STRATEGIES FOR EXPLOITING CLIMATE POTENTIAL THROUGH VENTILATIVE COOLING IN A RENOVATED HISTORIC MARKET

Annamaria Belleri*[1], Federico Noris[1], and Roberto Lollini[1]

1 EURAC research
1 Druso
Bolzano, Italy
**Corresponding author:*
annamaria.belleri@eurac.edu

ABSTRACT

Nearly all retail locations use ventilation and cooling systems to ensure adequate air exchange for health reasons and indoor comfort temperatures. These systems can run for over 2,000 hours per year and we expect that average operating hours will continue to rise across Europe because of the continued trend towards longer opening hours and increased number of opening days. Shopping malls often enclose large open spaces and atria with high solar and internal gains that can drive ventilative cooling. This study presents the methodology applied to a historical market located in Valladolid (Spain) for the assessment of the ventilative cooling potential and the definition of a ventilative cooling strategy. The climate suitability and potential was evaluated based on the building internal gains rate and the considered ventilation strategies options (e.g. night cooling, daytime direct ventilation). Significant performance indicators were defined for each considered ventilation strategy. Once we determined the climate suitability, we defined a ventilative cooling strategy, that exploits openings in the façade and in the skylight to promote stack effect ventilation. We sized openings area and location on the façade, taking into account design constraints, and we assessed their performances by dynamic simulations in Trnsys coupled with Trnflow airflow network. Results show the potential cooling load reduction, with the achievement of acceptable thermal comfort due to the ventilative cooling in the shopping mall. The proposed methodology can support the design decision process towards cost effective low energy shopping malls.

KEYWORDS

Climate potential, ventilative cooling, retail buildings, refurbishment, dynamic simulations

1 INTRODUCTION

Retail buildings are a significant part of the EU building stock and, among them, the wholesale and retail sector presents an average specific energy use of 200 kWh/m^{2}a and account for 7% of the total building stock in Europe (Atanasiu B., 2011). Nearly all retail locations use ventilation and air conditioning systems to ensure adequate air exchange and indoor comfort temperatures. These systems run for over 2,000 hours per year and average operating hours will continue to rise across Europe because of the continued trend towards longer opening hours and increased number of opening days.

According to the British Council for Shopping Centre (BCSC, 2012), natural ventilation solutions can reduce capital and maintenance cost over traditional mechanical heating, ventilation and air conditioning and they typically need less plant and equipment place.

Shopping malls often enclose large open spaces and atria with high solar and internal gains that can be drivers for ventilative cooling. However, nearly all retail buildings use mechanical ventilation systems as they require less design efforts assuring minimum requirements for indoor air quality.

The CommONEnergy EU FP7 project (www.commonenergyproject.eu) will contribute to the development of ventilative cooling strategies for the retrofit of existing shopping malls to exploit the architectural and climate drivers potential. The retrofitting solution sets developed within the project will be applied to three demo cases located in Spain, Italy and Norway, selected because of their high replication potential. This paper presents the methods and tools applied to assess the ventilative cooling potential and to define an efficient ventilative cooling strategy for one of the democases: the historic market of the city of Valladolid.

First, we evaluated the climate suitability and potential according to several building internal gains rates and ventilation strategies (e.g. night cooling, daytime direct ventilation). Once we determined the climate suitability, we defined a ventilative cooling strategy that exploits openings in the façade and in the skylight to activate stack effect ventilation. Coupled thermal and airflow building energy simulations allowed to assess the potential cooling load reduction, the air change rates and the indoor comfort conditions for several opening factors.

2 CASE STUDY

2.1 Building description

The “Mercado del Val” is an iron market located within the old town of Valladolid. Its construction was completed in 1882. Its floor plan is a rectangle of 112 meters long and 20 meters wide, with chamfered corners.

The Valladolid municipality planned a refurbishment intervention to transform the market into an innovative building that meets the contemporary commercial needs being respectful of its historic representativeness. As required by the Heritage Council, the refurbishment project aims at emphasizing the old iron structure by using glazed facade over the entire building perimeter. The new indoor layout configuration and the glazed façade will contribute to a better understanding of the global iron structure, to increase daylighting and to make the commercial activities visible from outside. The glazed façade is made by modular façade elements that aims at integrating thermal, daylighting and ventilation functions, being responsive when internal and external loads change.

Figure 1: Mercado del Val (Valladolid) building view. Source: www.commonenergyproject.eu

Figure 2: Mercado del Val (Valladolid), interior building view. Source: www.commonenergyproject.eu

2.2 Design constraints

The building shape has high potential for exploiting stack effect ventilation by integrating openings in the facade and exploiting the existing skylight openings located at 10 m height from the ground level where air can exhaust.

Therefore, the definition of a ventilative cooling strategy involves the whole building envelope as openings have to be located at opposite sides and at different height on the building envelope.
Main constraints regard inlet openings location at ground level. A large temperature difference between indoor and outdoor might cause cold draughts inside the building if the openings are placed near people's height. Therefore we decided to avoid openings within 3 m height of the building façade to prevent local discomfort situations. Inlet air at 5 m height, which is approximately the height of the upper part of the modular façade, would allow air mixing and prevent cold draughts in the occupied zones of the building. Additionally, inlet openings in the lower part of the façade might cause safety issues.
Lower inlet openings in urban environments might affect negatively indoor air quality due to transfer of outdoor pollution. Filters on the opening would cause a high pressure drop of the air reducing significantly natural ventilation effectiveness. In order to avoid water infiltration in case of precipitation, top hung windows could be used. Top hung windows have usually an opening angle of 20°, which reduces the opening effective area by 80%. Therefore, for the definition of the opening area we considered opening angles capabilities and actuators power. As enforced by the heritage council, skylights have to maintain the original design. This could reduce the effective area of the openings.

3 METHODS

The following methods were used within the first phases of the design project to analyse the climate potential and assess possible energy savings of a defined ventilative cooling strategy.

3.1 Climate suitability analysis

To estimate ventilative cooling potential we applied the method proposed by NIST (Emmerich S. J., 2011) to shopping mall building typology and fit it according to their specific needs.
This method assumes that the heating balance point temperature (T_b) establishes the outdoor air temperature below which heating must be provided to maintain indoor air temperatures at a defined internal heating set point temperature (T_{hsp}).
Therefore, when outdoor temperature (T_o) exceeds the heating balance point temperature, direct ventilation is considered useful to maintain indoor conditions within the cooling set point temperature (T_{csp}). At or below the heating balance point temperature, ventilative cooling is no longer useful but heat recovery ventilation should be used to meet minimum air change rates for indoor air quality control and reduce heat losses.
We considered the building occupied for 11 hours per day and set the cooling set point temperature to 25°C during the day and to 28°C during the night, as well as the heating set point temperature to 16°C during the day and 14°C during the night. Those set point temperatures refer to the operative temperature recommended by the standard EN 15251: 2008 for building Category II.
The heating balance point temperature (T_b) can be calculated using Equation 1. Table 1 reports the balance point temperature values calculated at different internal gains level.

$$T_b = T_{hsp} - \frac{q_i}{\dot{m}_{min} c_P + \sum UA} \quad (1)$$

where:
q_i = total internal gains [W/m²]
c_p = air capacity [J/kg-K]
$\dot{m}_{min}$ = minimum required mass flow rate [kg/s]

$\sum UA$ = envelope heat exchange [W/K]

The average U-value of the envelope was estimated at 0.49 W/m²K according to the local minimum building code requirements and the actual building shape.
The minimum ventilation rate which has been estimated as 1.7 l/s-m² (0.00204 kg/s-m²) according to the EN 15251 values for department stores (Cat. II – low polluting building).

Table 1. Heating balance point temperature calculated for different internal gain values.

	q_i = 10 W/m²	q_i = 20 W/m²	q_i = 40 W/m²	q_i = 80 W/m²
T_b	12.7 °C	9.4 °C	2.85 °C	-10.3 °C

For each hour of an annual climatic record for the Valladolid city we assessed the number of hours when:

1) Ventilative cooling is not required: when the outdoor temperature is below the heating balance point temperature no ventilative cooling can be used since heating is needed;
If $T_o < T_b$ then $\dot{m} = 0$
2) Direct ventilative cooling with ventilation rate maintained at the minimum: when the outdoor temperature exceeds the balance point temperature, yet falls below the lower limit of the comfort zone – given the width of the comfort zone (T_{csp}-T_{hsp}) - and outdoor dew point temperature is below 17°C (or 65% relative humidity), the cooling ventilation rate may be maintained at the minimum ventilation rate required by the EN 15251;
If $T_b \leq T_o < T_b + (T_{csp}-T_{hsp})$ and $T_{o\text{-}dp} \leq 17°C$ then $\dot{m}$ = 0.00204 kg/s-m²
3) Direct ventilative cooling useful: when the outdoor temperature is within the comfort zone – given the upper limit as the cooling set point temperature - and outdoor dew point temperature is below 17°C (or 65% relative humidity), the minimum cooling ventilation rate needed to maintain indoor air conditions within the cooling set point temperature are computed as Equation 2;
If $T_b + (T_{csp}-T_{hsp}) \leq T_o \leq T_{csp} - 1$ and $T_{o\text{-}dp} \leq 17°C$ then

$$\dot{m} = \frac{q_i}{c_P(T_{csp}-T_o)} \text{ [kg/s-m}^2\text{]} \tag{2}$$

4) Direct ventilative cooling not useful: when the outdoor temperature exceeds the cooling setpoint temperature and the dew point temperature is above 17°C (or 65% relative humidity) for at least one hour during the day, the ventilative cooling is no longer useful and nighttime cooling potential (NCP) over the following night is evaluated as the internal gains that may be offset for a nominal unit night-time air change rate have been computed as Equation 3:
If $T_o > T_{csp} – 1$ or $T_{o\text{-}dp} > 17°C$ then

$$NCP = \frac{H\rho c_P(T_{csp-night}-T_o)}{3600} \text{ [W/m}^2\text{-ach]} \tag{3}$$

where:
H = floor height [m]
ρ = air density [kg/m³]
$T_{csp-night}$ = temperature cooling set point at night [°C]

The weather file used for the analysis derives from historical data series (2000-2009) of a weather station located in the city of Valladolid, which is part of the Meteonorm database (Weather station ID 81410).

3.2 Coupled thermal and airflow simulations

In order to assess energy savings in terms of cooling need and to evaluate thermal comfort, we performed dynamic simulations using a specific Trnsys module for airflow and thermal models coupling, Trnflow.

The proposed strategy would allow to obtain stack effect ventilation by integrating openings in the upper part of the modular facade and exploiting the existing skylight openings (Figure 3). Openings area and location fits to the modular façade design to reduce frame dividers number.

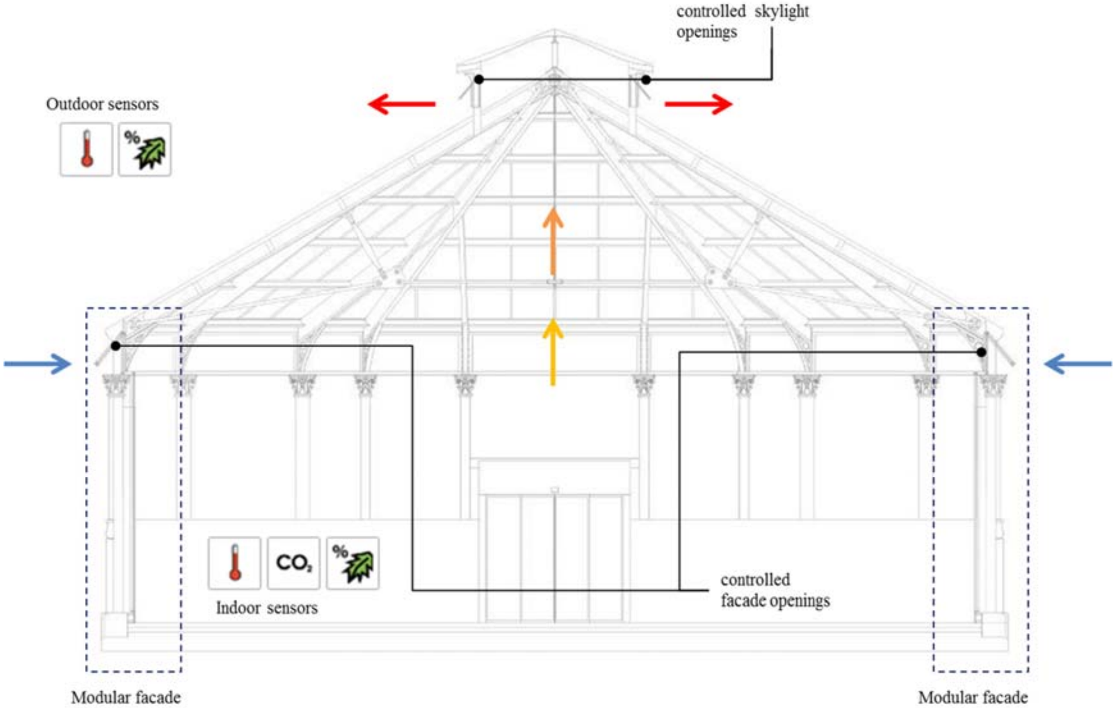

Figure 3. Building cross section with proposed strategy schema.

Table 2 reports the geometrical data about the operable area used in the simulations. Same windows are located both on south-west side and on north-east side covering 18 façade modules, all the modules directly connected to the atrium space. The window height matches the height of the upper part of the façade module. The skylight height matches the existing skylight opening height.

We considered the opening factors as varying between the standard top hung window opening angle and the maximum feasible opening factor:

- Opening factor 0.2 : top hung window with 18°C open angle
- Opening factor 0.4 : top hung window with 36°C open angle
- Opening factor 0.8 : top hung window with 72°C open angle

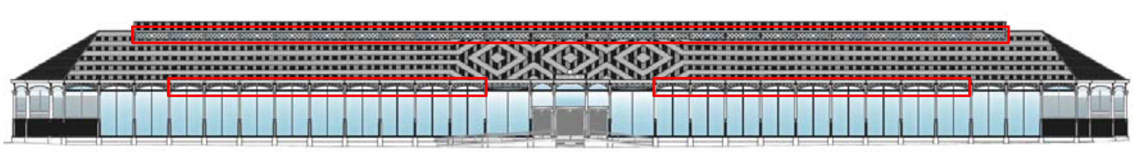

Figure 4: South-west front view of the building where openings locations are highlighted in red.

Table 2. Simulation input data on operable area.

	Opening type	Width [m]	Height [m]	Number of modules	Tot opening area [m²]	Height from the reference ground [m]
Window	Top hung	3.4	0.78	18	48	5.10
Skilight	Top hung	4	0.56	18	40	10.45

In each simulation model, both windows and skylights are operated in the same way and using the same opening factors. Windows are opened if outdoor temperature is above 12°C and controlled depending on the indoor - outdoor temperature difference and the control value at the previous time step.

If the controller was previously on and:

- $T_{in} \geq T_{out} + 2$ then windows stay open;
- $T_{in} < T_{out} + 2$ then windows close.

If the controller was previously off and:

- $T_{in} \geq T_{out} + 5$ then windows open;
- $T_{in} < T_{out} + 5$ then windows stay close.

However the control function is set to 0 if the outdoor temperature is lower than 12°C. Minimum run time period for window operation is set to 20 min.

When outdoor temperature conditions do not allow window opening, mechanical ventilation supply to the building the minimum air change rates required by the EN 15251 standard to maintain an acceptable level of indoor air quality:

- 7.35 kg/hr-m^2 (around 2 ach) during the occupied hours
- 3.02 kg/hr-m^2 (around 0.8 ach) during the non-occupied hours

Simulations were run from April to October both in free-floating mode to analyse comfort according to EN 15251 adaptive comfort model. To assess cooling needs, simulations were also run by setting an unlimited power cooling system with temperature set point of 25°C during the occupied hours according to the recommended indoor temperatures by EN 15251:2008 for department stores at comfort category II.

The results are compared with a baseline where mechanical ventilation always provides the minimum air change rates required by the EN 15251 standard with supplied air temperature equal to the outdoor temperature.

4 RESULTS AND DISCUSSION

In the following paragraphs we present and discuss the obtained results of the climate suitability analysis and the coupled thermal and airflow simulations.

4.1 Climate suitability analysis results

In the Valladolid weather file we identified 95 CD[1], 8567 CDH[2] and an average monthly diurnal temperature swing between 4.5 K (April) and 5.9 K (July).

The graph in Figure 55 shows the percentage of hours within a whole year when direct ventilative cooling is useful according to the classification method described in par. 3.1 and different levels of internal gains.

Depending on the internal gains level, direct ventilative cooling can be useful up to 90% of the hours within a year, whereas for around 10% of the hours the outdoor temperature is higher than the cooling set point temperature and therefore night-time ventilation potential has to be investigated.

[1] Cooling Days defined as the number of days with an average ambient temperature higher than 18°C.

[2] Cooling Degree Hours defined as the integral of the positive temperature differences between the hourly average ambient temperature and a base temperature of 18°C.

The higher are the internal gains, the higher is the number of hours when direct ventilative cooling is required.

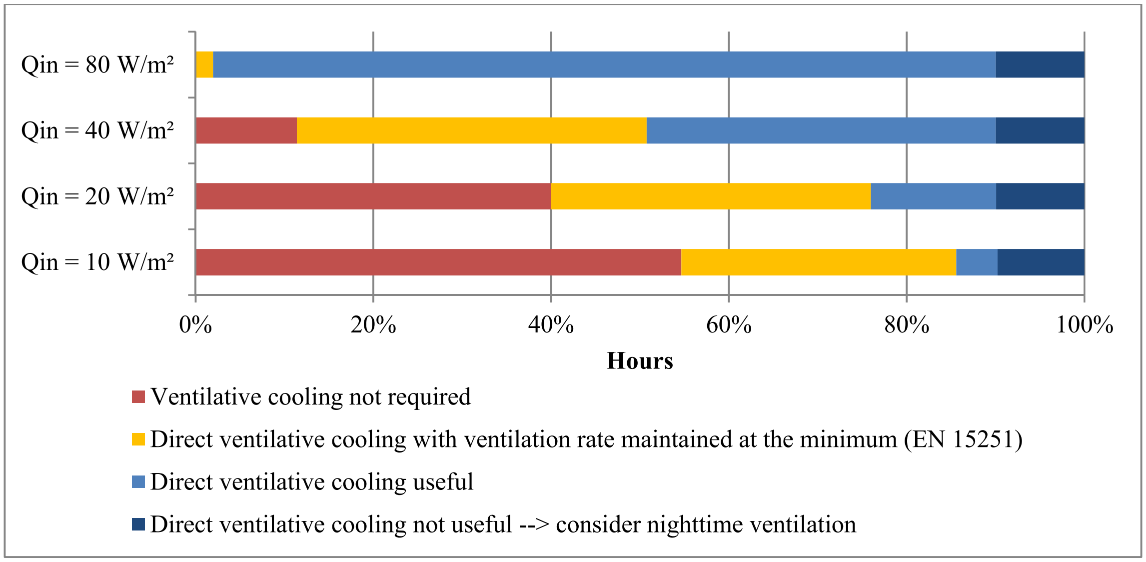

Figure 5: Percentage of hours within a year when direct ventilative cooling is required, useful or not useful in the Valladolid climate considering different values of internal gains.

Mean ventilation rates needed for direct ventilative cooling are reported in Figure 6 depending on internal gains level. For instance, considering the outdoor temperature series for Valladolid and an internal gain rate of 80 W/m^2, up to 4 ach are required on average to effectively cool the building during the occupied hours. As a consequence, the number of effective hours for direct ventilative cooling decreases with the decrease of internal gains.

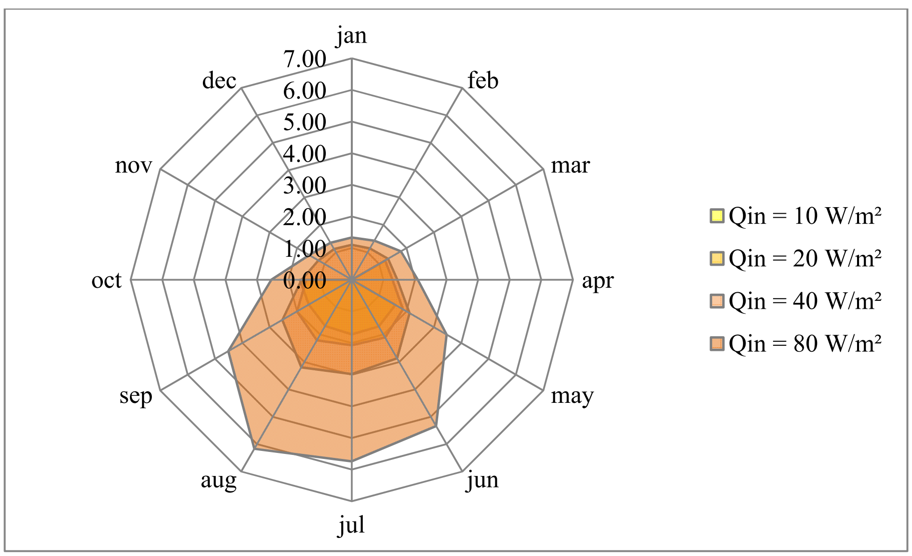

Figure 6. Average direct ventilative cooling rate (ach) for each internal gain level considered and percentage of effective hours within the year in Valladolid.

The graph in Figure 7 shows an estimation of the internal gains that may be offset for a nominal unit night-time air change rate. On average among the summer period an air change rate during the night would be able to offset around 23.5 W/m^2 of internal gains. The number of activation hours matches the percentages identified in the graph in Figure 5.

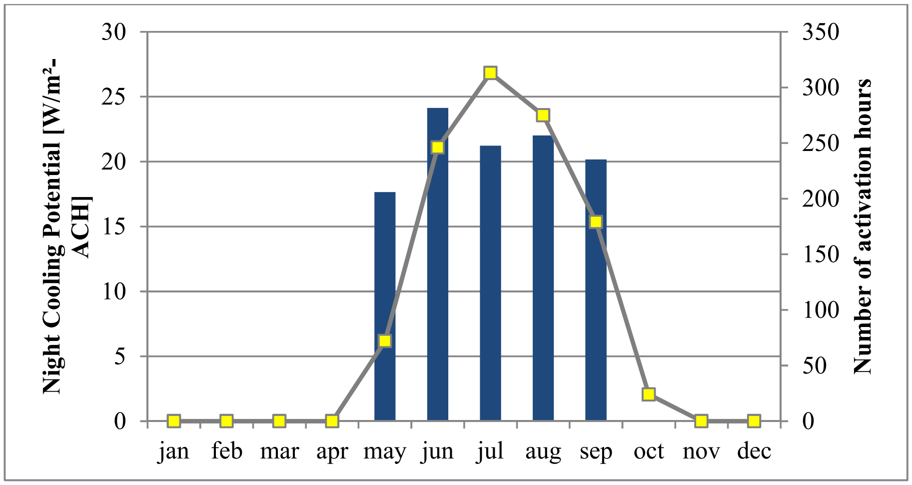

Figure 7. Night cooling potential and number of hours when night cooling can be activated in Valladolid.

4.2 Simulations results

As reported in Table 3, 41% of cooling need reduction can be obtained using an opening factor of 0.4 and 55% using an opening factor of 0.8. Windows with an opening factor of 0.2 cannot assure the minimum air change rates requirements and therefore simulation results show an increase in cooling need by 21% compared to the baseline model. In fact, in the baseline model the minimum air change rates requirements are provided at a constant rate by the mechanical ventilation system. The graph in Figure 8 represents the air change rates frequencies.

Figure 9 shows the simulations results in free floating mode. From April until October the baseline model predict temperatures within the acceptable comfort range, identified according to the adaptive comfort model (EN 15251:2008 standard), for over 85% of the occupied period. This means that, providing fresh air at the minimum air change rates required by the standard, adaptive thermal comfort requirements are met for 85% of the occupied hours. The discomfort is in this case mainly due to too hot temperatures.

Using a window opening factor of 0.8, the ventilative cooling strategy would allow us to reduce or almost zero the discomfort hours due to too hot temperature, even though the number of discomfort hours increase because of too cold temperatures.

Using a window opening factor of 0.2, the number of hours within comfort ranges is 86% compared to the 85% of the baseline case, even though the number discomfort hours is mainly due to too hot temperatures. While an opening factor of 0.2 would cause less 63% of operation hours of the mechanical ventilation system, during most of the time the air change rates are below the minimum required by the standard.

Table 3: Cooling need and number of operation hours of the mechanical ventilation system predicted by the baseline model and the models with ventilative cooling strategy.

	Cooling need [kWh/m²]	Cooling need reduction [%]	Number of operation hours of the mechanical ventilation system
open factor = 0.2	20.68	+21%	1897
open factor = 0.4	10.10	-41%	2858
open factor = 0.8	7.69	-55%	3617
baseline	17.04	-	5136

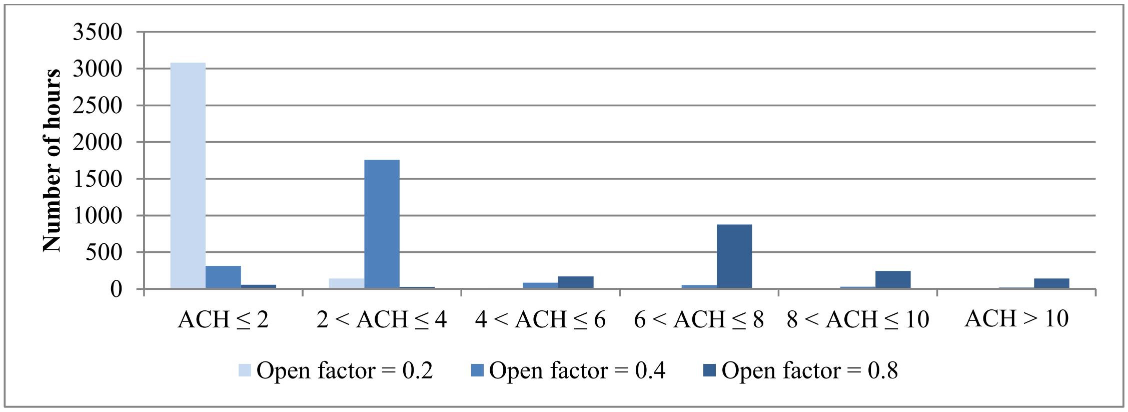

Figure 8: Frequency analysis of the predicted air changes per hour with different opening factors.

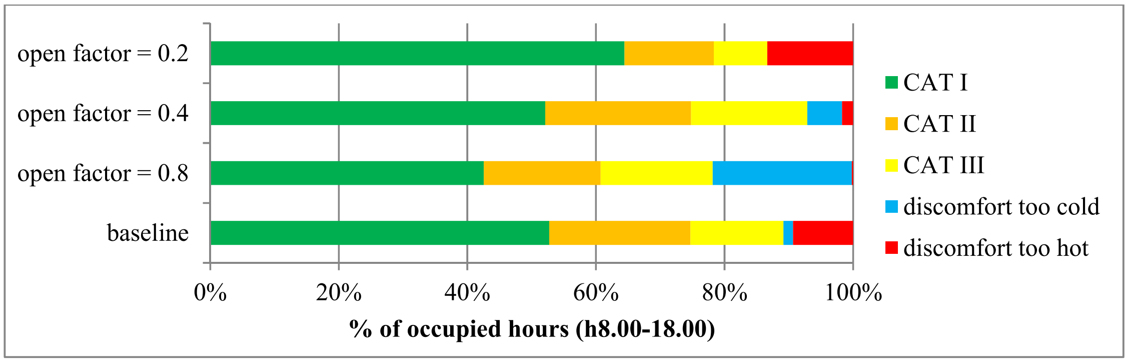

Figure 9: Percentage of occupied hours during which EN 15251:2008 requirements on thermal comfort are met by the baseline model and the models with ventilative cooling strategy.

In our simulation models, the window opening angle is not modulated according to indoor-outdoor temperature difference and therefore discomfort hours due to too cold temperatures increase by increasing the opening factors. This problem can be solved developing a more complex control strategy and using window actuators that allow different opening angles.
Therefore, our design proposal was to define a control strategy which considers opening factor modulation and optimizes it according to indoor-outdoor temperature differences.

5 ADDITIONAL CONSIDERATIONS AND NEXT DESIGN STEPS

Further integration constraints arise from the simulations results. Considering the openings geometry (W >>H) and the high opening angle needed (up to 70°), proper actuators must be selected.
In case of top hung windows, it is recommended the installation of actuators protected from water and solid bodies (dust etc.) and enough powerful to support with sufficient rigidity the maximum load that occurs when the window is completely opened.
Linear actuators are generally more powerful than chain actuators but actuator encumbrance inside the room has to be considered as it affects the aesthetic appearance. Very large windows might also require two thrust points.
Next design step will be focused on:

- the definition of a control strategy once constraints on window opening factor and operable area are defined;
- the optimization of the control strategy parameters;
- the integration of the ventilative cooling strategy within the whole building solution sets concepts (shadings, glazing system, daylighting concept) taking into account for the respective internal and solar gains;

- the integration of openings within the modular façade concept and its replicability on similar buildings;
- a CFD analysis of the building for results validation and evaluation of possible local discomfort situations.

6 CONCLUSIONS

The presented study focuses on the methodology applied to a historical market located in Valladolid (Spain) for the assessment of the ventilative cooling potential and the definition of a ventilative cooling strategy within its refurbishment project.

The climate suitability analysis showed that, depending on the internal gains level, direct ventilative cooling can be useful up to 90% of the hours within a year, whereas for 10% of the hours the outdoor temperature is higher than the cooling set point temperature and therefore night-time ventilation potential was investigated. Considering the outdoor temperature series for Valladolid and an internal gain rate of 80 W/m^2, up to 4 ach are required on average to effectively cool the building during the occupied hours.

According to the resulting climate performance indicators, we defined a ventilative cooling strategy that exploits openings in the façade and in the skylight to activate stack effect ventilation. Openings area and location on the facade have been sized taking into account design constraints and climate potential and tested by dynamic simulations in Trnsys coupled with Trnflow airflow network.

Results show up to 55% of potential cooling load reduction due to the ventilative cooling strategy in the shopping mall maintaining indoor temperatures lower than 25°C. Higher energy savings could be obtained by considering the adaptive behaviour of building occupants. Discomfort situations were mainly due to too cold indoor temperatures in case of high opening factors. Therefore, we suggested window openings to be automated, modulated and controlled depending on indoor and outdoor temperature and humidity.

The proposed methodology was applied to support the design decisions providing quantitative building performance evaluations and allowing a more robust cost estimation. The design team reacted positively at the proposed ventilative cooling solution.

7 ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 608678. The authors would like to thank Javier Antolín Gutierrez, Samaniego Muñoz J. Jesús and Luis A. Bujedo from Cartif for the simulation model production, the design team for the cooperative and positive approach to the collaboration and Magdalena Rozanska from Acciona for activities' coordination regarding the modular façade development.

8 REFERENCES

Atanasiu B., D. C. (2011). *Europe's building under the microscope. A country-by-country review of the energy performance of buildings.* Building Performance Institute Europe (BPIE).

BCSC. (20 de August de 2012). *Shopping centre natural ventilation design.* Obtido de Guidance 68: http://www.bcsc.org.uk/publication.asp?pub_id=459

Emmerich S. J., P. B. (2011). Impact of adaptive thermal comfort on climatic suitability of natural ventilation in office buildings. *Energy and Buildings, 43*(2101-2107).

Weather station ID 81410. (s.d.). Obtido de Meteonorm: http://meteonorm.com/