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Ventilative cooling in shopping centers' retrofit: the Mercado del Val case study

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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 paper presents the ventilative cooling strategy proposed, analysed and implemented in one of the three demo cases of the project: Mercado del Val, the historic market of the city of Valladolid. 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. Considering that indoor spaces of a shopping centre highly interacts among each other, a multizone based analysis of airflows is needed to evaluate the ventilative cooling strategy effectiveness and to assess potential energy savings. We sized openings area and location on the façade, taking into account design constraints, and we assessed their performances in terms of energy, thermal comfort and indoor air quality. Results show the potential cooling load reduction, with the achievement of acceptable thermal comfort due to the ventilative cooling in the shopping mall. The analysis performed supported the design decision process towards cost effective low energy shopping centre.

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Keywords:

1. Introduction

Nearly all retail locations use full air HVAC systems to ensure adequate air exchange, primarily for hygienic reasons, and indoor comfort temperatures. Considering the trend towards longer opening hours and increased number of opening days, the electricity consumption due to ventilation and conditioning systems is expected to continue to rise across Europe.

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Despite their higher energy consumption, mechanical ventilation systems are preferred to natural ventilation strategies because more controllable and reliable, since they are not affected by the uncertainty of natural forces. Thereby, within the design process the team never focused neither on opening sizing nor on control strategies definition for natural or hybrid ventilative cooling systems. So far, shopping centers' design has included a small proportion of automated windows, sized for smoke ventilation only. Depending on the external climate conditions, acceptable levels of thermal comfort and indoor air quality can be reached without or with partial use of the mechanical systems, leading also to operational and maintenance cost savings.

According to the British Council of Shopping Centre (1), in the UK climate annual electricity usage is known to be up to 50% less where natural ventilation is employed over mechanical ventilation depending on the mechanical systems. Furthermore, natural ventilation uses typically between 2-5% less plant space versus 5-8% used by HVAC, which can be utilized and improve net to gross ratios. Therefore, the CommONEnergy project (2) investigates ventilative cooling strategies among the energy efficient solutions for the retrofit of shopping centers' common areas (shop galleries and atria).

This paper presents the ventilative cooling strategy proposed, analyzed and implemented in one of the three demo cases of the project: Mercado del Val, the historic market of the city of Valladolid in Spain.

2. Case study

2.1. Building description

The "Mercado del Val" is an historic iron market built first in 1882 and located within the old town of Valladolid. Its floor plan is a rectangle of 112 meters long and 20 meters wide, with chamfered corners. The shorter building axis is rotated of 60° from absolute north. Therefore, the main building facades are oriented towards northeast and southwest.

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 multifunctional modular climate adaptive façade developed within the CommONEnergy project (2) adapts to the existing structure and aims at integrating thermal, daylighting and ventilation functions, being responsive when internal and external loads change.

(a) (b)

Fig. 1 The Mercado del Val before (a) and after (b) renovation. Source: courtesy of Llanos Urbanos architects

2.2. Definition of ventilative cooling strategy

The climate suitability analysis (3) 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 the remaining 10% of the time the outdoor temperature is too hot and therefore mechanical cooling is needed. Night-time ventilation potential was also investigated. According to the climate suitability analysis (3) and considering the outdoor temperature series for the climate of 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.

Furthermore, 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 ca. 10 m height from the ground level where air can exhaust. According to natural ventilation principles, the higher is the height difference between inlet (façade) and outlet (skylight) openings the higher is the stack effect.

However, inlet openings are not located in the lower part of the facade due to the following issues:

- the large temperature difference between indoor and outdoor might cause cold draughts inside the building. Inlet air at 5 m height, which is approximately the height of the upper part of the façade, would allow air mixing and prevent cold draughts in the occupied zones of the building;
- inlet openings in the lower part of the façade, if not protected might cause safety issues;
- lower inlet openings in urban environments might increase indoor air pollution. Filters would cause a high pressure drop of the air reducing significantly natural ventilation effectiveness.

Therefore, the inlet openings height matches the height of the upper part of the façade module (circa 6m). Since the heritage council required to preserve the existing steel structure, the renovated facade will be installed on the inner side of the existing structure. Therefore, windows can be opened only inwards as the steel arches would obstruct window movement.

Fig. 2 reports a scheme of the building ventilation strategy with openings' location and sensors needed to control openings. We considered two types of vents: facade vents (1.72 m width x 0.78 m height) and skylight vents (3.63 m width x 0.56 m height).

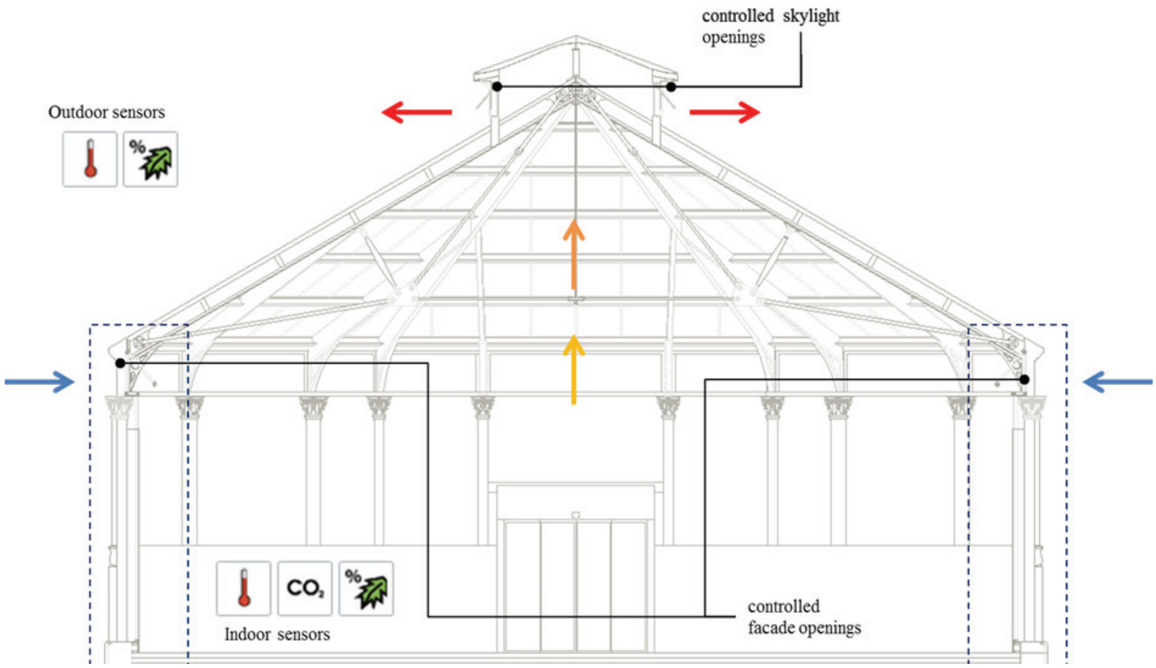

Fig. 2 Building cross-section with openings location and possible sensors for the control strategy.

2.3. Window automation

Windows automation occurs by means of chain actuators connected to the building management system, which controls the opening angle according to indoor and outdoor temperatures measured by the installed temperature sensors. Our simulation analysis did not take into account relative humidity controls. Chain actuators have to enable vents opening up to a 35° angle, which correspond to an opening factor of 0.4.

Considering the windows dimension and weight, double actuators would be necessary on each facade vent and triple actuators on each skylight vent. The multiple actuators should be equipped with a synchronization function, in which the actuators communicate directly with each other, which ensures the actuators operate at exactly the same speed and position.

Preliminary simulations results (3) showed that opening angle modulation is necessary to prevent cold draughts during spring and fall. Therefore, actuators have to be accessorized by a position feedback in order to provide two-way communication with the control panel and to enable feedback to the control software on: the exact position, for precision of opening and control, as well as a security indicator for open windows; the window status and an early indication of any errors with the actuator operation or the wiring.

Chain actuators can open windows up to maximum 35° angles, which correspond to an opening factor of 0.4. Chain actuators have a lower aesthetical impact as they can be integrated in the window frame. Several opening possibilities are available but, due to the existing steel structure on the outside part of the glazing system, the façade windows can open only inwards.

3. Ventilative cooling solution analysis

Considering that indoor spaces of a shopping center highly interacts among each other, a multizone based analysis of airflows is needed to evaluate the ventilative cooling strategy effectiveness and to assess potential energy savings. The Integrated Modelling Environment under development within the CommONenergy project allows to predict airflows throughout a building by performing coupled thermal and airflow building dynamic simulations.

The airflow network involves the main open space volume of the building where common areas are located.

Linkages between two thermal zones within the building are represented by large horizontal openings as big as the adjacent surface between the zones and whose opening factor is always set to 0.8. Wind pressure coefficients (Table 1) are predicted using Cp Generator tool (4), which considers also local obstacles, and surrounding buildings.

Table 1. Wind pressure coefficients array on south-west and northeast facade.

	0°	45°	90°	135°	180°	225°	270°	315°
South-west facade	0.142	-0.136	-0.275	-0.146	0.334	0.222	-0.039	-0.196
North-east facade	0.081	-0.040	-0.018	-0.303	-0.284	-0.221	-0.226	-0.111

During occupied hours window opening factors are controlled according to the following logic:

- If $16°C \leq T_{amb} < 22.5°C$ then window opening factor is set to 0.2;
- If $22.5°C \leq T_{amb} \leq 26°C$ then window opening factor is set to the maximum;
- $T_{amb} > 26°C$ then windows are closed and cooling system is activated.

Mechanical ventilation, infiltration losses and heating/cooling system is activated only when windows are closed. Relative humidity is not taken into account since HVAC system does not control it either. Night cooling mode during non-occupied hours is activated if the average outdoor temperature of the previous 8 hours is greater than 24°C.

We performed parametric analysis on the building simulation model by using the number of openings as variable in order to optimize the cost of investment in relation to the predicted energy savings. Parameters set are reported in Table 2.

G_0 represents the baseline model, fully mechanically ventilated and cooled. This model considers also other features of the multifunctional façade such as the optimized glazing system and solar control through automated shadings. In order to reduce the computational time we consider the longwave radiation exchange within the zone using the standard model. This leads to a 1% increase in cooling load and a 2% increase in heating load.

Table 2. Parametrization settings

ID	Maximum opening factor	Number of façade vents	Number of skylight vents	Opening area per facade [m²]	Number of skylight vents	Opening area on skylight [m²]
G_0	0	0	8	0	0	0
G_1	0.4	24	8	16.10	8	8.13
G_2	0.4	32	16	21.47	16	16.26
G_3	0.4	40	20	26.83	20	20.33
G_4	0.4	48	24	32.20	24	24.39
G_5	0.4	56	28	37.56	28	28.46
G_6	0.4	64	32	42.93	32	32.52
G_7	0.4	72	36	48.30	36	36.59

3.1. Thermal-airflow simulation results

This section presents the thermal-airflow simulations results in terms of energy and comfort.

3.2. Potential energy savings

Simulation results are here analyzed in terms of heating and cooling need and number of operation hours of the mechanical ventilation system. We estimated the electricity consumption for heating and cooling assuming that air conditioning is provided by a heat pump with COP = 4.21 and EER = 5.7 in cooling mode. The efficiency of the AHU is assumed as 0.72 Wh/m³, as declared in the technical report of HVAC plants.

The graph in Fig. 3 reports the estimated energy need for heating and cooling and the number of operation hours of mechanical ventilation. Up to 40% potential energy savings results from simulations predicted heating and cooling need and number of operation hours of mechanical ventilation.

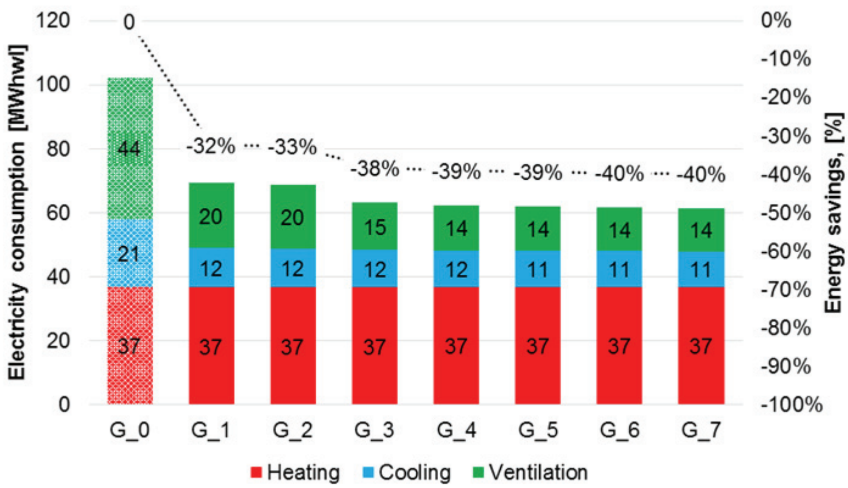

Fig. 3 Estimated electricity consumption for heating, cooling and ventilation and overall energy savings.

3.3. Adaptive comfort

The adaptive comfort analysis is based on free-floating simulations, where no cooling set point is active. This allows analyzing the passive behavior of the building during cooling season.

The graph in Fig. 4 compares the percentage of occupied hours when the operative temperature of thermal zone exposed to south is within the comfort categories ranges defined in the standard EN 15251 for the adaptive comfort model. reports the percentage of overheating hours and the number of days when daily weighted exceedance is above 6 K. Compared to the base case, the percentage of overheating hours and the daily weighted exceedance can be significantly decreased, except in the case when the number of façade windows (nr 24) is not enough to allow for ventilative cooling.

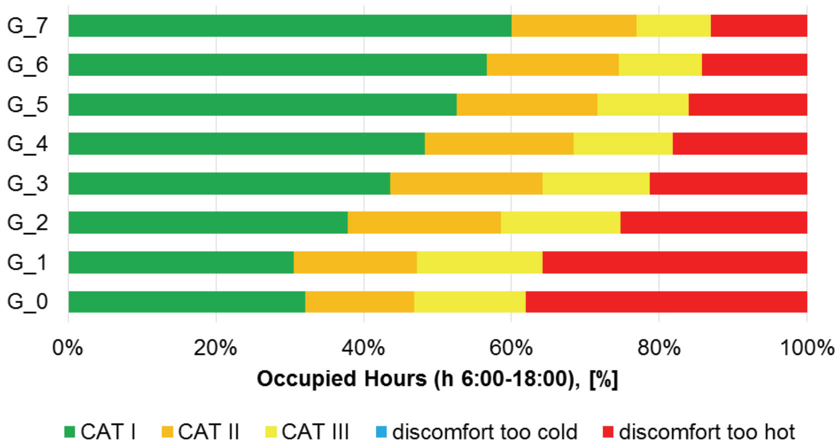

Fig. 4 Percentage of occupied hours when the operative temperature is within comfort ranges for categories defined in EN 15251. Operative temperature refers to zone on south side.

If the number of façade windows is higher than 48 (case G_4) there would be only a couple of days when daily weighted exceedance is above 6 K. This means that generally during a day the operative temperature is above the upper limit temperature for short period or slightly above the upper limit temperature for period no longer than 6 hours.

Table 3. Percentage of occupied period when upper limit temperature is exceeded and number of days when daily weighted exceedance is above 6.

	G_0	G_1	G_2	G_3	G_4	G_5	G_6	G_7
Overheating hours [%]	38	36	25	21	18	16	14	13
Nr of days when We > 6 K	22	39	16	6	2	2	1	1

3.4. Airflow rates

According to the EN 15251 values for department stores (Cat. II – low polluting building) the minimum ventilation rate is 1.7 l/s-m² (7.35 kg/hr-m²). Considering an area of 708 m² in the south part of the building, the required inlet mass flow rate through the south facade correspond to 2648 kg/hr.

The graph in Fig. 5 shows the frequency of inlet mass flow rates from windows on south facade when windows are opened during daytime. The number of hours when mass flow rates are below 2500 kg/hr in case G_1 is three times higher than the other cases. This means that this solution does not comply with the minimum required air change rates during most of the time. The higher is the number of openings, the higher are the predicted mass flow rates. Mass flow rates up to 30’000 kg/hr are predicted.

The graph in Fig. 6 shows the frequency of inlet mass flow rates when windows are opened during night-time. Mass flow rates are higher during night-time because the windows are set to be fully opened and not modulated and also because of the lower outdoor temperatures.

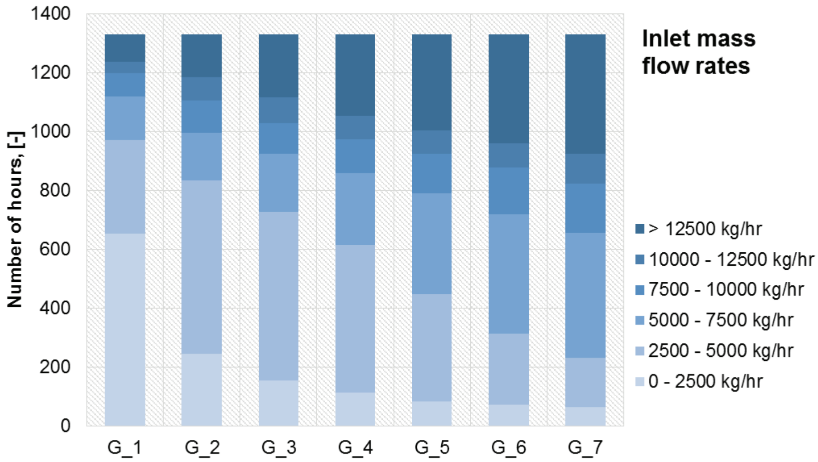

Fig. 5 Inlet mass flow rates frequency when windows are opened during daytime.

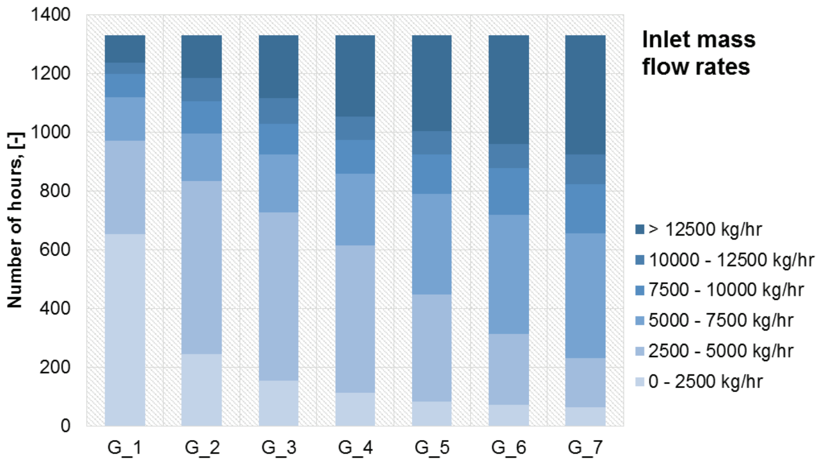

Fig. 6 Inlet mass flow rates when windows are opened during night-time.

3.5. Cost optimization

Finally, we identified the number of openable windows by trading-off energy, comfort and cost aspects. The graph in Fig. 7 shows the total electricity consumption per heating, cooling and ventilation per year compared to the estimated additional cost of investment for window automation. The graph compares the fully mechanically ventilated and cooled building with the mixed-mode building, naturally ventilated when climate conditions are suitable. The color refers to the number of days when daily weighted exceedance is above 6K and therefore to the overheating risk.

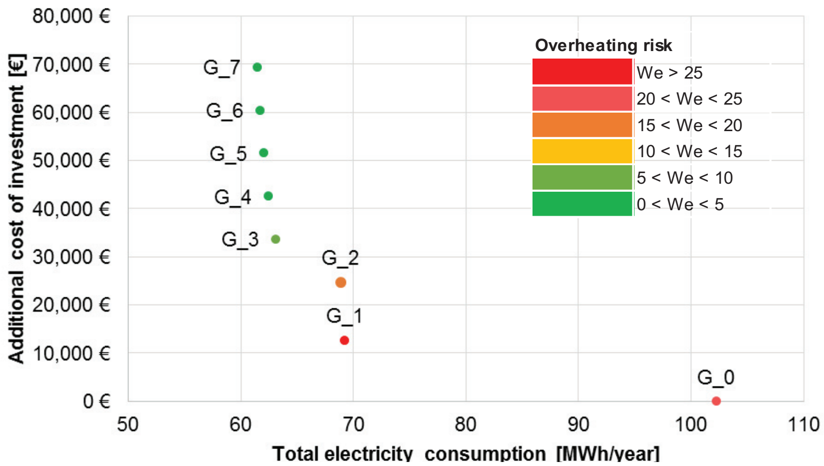

Fig. 7 Total electricity consumption per heating, cooling and ventilation per year compared to the additional cost of investment for window automation. The color refers to the number of days when daily weighted exceedance is above 6K and therefore to the overheating risk.

Cost of investment for window automation vary from 12,700 € up to 70,000 € depending on the number of windows that are automated. Assuming a cost of electricity of 0.15 €/kWh, cost savings in terms of operational costs amount at circa 5,000 €/year in the case with 24 openings in the facade and at 6,000 €/year in the case with 72 openings in the facade. The lower is the number of windows the lower is the cost of investment, but also lower are the energy savings. The solution represented by case G_4 is the optimal one as it has low overheating risk and energy consumption at the lowest additional cost. According to parametric simulations analysis, the optimal number of vents per facade is 24 and the optimal number of skylight vents is 12 per side. In total 48 facade vents and 24 skylight vents are needed.

4. Conclusion

The paper presented the analyses on energy, comfort and costs used to support the design of the historical market renovation in Valladolid (Spain). The Integrated Modelling Environment under development within the CommONenergy project allowed to predict indoor temperatures and airflows throughout the building by performing coupled thermal and airflow building dynamic simulations.

Results showed up to 40% potential energy savings for the mixed-mode ventilation strategy compared to the fully mechanically ventilated baseline over the total consumption for heating, cooling and ventilation. By properly sizing the openable area, natural ventilation allows also ensuring minimum required air change rates to keep an acceptable level of indoor air quality.

The results have been applied to support the design decisions providing quantitative building performance evaluations and allowing a more robust cost estimation. The optimal number of openable windows was suggested by trading-off energy, comfort and cost aspects. The automation of 48 façade vents and 24 skylight vents allows to reduce the overheating risk to a weighted exceedance above 6K for only 2 days over the year, to keep a good indoor air quality and to reduce the electricity consumption for cooling and ventilation by 40% compared to the baseline case.

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