Mixed-mode ventilative cooling opportunity for an existing shopping mall retrofit

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ABSTRACT

Shopping centres currently design has included a small portion of automated windows sized for smoke ventilation. Their presence is mandatory for fire regulation and they are usually operated just in case of fire. Nevertheless, these buildings can potentially take advantage of those openable windows to exploit the potential of natural ventilation to guarantee the minimum air change rate required by IAQ standards and for ventilative cooling purpose reducing cooling and electrical consumption.

The work presented in this paper investigate the retrofit performance potential of a mixed-mode ventilative cooling strategy tailor-made for an existing shopping centre. At the present, natural ventilation in the case study common areas is provided just on the basis of the energy manager judgment, without taking into account a robust control strategy based on indoor-outdoor climatic condition, thermal comfort and building use. A building model was created within TRNSYS environment and calibrated based on the real monthly electrical energy consumption. Then, with the support of the TRNFLOW plug-in, that couple thermal and airflow simulations, we were able to simulate and test the effectiveness of the tailor-made mixed-mode strategy. The simulation results show that windows opening can be operated starting from March to November. Running common areas with mixed-mode strategy over a year can allow to save 265 MWh which means cutting the electrical consumption by 23%.The initial costs for control strategies implementation can be paid in the first year of operation.

The main contribution of this work is to demonstrate the feasibility of a mixed-mode ventilative cooling solution for an existing shopping mall common area retrofit highlighting how the exploitation of existing automated windows makes the solution cost-effective.

KEYWORDS

mixed-mode strategy, electricity consumption reduction, shopping mall, common area retrofit, ventilative cooling

1 INTRODUCTION

At the present, few European shopping centres consider natural ventilation as a mean to meet air-change requirements or to exploit free cooling potential. These shopping centres are located in both mild climate (Carrilho da Graça G., 2012) and in more rigid climate as the Field's

shopping centre (Tranholm G.T., 2012), proving how it is possible to take advantage of different climatic potentiality when proper design and control strategies are developed.
The common practice of mixed-mode ventilation in shopping malls is indeed to have a naturally ventilated large common space that is linked to individually air-conditioned retails lots (Hamlyn D., 2012). Most of the projects that exploit mixed-mode ventilation in shopping centres (Windowmaster, 2015) take advantage of the openable windows and skylights already designed for smoke ventilation. Openable windows located in big atria and galleries, the so-called transitional spaces of a shopping centre, are required for smoke ventilation by fire regulation and are usually operated just in case of fire. The potential of these zones, such as the big volume involved and the range of more relaxed range of interior thermal conditions compared to the adjacent stores, as suggested by Hamlyn et al. (Hamlyn D., 2012), combined with the fact that no extra investment is necessary for windows automation, could allow for a very cost-effective retrofit solution in order to reduce electricity consumption for both ventilation and cooling.
A previous study (Avantaggiato M., 2015) showed how, when facing a retrofit, the ventilative cooling design have to consider the level of internal gains in order not to oversize the airflows. Overlooking this interdependency could lead to discomfort condition due to drafts and to extra investment costs for openings´ actuators, which might not be necessary. Since employing mixed mode ventilative cooling can significantly reduce the cooling load, the impact of more efficient cooling systems could happen not to be relevant anymore. This suggests that when approaching both retrofit and a new design, ventilative cooling should therefore be considered before any HVAC improvements or before a new detailed design of any HVAC equipment.
The aim of this study is to explore the ventilative cooling opportunity of a mixed-mode ventilation strategy tailor-made for an existing shopping centre. At the present, in the case study, the Donauzentrum shopping centre, natural ventilation in common area is activated just on the basis of the energy manager judgment, without taking into account a robust control strategy based on indoor-outdoor climatic condition, thermal comfort and building use. The outcome of this work is to define and test the thermal and economic performance of a new control strategy for the automation of the windows based indoor-outdoor climatic condition, thermal comfort and users' occupancy of the common areas.

1.1 Case study

The case study presented in this paper is the "Donauzentrum" shopping centre, located in Wien, Austria. It opened in 1975 with 22'800 m^2 of retail space while today the total area occupied is around 130'000 m2 including over 260 retail, dining and entertainment business. Since 1975, indeed, the mall has been several times extended and remodelled until reaching the present configuration into 2010.
Within the research activities of the CommONEnergy project, just part of the entire shopping centre has been considered which general characteristics are presented in Table 1 while Figure 1 on left shows the different block of the mall considered for the analysis. Blocks BT 4-5 and BT 1-3,9 are the oldest part and are also bridged by an above-ground tunnel used as shopping area. Block BT 7 is newest area of the mall, partly retrofitted in 2010.

Table 1 General info about Donauzentrum shopping centre

General info			
Building footprint [m²]	58145	Common areas and galleries [m²]	11257
Gross Leasable Area [m²]	81364	Number of opening hours per day [h/d]	11
Food store vending area [m²]	8131	Number of opening days per week [d/w]	9
Tenants vending area [m²]	73233	Number of closing days per year [d/y]	10

1.2 Retrofit solution set

This shopping centre is one of the reference shopping centre within the EU FP7 CommONEnergy project (Bointer,R, 2014). One of the objective of the EU FP7 CommONEnergy (FP7-2013 grant agreement no 608678, 2014-2017) project is the development of architectural and energy systems retrofitting solution sets with the aim at reducing shopping centre energy needs, enhancing the overall energy efficiency to provide appropriate indoor environmental quality (IEQ) and exploiting renewable energy sources (RES).

A solution set is meant to be a combination of energy conservation (passive solutions) and energy efficiency measures (active solutions). The measures are integrated looking for and exploiting synergies among HVAC, lighting, refrigeration, energy use as well as for building correlated services (parking, RES harvesting and local energy production etc.).

The definition of the solution-set involves several steps. First step concerned the collection of data about the reference building features, operation modes and measured data to build an energy simulation model. Second step has been the creation of a building energy model enable to predict the energy consumption and loads on hourly basis, as well as indoor conditions and interactions among solutions. The model has been then calibrated against utility data in order to deliver results to be considered valuable to the building owners. The Integrated Modelling Environment (IME), a TRNSYS-based simulation environment, developed within the project (Dipasquale, 2016) is used to support all the shopping mall retrofitting phases. More info related to the methodology used for the calibration of the building energy model can be found in (Cambronero Vàzquez, 2017). Once the baseline was finalized, the further step was the identification of inefficiencies and possibilities for the implementation of new solutions. The inefficiencies identification was supported by the analysis of the baseline outcomes model and by several interviews to the facility manager. These interviews were really fruitful to identify not only possibilities for the implementation of new solutions but also to understand the ideas of the management about future energy efficient actions. In the last steps we have the definition and implementation of the solution-set, the assessment of the potential energy saving and an economic analysis of the solution-set proposed. More information about the methodology followed for the solution-sets definition and the complete methodology can be found in the project report (Cambronero Vàzquez, 2017).

Related to Donauzentrum case study, it comes out that one of the main interest of the management was the exploitation of ventilative cooling in common areas. Existing skylight windows were already used for natural ventilation purpose but without a specific strategy, just manually operated under the energy manager judgment. Taking into account this main demand, we carried out a feasibility study to define a mixed-mode ventilative cooling strategy. Particularly we define a control strategy in order to automatically operate and control the windows and the mechanical ventilation system on the bases of different conditions which are going to be presented in paragraph 2.2.

The most suitable natural ventilation strategy identified for the common areas is an enhanced stack ventilation, which use skylight and upper windows to flush out the warm air stacked in the upper part of the common areas because of thermal stratification. The fresh air enters at lower part from the entrance doors and is driven through the building by vertical pressure differences resulting from thermal buoyancy. Being the shopping centre locate in a dense urban contest and because of common areas features, the author believe that the main driving force is thermal buoyancy. For these reason the effect of wind pressure has been overlooked

The design of the ventilation strategy take advantage just of the existing openable windows, skylight and entrance doors, resulting in a very cost-effective solution since the investment costs are restrained to the connection of the window automation system to a building management system. A previous study about feasibility of ventilative cooling in shopping centres (Avantaggiato M., 2015) showed the evidence of dependence between the level of lighting power density and the percentage of hours of direct ventilative cooling use. The analysis of the actual electricity consumption of the shopping mall has showed how more than 50% of this consumption is due to lighting and electric equipment (Cambronero Vàzquez, 2017).Being beneficial for both electricity consumption savings and for ventilative cooling purpose, we proposed as first step in the solution-set the reduction of internal gain due to lighting and appliances. Table 2 shows the value of lighting and appliance level considered before and after a potential retrofit of Donauzentrum. In the same table we can see the effect of these improvements on electricity consumption for lighting and appliances and the cooling consumption. The impact of reduced internal gains is relevant especially for the electricity cooling consumption of the common area, resulting in a reduction of more than 50% of its consumption. This first improvement allowed to reduce the cooling demand of the common areas which results to be beneficial for the mixed-mode ventilative cooling effectiveness (Avantaggiato M., 2015).

Table 2 Comparison in term lighting, appliance level and electricity consumption before and after the application of the retrofit solution

	Lighting level	Appliance level	Electricity consumption for lighting and appliances		Electricity consumption for cooling	
	W/m^2	W/m^2	MWh/year	reduction %	MWh/year	reduction %
Before	35-22[1]	10	1764	-11	1071	-57
After	4	5	1564		457	

More information related to the complete solution-set for the Donauzentrum shopping centre are reported in (Cambronero Vàzquez, 2017).

2 METHODOLOGY

In order to compare the effect of the mixed-mode ventilative cooling strategy two different yearly-based simulations have been run which represent two different scenario. A ***reference scenario*** where ventilation demand and cooling demand is fully covered by the HVAC system, which represent the situation after the improvement of the internal gain proposed in paragraph 1.2, and a ***mixed mode scenario*** in which depending on the outdoor and indoor conditions, the different MODEs which are going to be present in paragraph 2.3 can be operated.
For the baseline scenario, the heating and cooling set-points are the one reported in section 2.1. For the mixed-mode scenario a different cooling set-point has been used. From a real assessment of thermal comfort in shopping centre common areas, it comes out that operative temperature of 28 ºC are judged as comfortable by costumers (Belleri, 2017). In order to make sure not to overcome this threshold because of the internal and solar gain affecting the mean radiant temperature, the cooling set point has been kept at 27 ºC.

2.1 Building energy model

According to the methodology reported in paragraph1.1, based on the information collected related to the actual state of the mall, a building energy model was created within TRNSYS environment. Figure 1(right) shows a sketch-up of the building model used for the whole study. All details related to the building energy model used for the simulation (e.g. internal gains, building thermal features, schedule, etc.) are collected in the project report (Cambronero Vàzquez, 2017) .For the content of this paper we are going to report just the information related to the simplified modelling of the HVAC system.
The model includes three different typologies of openings, the characteristics of which are collected in Table 3:

- entrance doors (WI_E) ;
- skylights (WI_SK) ;
- windows integrated in the lateral glazed facades (WI_LW) .

[1] These value refer to the average lighting level of two different common areas of the shopping centre.35 W/m^2 refer to BT1-3/9-4-5 while 22W/m^2 to BT7 (see **Error! Reference source not found.**-left).

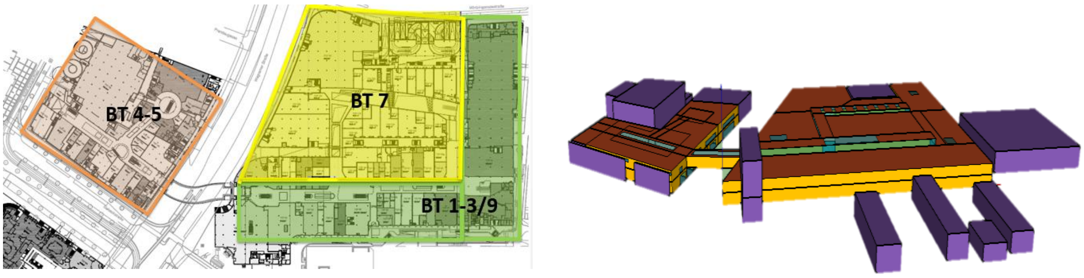

Figure 1 Different building block of Donauzentrum (left), Sketch-up of the building model used for the study (right)

Common areas and tenants are served by the same HVAC system. The system recovers 80% of the exhausted air and mix it with the outside fresh air. Air extractors balance the inlet mass flow. The system is a constant air volume system and the inlet air temperature is adjusted according to the outdoor temperature. If the outside temperature is lower than 13°C the inlet air temperature is the one resulting from the mixture between the temperatures of the recirculated air, assumed to be 80% of the total air flow, and the outside temperature. When the outside temperature is indeed greater than 13°C, the supplied air temperature is equal to the outside one. Heat recovery between recirculated and outside temperature is also taken into account (Table 3). This control has been set for all the days in which the shopping centre is opened. A CO_2-based ventilation regulates the airflows based on the occupancy of the shopping mall. Since no information about the working airflows of the ventilation unit were provided, we assumed that the ventilation unit provides 37.8 m^3/h per person as recommended by the European standard EN 15251, for retail buildings, referring to Category II (EN ISO 15251, 2008) . Infiltration rates are set to 0.5 ach in each zone of the model but they change according to the wind pressure (Coblentz & Achenbach). The mall is connected to the local district heating system, which provides thermal energy for heating to the whole mall. A typical dry cooler provides cooling to the newest part BT7. In BT1-3/9 and BT4-5 block cooling is generated by a standard chiller coupled with an open cooling tower. The heating demand of the mall has been calculated by assuming a constant set point temperature of 18°C from 9 a.m. to 8 p.m. and a setback temperature of 13.5°C during night. The cooling demand has been calculated by imposing a set point temperature of 25°C from 9 a.m. to 8 p.m. The cooling system is turned off during the night. No additional air humidification is considered during the winter time. System efficiencies considered in the analysis are reported in Table 3.

Table 3 Efficiencies of the systems considered in the studies

Building Block	Ventilation specific power	EER	Heat Recovery	District Heating
BT 1-3-4-5-9	1.5 Wh/m^3	3	60%	0.9
BT 7	0.9 Wh/m^3	3.5	40%	0.9

2.2 Mixed-mode ventilative cooling modelling

Figure 1 (right) shows the common areas involved in the ventilation strategy. In order to assess energy savings in electricity consumption reduction and to evaluate the thermal condition inside common areas, we performed dynamic simulations using a specific Trnsys module for airflow and thermal models coupling, Trnflow.

Both skylights (WI_SK) and façade windows (WI_LW) are top-hung windows with a maximum opening angle equal to 45º which correspond to an opening factor of 0.5.

Figure 2 shows the common area involved in the strategy while Figure 3 shows some pictures of the existing openable windows typology in the same common areas. All the details of the opening considered in airflow network implemented in TRFLOW are showed in Table 4.

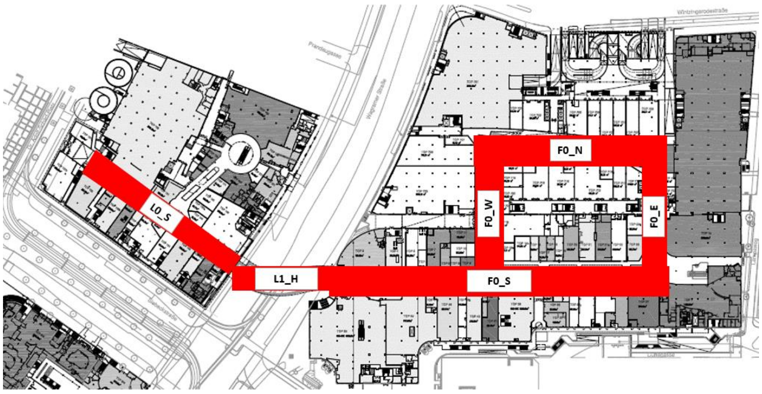

Figure 2 Common Areas involved in the ventilation strategy

Figure 3. Some of the openable windows considered in the ventilation strategy

Table 4 Details of the openings considered in the airflow network implemented in TRNFLOW

Zone	Reference link	Number of openings	Height [m]	Width [m]	opening area [m^2]	Height from the ground [m]	max Opening factor
L1S	WI_SK_1	76	1	1	1	12	05
L1H	WI_SK_2	32	0.6	0.6	1.2	12	0.5
F0S	WI_SK_3	12	0.9	1.9	1.71	16	0.5
L0S	WI_E_1	1	10.1	4.6	46.5	0.10	0.2
L0S	WI_E_2	1	10.1	4.6	46.5	0.10	0.2
L1S	WI_E_3	1	12.8	5.8	74.2	0.10	0.2
F0S	WI_E_4	1	11.7	4.8	56.2	0.10	0.2
F0S	WI_LW_1	24	0.6	2	1.2	12.1	0.5
F0S	WI_LW_2	8	1.6	2	3.2	12.1	0.5

2.3 Control rules for mixed-mode ventilative cooling

The control rules for the mixed-mode operation have been developer taking into account both indoor and outdoor parameters. When the condition for the opening of the windows are reached the mechanical ventilation is switched off and vice versa, resulting in different working mode. The inputs needed for the control of mixed-mode ventilation and cooling are:

- Occupancy time schedule of the common areas which is from 9 a.m. to 8 p.m.;
- Outdoor air temperature, T_{ext}, [ºC];

- Minimum outdoor temperature for windows opening, T_{ext_min}, [°C] which in this case is equal to 14 °C;
- Heating temperature setpoint, T_{set_H}, [°C];
- Cooling temperature setpoint, T_{set_C}, [°C];
- Temperature threshold for night cooling activation T_{set_NC}, [°C], which has been set equal to 22 °C;
- Air temperature inside the common areas, T_{zone}, [°C];
- Average air temperature inside the common area within the previous eight hours $T_{zone\_avg\_8h}$, [°C].

Based on input conditions different ventilation modes has been defined:

- ❑ MODE 0: during opening hours, when the outdoor temperature is below the T_{ext_min} ,minimum airflow rates are provided by mechanical ventilation and cooling demand is covered through mechanical cooling system;
- ❑ MODE 1: when the outdoor temperature is below the T_{ext_min} and the T_{zone} falls into the three condition expressed in Figure 4, window WI_SK and WI_LW are open with a factor 0.5 with a windows opening factor equal to 0.5 while 0.3 for entrance doors (WI_E). When windows are operated, the HVAC system is off;
- ❑ MODE 2: out of the opening hours and between 3 a.m. and 6 a.m., if the temperatures inside the zones in the previous eight ($T_{zone\_avg\_8h}$) hours were higher than T_{set_NC} °C, natural night cooling can be operated. In this mode, just WI_SK and WI_LW windows typology are used with maximum opening;
- ❑ MODE 3: during not occupied period and out of the interval between 3 a.m. and 6 a.m., just infiltration are considered, for all the year.

The control scheme is presented in Figure 4.

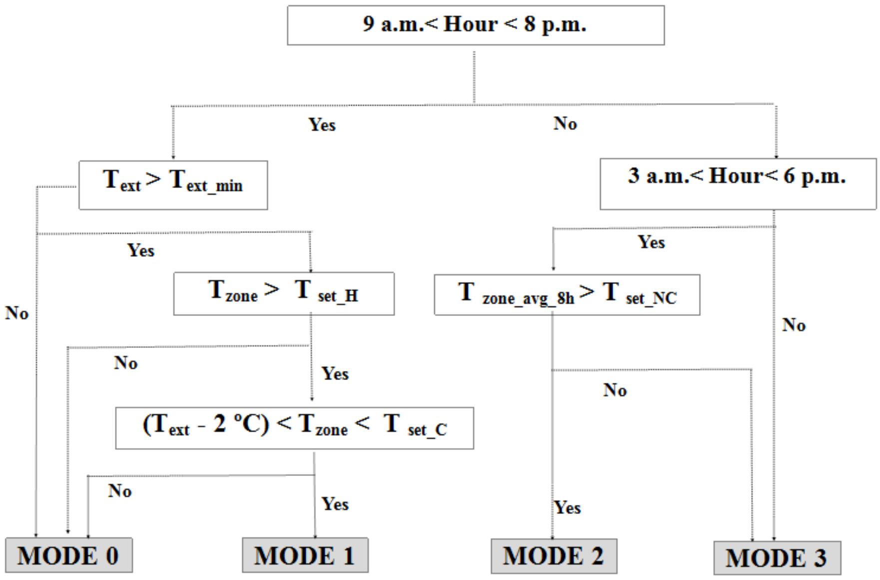

Figure 4 Control strategy scheme for mixed-mode ventilation in common areas in Donauzentrum

3 RESULTS

Based on the outdoor climate and indoor thermal conditions, daytime natural ventilation (MODE 1) can be activated from end of March up to early November while night cooling (MODE 2) is applied from early May to early September. According to simulations results, the building run in MODE 1 for 25% of the shopping mall opening hours while MODE 2 run for 9% of the closing hours. Running common area with mixed-mode strategy over a year can allow to save 265 MWh which means cutting the electrical consumption by 23%. The heating demand is not affected which prove how the mixed-mode control strategy prevents the opening of the windows when the outside conditions are too rigid and the recirculation of outside colder air may create a decrease of indoor temperature with consequent increase in the heating demand for compensation. **Error! Reference source not found.** shows the monthly electricity consumption for both reference and mixed-mode scenario. The cut of mechanical ventilation electricity consumption in the mixed-mode scenario is highlighted during mid-season months when suitable outdoor temperature allow outdoor condition for recirculating fresher air from outside

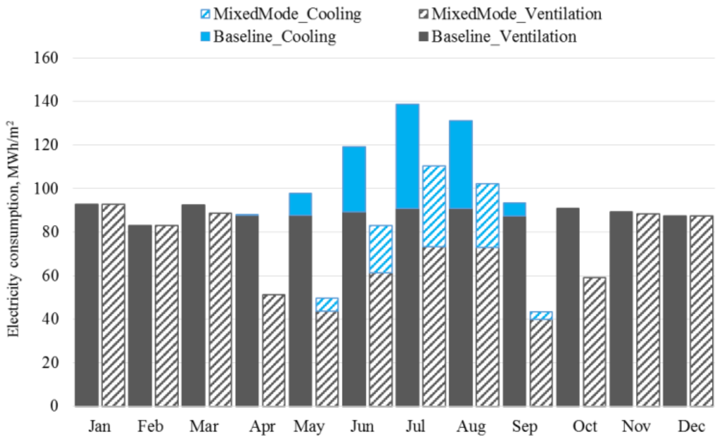

Figure 5 Monthly trend of electricity consumption for ventilation and cooling for Baseline scenario and Mixed-mode scenario

In Figure 6 and Figure 7 we report the mixed-mode operation respectively during a temperate and warm week of June. The grey column refers to the operation of the windows during day while the blue one to the operation at night. The main difference we might notice between the two graphs is that when the outdoor temperature is quite limited (below 24 ºC, Figure 6) the operation of the window is really often during the day. Once the outdoor temperature starts raising over suitable threshold for natural ventilation application (Figure 7) the operation during the day is limited with a preference for the active cooling system to maintain comfortable temperature inside common areas. Under mixed-mode operation comfortable condition can be provided during the day with operative temperature below 28 ºC.

The effect of internal and solar gains is visible in the difference between the average air temperature and the operative temperature of the zones.

The operation costs that can be save by running the building in mixed-mode condition and the accepting new comfortable ranges in the common areas, are estimated to be around 26500 €/year[2].

With an initial investment cost of 100 € per window module or entrance door which takes into account of the connection of windows automation to a building management system, installation and engineering and permitting costs, the solution turns to be very cost effective. Over an expected working period of 25 year, the estimated Pay Back Time is less than one year (with a discount factor lower than 8%) Further information about the economic analysis assumption can be found (Cambronero Vàzquez, 2017).

The potential of mixed-mode operation especially on cooling side can be improved including a new portion of openable windows. The cooling effect can be boosted both during daytime and night-time because of the increased airflow that turn to be beneficial for air temperature offset and for indoor air quality issue

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[2] The electricity price for Donauzentrum shopping centre is assumed to be 0.10 €/kWh

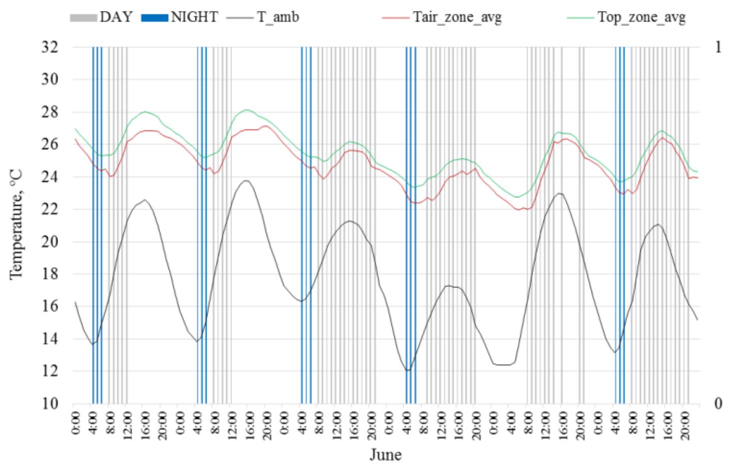

Figure 6 Temperature trends in correlation with windows operation during day (grey column) and nigh (blue column) during a temperate week of June (1st-6th)

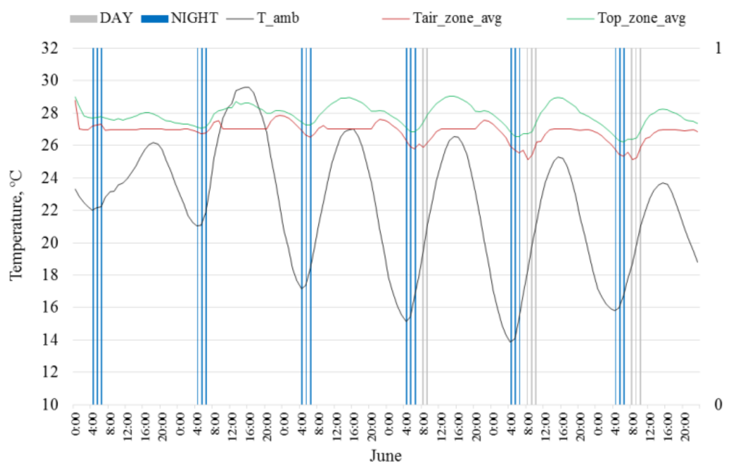

Figure 7 Temperature trends in correlation with windows operation during day (grey column) and nigh (blue column) during a warm week of June (1st-6th)

4 CONCLUSIONS

The paper investigates a mixed-mode ventilative cooling retrofit opportunity for an existing shopping mall located in the city of Wien. The developed strategy interests the shopping mall common areas (shop galleries and atria) where openable windows were operated without a robust automated control but just on the energy manager judgement.

Considering an energy retrofit intervention on common areas, a first reduction of the internal gain for lighting and appliances is considered in order to reduce the cooling demand of these zones. Afterwards a control strategy for running the building in mixed-mode condition has been developed based on indoor-outdoor climatic condition, thermal comfort and users' occupancy: Simulations results show how the daytime ventilative cooling can potentially work from end of March up to early November for a 25% of shopping mall opening hours. The exploitation at nighttime is limited to a 9% of unoccupied period and can run from early May to early September. Over a year running common area with mixed-mode strategy can allow to save 265 MWh which means cutting the electrical consumption by 23% which estimation in term of operational cost saved is about 26500 € per year. Under mixed-mode operation, comfortable condition can be provided during the day with operative temperature below 28 ºC. With an estimated initial costs of 100 euro per module, the investments cost can be paid in the first year of operation.

The potential of mixed-mode operation especially on cooling side can be improved including a new portion of openable windows which allow for a booster of the cooling effect both during daytime and night-time because of the increased airflows.
For the real implementation of the mixed-mode operation a fine tuning of the control strategy should be operated taking into account a signals that override the opening of the windows in case of rain or in case of strong wind at windows level.
The study has demonstrated the feasibility of mixed-mode operation for shopping mall common area proving its effectiveness and cost effectiveness as retrofit solution when the synergy with the level of internal gain is taken into account. Overlooking this interdependency could lead to discomfort condition due to drafts and to extra investment costs for openings´ actuators, which might not be necessary.

5 ACKNOWLEDGEMENTS

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