown.

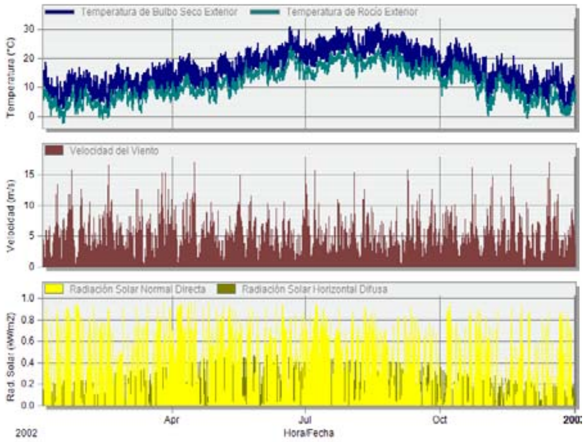

Figure 11. Main weather data of Barcelona

3.3.2 Opaque construction elements

The opaque construction elements of the actual model have been configured in accordance with the information available in the architectural project of the building (Pastor and Toral 2006), while the construction elements of the reference model have been set to strictly fulfil the regulations in force at the time when La Clota was designed (NBE-CT-79). On the other hand, the opaque construction elements of the improved model have been configured to achieve a level of isolation similar to the actual model, but increasing that thermal mass in contact with interior spaces. Theoretically, this strategy would allow greater use of solar gains (in winter) and natural ventilation (in summer).

As a summary, Table 5 lists the opaque construction elements corresponding to each model.

Table 4. Summary of the main features of all three models

	ACTUAL	REFERENCE	IMPROVED
Orientation	40º from North	West	South
Ventilation chimney	Yes	No	No. Instead, larger windows on north façade
Glazed gallery	Yes	No: common balcony	Yes
Opened access corridor to the flat	Yes	No	Yes
Opaque elements	$U_{ext\ walls}$ = 0.488 W/m^{2}K	$U_{ext\ walls}$ = 1.207 W/m^{2}K (according the regulation in force when La Clota was designed)	Same insulation level than actual model, but increased thermal mass
Glazing	U_{global} = 2.658 W/m^{2}K	U_{global} = 3.166 W/m^{2}K	The same as actual model
Window shading devices	Yes	No	Yes. Identical devices than actual model and additional overhangs

Table 5. Transmittance of the opaque construction elements for every model

	Actual model	Reference model	Improved model
External walls. North and South façades	U = 0.488 W/m^{2}K	U = 1.207 W/m^{2}K	U = 0.605 W/m^{2}K
Partitions that separate different apartments	U = 0.720 W/m^{2}K	U = 1.727 W/m^{2}K	U = 0.652 W/m^{2}K
Internal partitions that separate different zones in the same apartment	U = 1.727 W/m^{2}K	U = 1.727 W/m^{2}K	U = 1.727 W/m^{2}K
Internal floors	U = 1.796 W/m^{2}K	U = 1.796 W/m^{2}K	U = 0.677 W/m^{2}K
External doors giving onto the corridor	U = 0.726 W/m^{2}K	U = 0.726 W/m^{2}K	U = 0.726 W/m^{2}K
Internal doors located on the internal partitions	U = 2.083 W/m^{2}K	U = 2.083 W/m^{2}K	U = 2.083 W/m^{2}K

3.3.3 Glazing

The glazing materials of the actual model have been configured in accordance with the information available in the architectural project of the building (Pastor and Toral 2006). The glazing materials of the reference model have been set to strictly comply with the regulations in force at the time when La Clota was designed (NBE-CT-79). However, both cases count on double glass openings. The glazing materials of the improved model are identical to the actual model, since in this case it was considered not to make adjustments. In the simulations, spectral data provided by the organization International Glazing Database (IGDB) are used.

Table 6 presents the properties of glazing materials used in the simulation models.

Table 6. Glazing materials properties

	Actual and improved models	Reference model
Global transmittance (U)	2.658 W/m^{2}K	3.166 W/m^{2}K
Global solar transmission (SGHC)	0.687	0.765
Direct solar transmission	0.585	0.715
Light transmission	0.769	0.808

In actual and improved models, the gallery external windows include a solar protection device consisting of horizontal slats, whose geometrical properties are shown in Figure 12. A conductivity of 0.9 is assumed for the slats material. Regarding the optical properties, it is considered a reflectivity (direct and diffuse solar, direct and diffuse visible) of 0.5 and an emissivity of 0.9. These optical properties are assumed both for the front and the back faces of the slats.

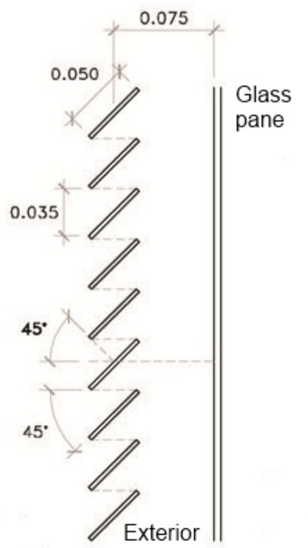

Figure 12. Solar protection device for gallery external windows

3.3.4 Occupancy, appliances and lighting

Same data related to the occupation, internal gains from appliances and lighting were used in all three models (actual, reference and improved).

In habitable zones (living room, bedroom and bathroom) it has been set an occupancy density of 0.02 person /m^2 with a metabolic rate of 140 W/person and a metabolic factor of 0.87. All these parameters, together with the occupancy schedule presented in Table 7, are used to calculate the occupancy gains in the apartment.

Table 7. Occupancy schedule

Period: full year			
Labour days		Weekends	
Hour	Value	Hour	Value
00:00 - 06:00	0.5	00:00 - 08:00	0.5
06:00 - 09:00	1.0	08:00 - 11:00	1.0
09:00 - 14:00	0.0	11:00 - 24:00	0.5
14:00 - 20:00	0.5		
20:00 - 23:00	1.0		
23:00 - 24:00	0.5		

Regarding internal gains from appliances, in habitable zones (living room, bedroom and bathroom) it has been assumed a gain global index of 10 W/m^2. This value, as well as the appliances schedule described in Table 8, is used to determine the gains from appliances in the apartment.

Table 8. Appliances schedule

Period: full year			
Labour days		Weekends	
Hour	Value	Hour	Value
00:00 - 06:00	0.2	00:00 - 08:00	0.2
06:00 - 09:00	1.0	08:00 - 11:00	1.0
09:00 - 14:00	0.2	11:00 - 23:00	0.5
14:00 - 20:00	0.5	23:00 - 24:00	0.2
20:00 - 23:00	1.0		
23:00 - 24:00	0.2		

Regarding to lighting, in habitable zones (living room, bedroom and bathroom) it has been considered an artificial lighting system power of 5 W/m^2·100lux, as well as a minimum level of illuminance of 200 lux. The use of this artificial lighting system is represented for the lighting schedule presented in Table 9.

Table 9. Lighting schedule

Period: full year			
Labour days		Weekends	
Hour	Value	Hour	Value
00:00 - 06:00	0.0	00:00 - 08:00	0.0
06:00 - 08:00	1.0	08:00 - 09:00	0.5
08:00 - 09:00	0.5	09:00 - 19:00	0.0
09:00 - 19:00	0.0	19:00 - 21:00	0.5
19:00 - 21:00	0.5	21:00 - 23:00	1.0
21:00 - 23:00	1.0	23:00 - 24:00	0.0
23:00 - 24:00	0.0		

3.3.5 HVAC system

In all three models it has been used a fan coil HVAC system with independent circuits of cold and hot water. Thus, it was possible to simulate heating and cooling either working simultaneously or alternatively, depending on thermal loads in each habitable zone.

Hot water for heating is generated by a gas boiler with a seasonal performance of 0.85. A 5% of distribution heat losses are considered. Chilled water for cooling is generated by vapour compression chiller with a Coeficient Of Performance (COP) of 2.5 and distribution losses of 5%.

For fan modelling it has been assumed a pressure rise of 150 Pa and a motor efficiency of 70%. Also it is considered that 100% of the motor waste heat is added to the air stream.

3.4 Simulations performed

In order to compare the environmental and energy performance of the three analysed models (actual, reference and improved) it was decided to run simulations both in mechanical and passive mode. In mechanical mode, mechanical ventilation, heating and cooling systems are considered. In passive mode, it is only considered the impact of passive techniques, such as the use of solar protections and natural ventilation.

Moreover, as a part of this first phase of the study, several CFD simulations (Computational Fluid Dynamics) were also developed, aiming at verifying some specific aspects related to thermal and environmental performance of the models. These models were developed with the CFD module integrated in the same software used in the energy simulations (DesignBuilder 2010). Boundary conditions assumed for CFD analysis were calculated by EnergyPlus (Zhiqiang John Zhai and Qingyan Yan Chen 2006)

3.4.1 Mechanical mode simulations

Simulations are run for a full year. The mechanical HVAC system can work continuously in order to satisfy the requirements of either heating or cooling, according to the needs of every habitable zone. Heating is controlled by means of a set point temperature of 21 ºC and a set back temperature of 18 ºC. Cooling is controlled by means of a set point temperature of 25 ºC and a set back temperature of 28 ºC. Periods in which heating and cooling systems will be activated are set in the schedules presented in Table 10 and Table 11.

Table 10. Heating system schedule

Period: full year			
Labour days		Weekends	
Hour	Value	Hour	Value
00:00 - 06:00	0.5	00:00 - 08:00	0.5
06:00 - 09:00	1.0	08:00 - 11:00	1.0
09:00 - 14:00	0.0	11:00 - 21:00	0.5
14:00 - 20:00	0.5	21:00 - 23:00	1.0
20:00 - 23:00	1.0	23:00 - 24:00	0.5
23:00 - 24:00	0.5		

Table 11. Cooling system schedule

Period: full year			
Labour days		Weekends	
Hour	Value	Hour	Value
00:00 - 06:00	0.0	00:00 - 08:00	0.0
06:00 - 09:00	1.0	08:00 - 11:00	1.0
09:00 - 14:00	0.0	11:00 - 21:00	0.5
14:00 - 20:00	0.5	21:00 - 23:00	1.0
20:00 - 23:00	1.0	11:00 - 24:00	0.0
23:00 - 24:00	0.0		

In those schedules, the value 0.0 indicates that system is not working, the value 1.0 indicates that the system is regularly working, and the value 0.5 means that the system is working in a setback mode: some buildings require a low level of heating/cooling during unoccupied periods to prevent the building becoming too cold/hot and to reduce peak heating/cooling requirements at startup.

Maximum mechanical ventilation flow rate has been set at 12.5 l/s·person, but this value is modified by the schedule presented in Table 12, depending on the hour of the day. In the same way, in the three models it is considered the use of night natural ventilation (only from May to October) in order to reduce cooling loads in function of the exposed thermal mass. The natural ventilation also counts on an operation schedule, indicated in Table 13.

Table 12. Mechanical ventilation schedule

Period: full year			
Labour days		Weekends	
Hour	Value	Hour	Value
00:00 - 06:00	0.5	00:00 - 08:00	0.5
06:00 - 09:00	1.0	08:00 - 11:00	1.0
09:00 - 14:00	0.0	11:00 - 24:00	0.5
14:00 - 20:00	0.5		
20:00 - 23:00	1.0		
23:00 - 24:00	0.5		

Table 13. Night natural ventilation schedule

Period: from 1st April to 31 October			
Labour days		Weekends	
Hour	Value	Hour	Value
00:00 - 06:00	1.0	00:00 - 08:00	1.0
06:00 - 23:00	0.0	08:00 - 23:00	0.0
23:00 - 24:00	1.0	23:00 - 24:00	1.0

Both for the actual and improved models, external blinds for the gallery glazed surfaces are active during summer (from May to October) and inactive during winter (from November to April).

3.4.2 Passive mode simulations

Passive mode simulations are run separately for cold and warm periods of the year.

In simulations for cold period (from November to April) the effect of the gallery has been enhanced (in actual and improved models), as a passive heating resource. In order to avoid overheating inside the apartment, only a 20% of the external glazing total surface remains opened when the indoor temperature is higher than 24 ºC. The glazed door placed between the living room and the gallery is closed during the night with the purpose of reducing heat losses, while during the day the 80% of its surface remains opened in order to favour the convection heat gains. The gallery external blinds are also used to avoid overheating, since they are activated when the indoor temperature is higher than 24 ºC.

In simulations for warm period (from May to October) the effect of natural ventilation has been enhanced, as a passive cooling resource (Artmann et al. 2007) in function of the exposed thermal mass.

Both in actual and improved models, either external or internal glazing of the gallery are 80% opened, only if the outdoor air temperature is higher than 20 ºC and lower than indoor air temperature. Windows giving onto the corridor are 60% opened. In actual model also the ventilation chimney is considered active. The gallery external blinds are used to reduce solar gains and they are active when the indoor temperature is higher than 24 ºC.

4. RESULTS

In this section will be shown, in a synthetic way, the results from simulations either run in mechanical or in passive mode, as well as the results from the CFD analysis,

4.1 Results from mechanical mode simulations

4.1.1 Energy consumption

An energy consumption summary of three models is presented in Table 14, Table 15 and Table 16. These tables specifically show monthly and annual energy consumption derived from HVAC systems operation, which includes fan electrical consumption, boiler gas consumption, and also chiller and circulation pumps electrical consumption.

Table 14. Energy consumption, reference model

DATE	Fans (kWh)	Pumps (kWh)	Boiler (kWh)	Chiller (kWh)	Total (kWh)
Jan	67.19	3.68	113.68	0.00	184.55
Feb	61.10	3.01	53.60	0.00	117.71
Mar	68.26	5.75	10.12	2.52	86.64
Apr	65.16	14.65	0.00	15.81	95.62
May	67.19	21.48	0.00	40.70	129.37
Jun	66.23	33.88	0.00	112.05	212.15
Jul	67.19	46.70	0.00	196.57	310.46
Aug	67.72	47.77	0.00	209.61	325.10
Sep	65.69	32.80	0.00	87.57	186.07
Oct	67.19	16.46	0.00	22.93	106.58
Nov	65.69	0.89	12.23	0.00	78.81
Dec	67.72	3.74	110.28	0.00	181.74
Annual	796.35	230.80	299.92	687.76	2014.81

Table 15. Energy consumption, actual model

DATE	Fans (kWh)	Pumps (kWh)	Boiler (kWh)	Chiller (kWh)	Total (kWh)
Jan	27.65	2.12	45.40	0.00	75.16
Feb	25.14	1.15	10.07	0.00	36.36
Mar	28.09	5.03	0.52	5.90	39.53
Apr	26.81	11.79	0.00	20.65	59.25
May	27.65	6.71	0.00	7.08	41.44
Jun	27.25	13.35	0.00	49.36	89.96
Jul	27.65	19.01	0.00	101.02	147.68
Aug	27.87	21.22	0.00	121.62	170.70
Sep	27.03	12.86	0.00	39.89	79.78
Oct	27.65	4.90	0.00	5.36	37.91
Nov	27.03	1.13	2.70	0.20	31.07
Dec	27.87	2.50	38.59	0.00	68.95
Annual	327.68	101.77	97.28	351.07	877.80

Table 16. Energy consumption, improved model

DATE	Fans (kWh)	Pumps (kWh)	Boiler (kWh)	Chiller (kWh)	TOTAL (kWh)
Jan	25.67	1.67	17.47	0.02	44.83
Feb	23.35	1.35	2.41	0.16	27.26
Mar	26.08	3.09	0.18	1.81	31.16
Apr	24.90	4.94	0.00	4.66	34.49
May	25.67	3.96	0.00	5.26	34.89
Jun	25.31	10.08	0.00	44.59	79.97
Jul	25.67	14.36	0.00	92.11	132.15
Aug	25.88	15.52	0.00	112.07	153.46
Sep	25.10	9.82	0.00	35.61	70.53
Oct	25.67	3.89	0.00	4.25	33.82
Nov	25.10	3.84	0.15	2.68	31.77
Dec	25.88	1.38	4.30	0.07	31.62
Annual	304.29	73.89	24.51	303.27	705.97

In Figure 13 a comparison between three models monthly consumption is shown. Values appeared in this graphic are the sum of fan, chiller, boiler and pumps consumption.

4.1.2 Energy savings

Table 17 shows the energy savings (energy reduction percentage) of the actual and improved model in comparison with reference model, as well as the reduction percentage of the improved model with respect to the actual one.

Table 17. Energy savings achieved by every model

MODEL	Annual consumption (kWh)	% Savings Vs. Reference model	% Savings Vs. Actual model
Reference	2014.81		
Actual	877.80	56.4%	
Improved	705.97	65.0%	19.6%

4.1.3 Heat balance

Table 18, Table 19 and Table 20 show monthly and annual heat losses/gains obtained for the living room zone in the three models. These losses/gains have been grouped into three categories:

1. Solar: gains due to solar radiation that enters through external and internal glazing.

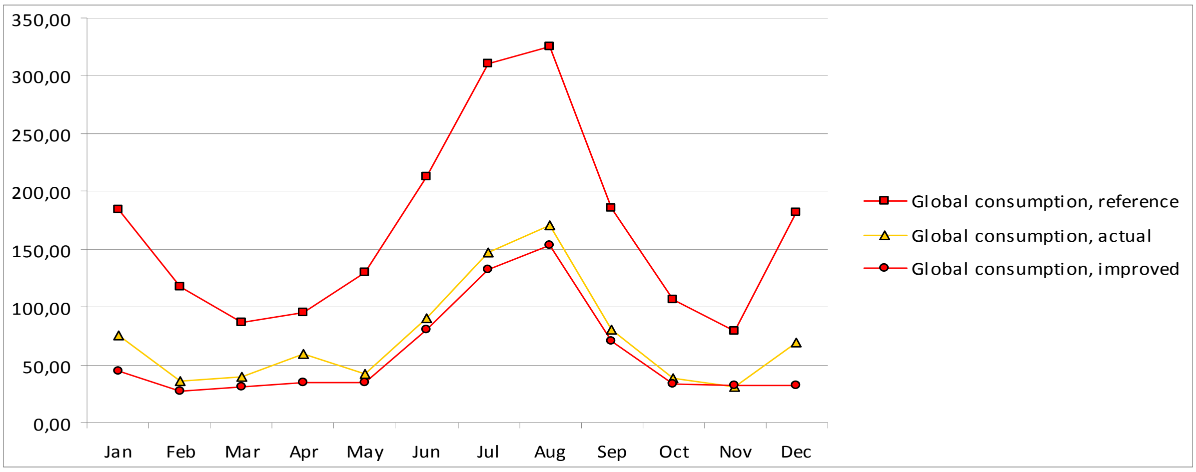

Figure 13. Energy consumption comparison between models

2. Ventilation: losses/gains caused by the incoming outside air. Ventilation through windows, doors and vents is here included.

3. Envelope: losses/gains by conduction associated to construction elements (walls, partitions, roofs, floors and glazing). It is considered the effect of constructions thermal mass.

Table 18. Heat balance, reference model

DATE	Total solar (kWh)	Total ventilation (kWh)	Total envelope (kWh)	Total GLOBAL (kWh)
Jan	62.20	-44.21	-145.62	-127.63
Feb	86.32	-42.80	-133.40	-89.88
Mar	113.66	-40.30	-143.97	-70.61
Apr	136.30	-64.29	-118.38	-46.37
May	143.23	-101.45	-87.67	-45.89
Jun	150.83	-117.38	-37.67	-4.22
Jul	172.14	-100.04	-13.87	58.23
Aug	141.51	-85.33	2.68	58.86
Sep	120.14	-121.06	-31.69	-32.61
Oct	90.55	-89.97	-77.43	-76.85
Nov	60.72	-31.93	-109.54	-80.74
Dec	56.57	-43.54	-142.02	-128.99
Annual	1334.19	-882.29	-1038.58	-586.68

Table 19. Heat balance, actual model

DATE	Total solar (kWh)	Total ventilation (kWh)	Total envelope (kWh)	Total GLOBAL (kWh)
Jan	47.32	-64.38	-45.36	-62.43
Feb	45.64	-39.99	-42.36	-36.71
Mar	33.24	-36.31	-33.16	-36.23
Apr	23.86	-48.20	-6.57	-30.91
May	11.45	-64.14	-20.97	-73.65
Jun	11.51	-80.28	1.03	-67.74
Jul	12.47	-65.63	12.20	-40.96
Aug	10.02	-66.97	21.22	-35.74
Sep	7.32	-82.22	2.39	-72.51
Oct	5.05	-62.44	-26.14	-83.54
Nov	35.96	-39.70	-43.21	-46.95
Dec	43.64	-51.21	-49.63	-57.20
Annual	287.48	-701.48	-230.56	-644.56

Table 20. Heat balance, improved model

DATE	Total solar (kWh)	Total ventilation (kWh)	Total envelope (kWh)	Total GLOBAL (kWh)
Ene	54.23	-23.97	-67.58	-37.33
Feb	43.18	-10.95	-57.97	-25.74
Mar	30.94	-9.51	-60.44	-39.01
Apr	32.25	-33.17	-48.46	-49.39
May	37.16	-58.48	-51.14	-72.46
Jun	39.21	-96.39	-18.52	-75.70
Jul	41.15	-92.34	-7.47	-58.66
Aug	35.07	-93.83	7.55	-51.22
Sep	26.89	-105.19	-9.19	-87.48
Oct	19.32	-62.01	-40.78	-83.46
Nov	42.22	-12.66	-65.37	-35.81
Dec	50.63	-15.63	-63.53	-28.53
Annual	452.26	-614.12	-482.92	-644.79

Heat losses/gains in the three models permit to generally establish which design strategies will have higher impact on the building energy performance. This is graphically shown in Figure 14, which makes possible to compare separately solar, ventilation and envelope losses/gains for each model. In Figure 15 a similar comparison can be observed, but in this case the three categories of losses/gains are grouped.

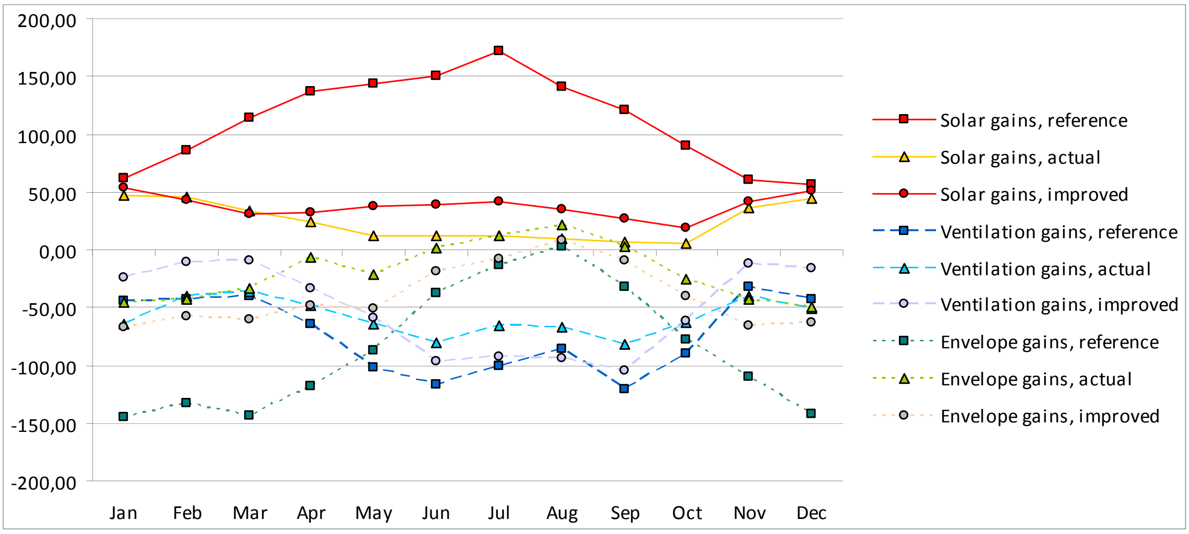

Figure 14. Gains breakdown comparison between models

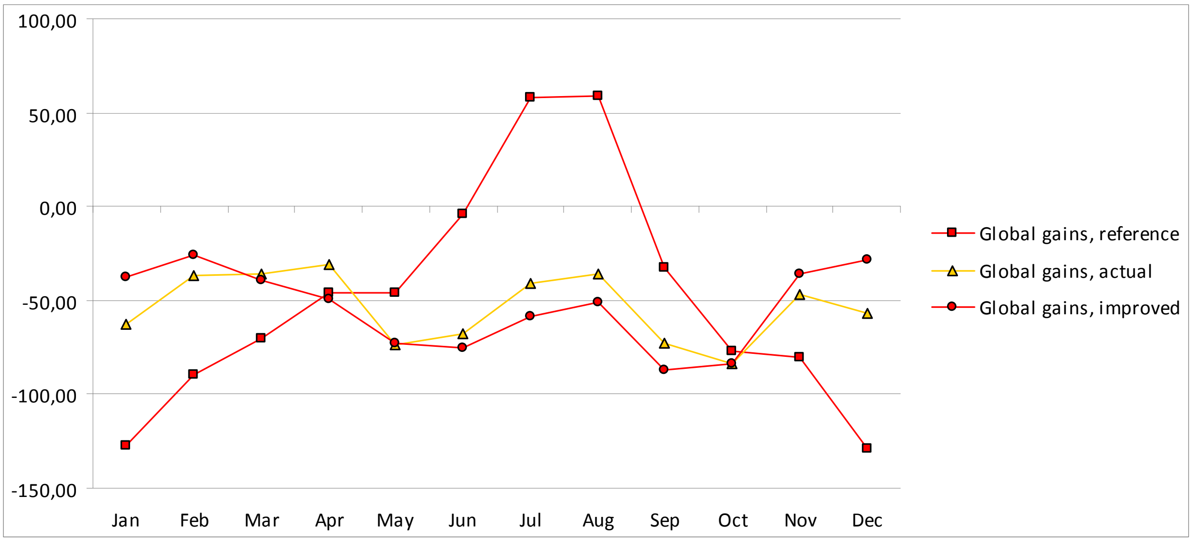

Figure 15. Global gains comparison between models

4.2 Results from passive mode simulations

In passive mode there isn't any consumption associated to HVAC systems. That is why in this case the comparison parameter will not be the energy consumption, but the number of hours that operative indoor temperature is above/below a reference temperature. For winter simulations it will be considered the number of hours below 21, 20 and 19 ºC. For summer simulations, it will be contemplated the number of hours with an indoor temperature above 26, 27 and 28 ºC. This is an accumulative value: i.e. the number of hours that temperature is below 21 ºC, already includes the number of hours with a temperature below 20 and 19ºC.

The living room operative temperature is evaluated for every three models. In Table 21 and Table 22, besides the number of hours, the improvement percentage of actual and improved models in relation to reference model is presented, as well as the level of improvement of improved model with respect to the actual one.

Table 21. Passive comfort, winter

RANGE	Refer.	Actual	Impr.
Hours at or below 21 ºC	2,543.3	805.8	405.0
Improvement Vs. reference		68.3%	84.1%
Improvement Vs. actual			49.7%
Hours at or below 20 ºC	1,403.8	168.3	27.3
Improvement Vs. reference		88.0%	98.1%
Improvement Vs. actual			83.8%
Hours at or below 19 ºC	593.0	15.5	0.0
Improvement Vs. reference		97.4%	100.0%
Improvement Vs. actual			100.0%

Table 22. Passive comfort, summer

RANGE	Refer.	Actual	Impr.
Hours at or above 26 ºC	1,284.0	865.5	661.5
Improvement Vs. Reference		32.6%	48.5%
Improvement Vs. Actual			23.6%
Hours at or above 27 ºC	897.5	520.3	327.3
Improvement Vs. Reference		42.0%	63.5%
Improvement Vs. actual			37.1%
Hours at or above 28 ºC	547.5	220.8	99.8
Improvement Vs. Reference		59.7%	81.8%
Improvement Vs. Actual			54.8%

4.3 Summary of mechanical and passive simulations results

Results obtained up to now clearly show that actual model presents a noticeably better performance than reference one (conventional building).Concerning mechanical mode simulations, in which consumption of all HVAC systems are considered, actual model achieves 56.4% of energy savings with respect to reference model. Results from passive mode simulations show improvement percentages even more significant: up to 59.7% in summer and 97.4% in winter. That is why it could be concluded that actual model does not require a heating system; although it would be necessary to run further simulations with severer climatic conditions. Moreover, it also should be taken into account that mechanical ventilation is not considered in passive mode simulations.

On the other hand, improved model has a better performance than actual one. In mechanical mode simulations, the improved model percentage of savings is 19.6% in comparison with actual model and 65.0% with respect to reference model. In passive mode simulations, for summer period, the improvement percentage achieves a value of 54.8% in comparison to actual model, and 81.8% in relation to reference model. For winter period, improved model reaches a value of improvement around 83.8% with respect to the actual model, and 98.1% with regard to the reference one.

Results related to losses and gains makes possible to deduce which design decisions have higher impact in building performance:

1. Owing to their better orientation, as well as to the use of shadowing devices, actual and improved models presents, during summer, solar gains noticeably lower than the reference one.
2. In contrast, improved model has higher solar gains than the actual one, during summer. This is caused by the inclusion of larger windows on north façade.
3. Despite what is mentioned in the previous point, improved model presents lower global energy losses than the actual one. This is caused by a greater impact of natural ventilation (night ventilation when the building is working in mechanical mode), as well as by the use of construction elements with more thermal mass inwards exposed (Shaviv et al. 2001).

Modifications introduced in improved model hardly imply greater economic invest in comparison to the actual model, especially because the ventilation chimney has been removed. In this sense, it can be stated than the obtained improvements are almost exclusively related to the applied design strategies, which are:

- Passive solar heating
- Cooling through natural ventilation
- Envelope composition
- Use of shading devices

4.4 Results from CFD simulations

CFD simulations were run in order to go into specific operating aspects in depth. One of the most interesting points was to assess the ventilation chimney contribution to the apartment passive cooling, as well as to compare this strategy with another one consisting of generating bigger windows on north façade to improve the natural crossed ventilation.

The following images show the conditions for the living room, which is the most representative zone of the dwelling, at nine o'clock in a summer morning and working in passive mode (without mechanical HVAC systems). Three different scenarios have been studied:

1. Actual model with closed windows and opened vents, either the vent placed on north façade or the one connecting the living room and the ventilation chimney (Figure 16 and Figure 17).
2. Actual model with all windows and vents opened (Figure 18 and Figure 19).
3. Improved model with opened windows. No vents have been placed in this case, since it was decided to implement larger windows on north façade instead to improve natural cross ventilation (Figure 20 and Figure 21).

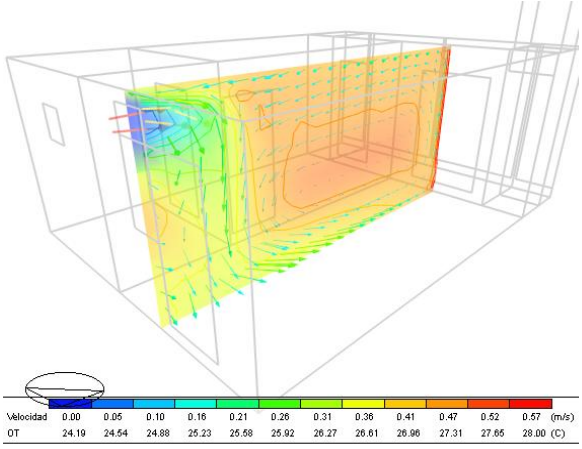

Figure 16. Scenario 1, vertical CFD section

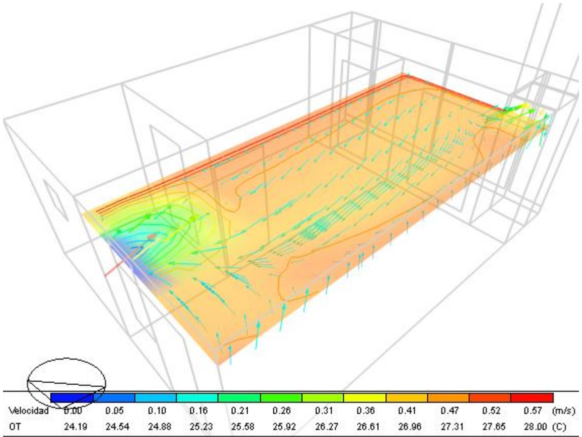

Figure 17. Scenario 1, horizontal CFD section

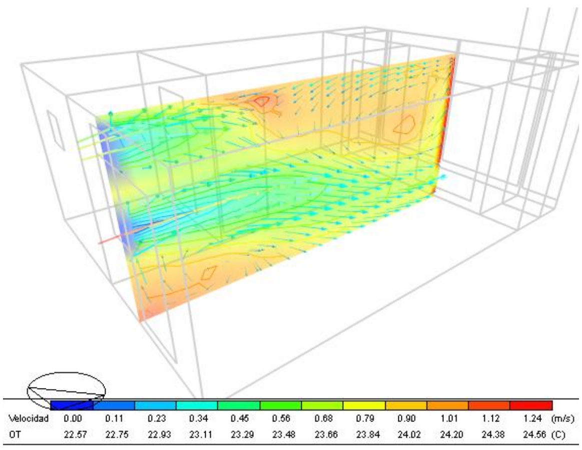

Figure 18. Scenario 2, vertical CFD section

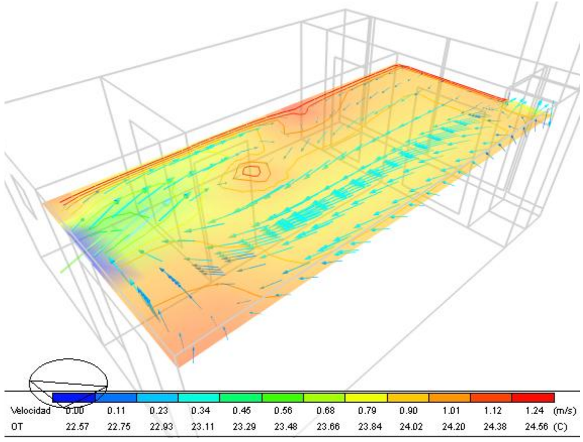

Figure 19. Scenario 2, horizontal CFD section

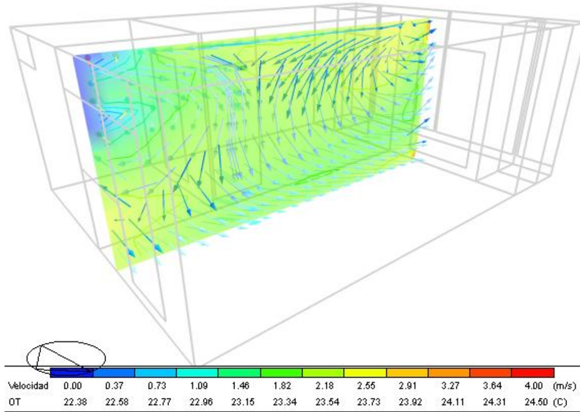

Figure 20. Scenario 3, vertical CFD section

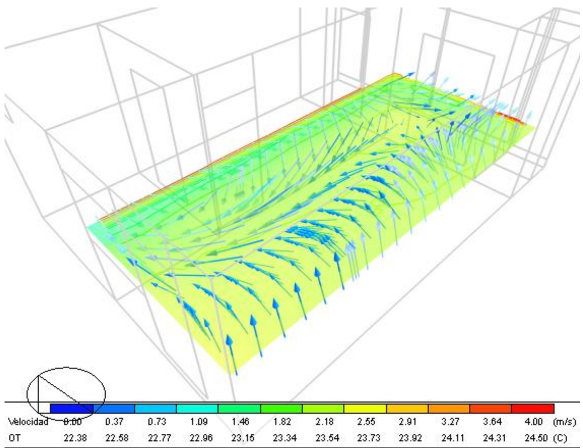

Figure 21. Scenario 3, horizontal CFD section

Results from CFD analysis validate one of the initial hypothesis: the current configuration for the ventilation chimney does not represent an efficient strategy for passive cooling. In Scenario 1, in which only vents of the actual model are opened and therefore the ventilation chimney is the unique active ventilation method in the apartment, operative temperatures are too high. It can be assumed that this situation is mainly caused because night ventilation is not able to extract the needed heat from the internal construction elements. On the other hand, air movement within the zone is limited and it doesn't have proper distribution.

In Scenario 2, where besides vents windows of the actual model are opened too, zone conditions considerably improve. Not only operative temperatures go down, but also the air movement is higher and it presents a better distribution. However, Scenario 3, corresponding to improved model with bigger opened windows, presents the best performance (Kobayashi et al. 2010). This fact proves that the most feasible option to enhance passive cooling is to increase cross ventilation.

5. CONCLUSIONS

As a result of the procedure, it can be stated that this methodology becomes very useful to know in detail the behaviour of some passive mechanisms, and also to perform an accurate analysis that allows us to determine the priorities for energy efficiency measures in a particular region and establish the principal replication lines for it.

According to the modelling criteria set in this preliminary stage of the study, results from the analysis show that La Clota not only fulfils the requirements set by POLYCITY project, but is able to achieve significant energy savings as well as better comfort conditions in comparison with a conventional residential building planned at the time that La Clota was designed. This means that design criteria in La Clota were properly taken.

On the other hand, the comparative analysis between improved and actual model indicates that a more rigorous application of passive design strategies would result in even more significant improvements. In this sense, it has to be remarked that main problem doesn't lie in design strategies assumed, but in analysis tools used during the design process. The use of advanced simulation tools from initial design stages would have allowed making design decisions with higher impact and lower cost.

In future phases of this study it will be important to extend the acquired experience to a larger model of the building, a model focused not only in one apartment, in order to take into account the role of the exposed construction elements (roof, external lateral walls, floor adjacent to underground parking). Also, it will be useful to get detailed information about dwellings behaviour in accordance with their position in the building.

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