Delivery and performance of a ventilative cooling strategy: the demonstration case of a shopping centre in Trondheim, Norway

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ABSTRACT

Nearly all retail locations use mechanical cooling systems to ensure indoor comfort temperatures and mechanical ventilation to ensure adequate air exchange, primarily for hygienic reasons. Because of the big volumes involved and the lack of knowledge in natural ventilation design, shopping centres designers have been relying on basic HVAC equipment, without considering the potential of ventilative cooling to reduce cooling needs and to maintain an acceptable indoor environmental quality.

The CommONEnergy FP7 project investigated the retrofit opportunities to exploit ventilative cooling in shopping centres' common areas (shop galleries and atria) considering external climate conditions and architectural features. The paper presents the development and demonstration of a ventilative cooling strategy in the demo case located in Trondheim (Norway). The strategy combines the effect of opened sliding doors and skylight openings to enhance stack ventilation and ventilate/cool the common areas and thus to reduce fan operation time. In order to prevent cold draughts, skylights windows groups are controlled separately and the opening angle of the skylight windows is modulated according to the outdoor temperature and the indoor temperatures as measured by sensors distributed within the common areas. The control strategy was first tested on the building energy simulation model coupled with an airflow model, then implemented in the integrated Building Energy Management System (iBEMS). The building energy model supported the monitoring based-commissioning phase by providing a set of benchmarking scenarios.

Thanks to the ventilative cooling solution, the total electricity consumption for heating, cooling and ventilation of the common areas over the whole reference year is predicted to reduce by an 11%. Simulation results also showed that, with the defined control strategy, natural ventilation is effective in providing the minimum required air change rates for 98% of its activation time and to provide acceptable indoor environmental quality.

The proposed solution is active in the shopping centre since summer 2016. First monitored data showed that, when natural ventilation is activated, indoor temperatures stay below 26°C. When natural ventilation is not activated, indoor temperatures can increase up to 28°C. The first measured data clearly highlighted room for improvement of the implemented control strategy and continuous commissioning is ongoing.

KEYWORDS

Ventilative cooling; shopping centres; commissioning; natural ventilation; control strategy

1 INTRODUCTION

Data collected from several European retailers' sustainability reports show that on average heating, cooling and ventilation energy consumption account for 20% of the total energy consumption in food retailers and up to 40% in non-food retailers (Schönberger, Galvez Martos & Styles 2013).

Nearly all retail locations use mechanical cooling systems to ensure indoor comfort temperatures and mechanical ventilation to ensure adequate air exchange, primarily for hygienic reasons (Retail forum for sustainability, 2009). Because of the big volumes involved and the lack of knowledge in natural ventilation design, shopping centres designers have been relying on basic HVAC equipment, without considering the potential of ventilative cooling to reduce cooling needs and to maintain an acceptable indoor environmental quality.

Despite their higher energy consumption, mechanical ventilation systems are preferred to natural ventilation strategies because more easy to control 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 centres' design has included a small proportion of automated windows, sized for smoke ventilation only.

The EU FP7 CommONEnergy project investigated the retrofit opportunities to exploit ventilative cooling in shopping centres' common areas (shop galleries and atria) considering external climate conditions and architectural features. The paper presents the development and demonstration of a ventilative cooling strategy in the demo case located in Trondheim (Norway). The strategy combines the effect of opened sliding doors and skylight openings to enhance stack ventilation and ventilate/cool the common areas and thus to reduce air-handling unit (AHU) operation time.

2 DEMO CASE DESCRIPTION

The demo case is a suburban shopping centre, built on the outskirts of Trondheim in Norway. Opened in 1987 and covering an area of 38,000 m², it houses 70 shops on three floors, with 1,000 outdoor parking spaces.

All the shops face the common areas, which have a circular layout. This circulation space surrounds a central atrium with escalators and shops. Cafeterias or restaurants are located in two intermediate floors in the atrium.

The heating and cooling needs are covered by two air to water heat pumps (AWHP), supplemented by district heating and two additional cooling machines when needed. The dual AWHPs provide heating/cooling to the main ventilation units, and they are manually switched from heating to cooling mode in the mid-season.

An air-handling unit with heat recovery and a capacity of 20,000 m³/hr supplies treated air to the common areas. The ventilation system is central damped and there are no automatic dampers. The air intake is on the building roof.

The ventilation unit operates 15 hours/day (from h 06:30 to 21:30) from Monday to Friday and 14 hours on Saturday (from h 06:30 to 20:30). On Sundays, when shopping centre is closed, the system is off. Temperature set points vary between 14°C and 19°C depending on the outside temperature and on exhaust temperature from the atrium/ common area.

The main entrance is a full height glazed atrium with four sliding doors (1.56m x 2.30m each), two entrance doors are located at ground floor (DR1 and DR2) and the other two at first floor (DR3 and DR4), as shown in Figure 1. The doors are controlled by motion sensors or by manual on/off switch, which are eventually overridden in case of fire.

Figure 1: Main entrance of the shopping centre.

Main atrium (Figure 2) has 20 skylight openings equipped with linear actuators and a 3-phase gear motor with 180 cm railway. Among the 20 skylight openings, 10 are located on the west side (SK2) and the other 10 on the east side (SK1) of the skylight. Each opening is 1.2 m wide and 2.0 m high. The skylight windows are top hinged with an outward motion for approximately 45° opening angle off the sloping windows.

Natural ventilation through openable windows in the central atrium skylights helps vent out stale air in the summer.

The skylight windows are currently operated by a window automation system. The opening of the windows can be modulated (5 steps), but the algorithm that controls this practice is propriety from the manufacturer and the building manager cannot modify the control strategy.

Figure 2: Skylights in the central atrium and the cafeteria located on the mezzanine below. Openable windows are present on both sides of the skylight.

Several inefficiencies have been identified in the common areas ventilation:

- Mechanical ventilation system and window automation control are not integrated. Therefore, mechanical ventilation in the common areas cannot be switched off when natural ventilation is activated;
- The control protocol of skylight openings is encrypted in the window automation system and therefore, in case of complaints about natural ventilation operation, the energy manager manually shuts off the system and closes the openings;
- Cold draughts problems occur mainly in the cafeteria area, located in the atrium at the second mezzanine floor;

- Overheating problems are occurring in the main entrance due to the extensive glazed façade. Therefore, doors are kept open to cool down the entrance area.

3 NATURAL VENTILATION STRATEGY

The proposed natural ventilation strategy combines the effect of existing sliding doors and skylight openings to enhance stack ventilation and ventilate/cool the common areas.

The integration of natural ventilation together with mechanical ventilation allows exploiting the benefits of windows opening and stack effect for ventilating/cooling the common areas. Although some shopping centres have automated windows for natural ventilation, their control is often not linked to the HVAC system control. Therefore, the advantages obtained by ventilative cooling are neglected with an additional energy consumption from the HVAC system.

The flow chart in Figure 3 represents the control logic, which is described in detail in (Belleri, Avantaggiato 2017). The control scheme activates natural ventilation during opening time if it does not rain and the wind velocity does not exceed 7m/s (WS_MAX) and the outdoor temperature is within the comfort range and the measured indoor temperature exceeds the heating set point. The skylight windows on east (SK1) and west (SK2) side are controlled separately and depending on indoor temperature measured in the cafeteria and the common areas at first and ground floor.

Additionally, as required by the window manufacturer, if wind speed is above 4 m/s (WSn_MAX) and prevails from the opposite direction of east/west window row, that window row will stay close.

This results in 9 possible different configurations of windows and doors opening. Table 1 reports the possible openings configurations according to the defined control schemes. The AHU is turned off whenever doors or skylights are opened.

Table 2 reports the list of input for the control rules. Some inputs are monitored variables and some other are constant values that can be pre-defined and optimized in the commissioning phase.

Table 1: Configuration of control rules' output signals as defined in the control schemes (for windows/doors: 0 means the opening is closed, 1 means the opening is opened; for the AHU: 0 means the AHU is off, 1 means the AHU is on)

Control scheme	**Skylight windows group 1 (OF_SK1)**	**Skylight windows group 2 (OF_SK2)**	**Door 1 (OF_DR1)**	**Door 2 (OF_DR2)**	**Door 3 (OF_DR3)**	**Door 4 (OF_DR4)**	**AHU**
Sc_1a	1	0	0	0	1	1	0
Sc_1b	1	0	1	1	1	1	0
Sc_1c	0	1	1	1	0	0	0
Sc_1d	1	1	0	0	1	1	0
Sc_1e	1	1	1	1	1	1	0
Sc_1f	0	1	1	1	1	1	0
Sc_1g	1	0	1	1	0	0	0
Sc_1h	0	1	0	0	1	1	0
Sc_1i	1	1	1	1	0	0	0
Sc_2	0	0	0	0	0	0	1
Sc_3	0	0	0	0	0	0	0

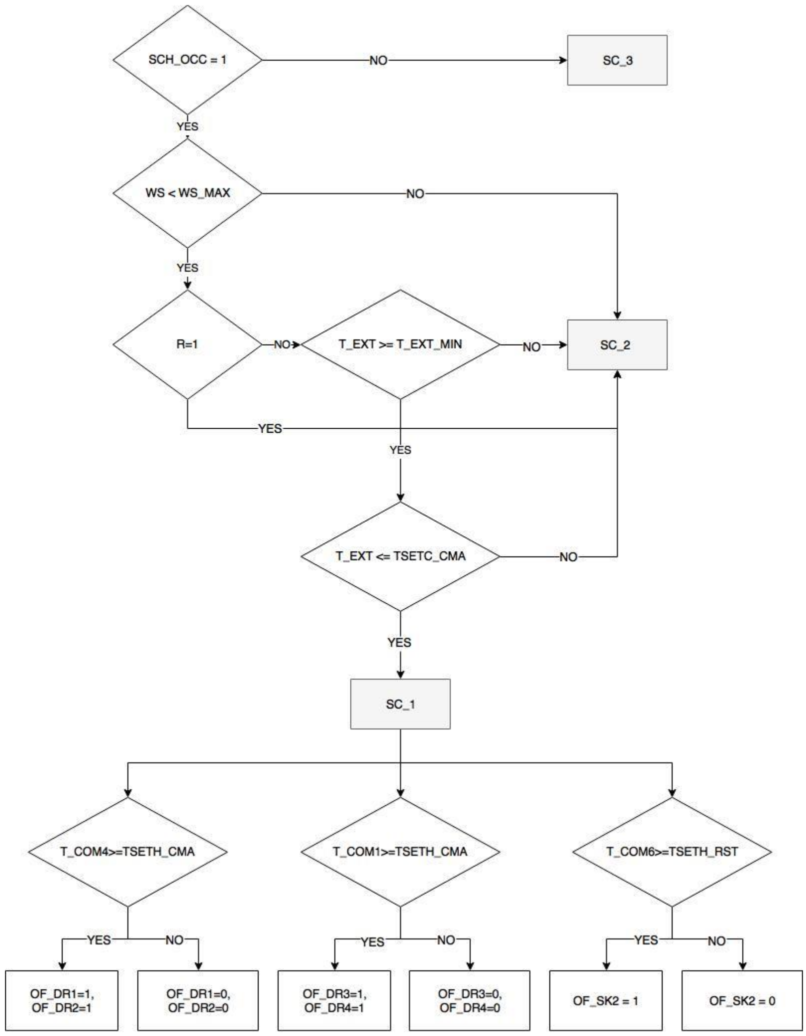

Figure 3: Control strategy scheme.

Table 2: Control rules input list.

Input ID	**Unit**	**Description**	**Type**
SCH_OCC	-	Occupancy schedule [0;1]	Scheduled
T_EXT	°C	Outdoor air temperature	Monitored
WS	m/s	Wind speed	Monitored
WD	°	Wind direction	Monitored
R	-	Precipitation sensor [0;1]	Monitored
T_COM4	°C	Indoor air temperature of the common area at ground floor	Monitored
T_COM1	°C	Indoor air temperature of the common area at first floor	Monitored
T_COM6	°C	Indoor air temperature of the cafeteria	Monitored
WS_MAX	m/s	Maximum wind speed	Setpoint
WSn_MAX	m/s	Maximum wind speed in the direction opposite to the normal of the window plane	Setpoint
T_EXT_MIN	°C	Minimum outdoor temperature for the activation of natural ventilation	Setpoint
T_EXT_MAX	°C	Maximum outdoor temperature for the activation of natural ventilation	Setpoint
TSETH_CMA	°C	Lower temperature limit of the comfort zone for common areas	Setpoint
TSETH_RST	°C	Lower temperature limit of the comfort zone for cafeteria	Setpoint
TSETC_CMA	°C	Higher temperature limit of the comfort zone for common areas	Setpoint

In order to prevent cold draughts, the opening angle of the skylight windows is modulated on 5 steps (0.2 - 0.4 - 0.6 - 0.8 - 1) depending on the outdoor temperature and the indoor temperatures measured by sensors distributed within the common areas, as the function shown in Figure 4.

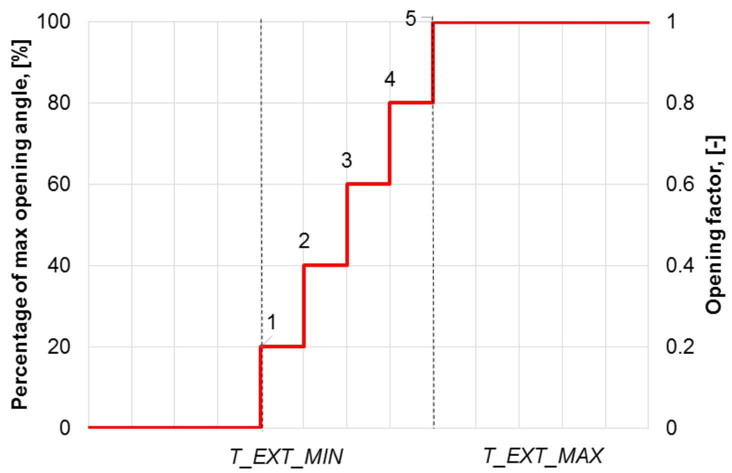

Figure 4: Skylight opening angle modulation depending on outdoor temperature.

4 IMPLEMENTATION AND COMMISSIONING

Since the ventilative cooling strategy involves different building systems (i.e. door and window actuators and air-handling unit), building energy simulations within a structured modelling environment supported the development and test of control strategies, the tuning of set-points, as well as the prediction of system performance improvement.
Input/output and control schemes are described using a predefined format agreed between the energy modeller and the system integrator so that we can manage control rules both in the Integrated Modelling Environment (IME) and in the intelligent Building Energy Management System (iBEMS) in a synergic way. Each input and output is identified by the same variable name in the IME, the iBEMS and the monitoring plan.

4.1 iBEMS architecture

Thanks to its integrated approach, the iBEMS architecture leverages the information and synergy between each of the systems and is able to provide a truly integrated function to the building. The system architecture foresees at least one automation server to which are potentially connected different subsystems for lighting, refrigeration, HVAC, energy storage and renewable energy technologies control.
In the demo case, the iBEMS is controlling directly the motors of the windows using a dedicated control for activating the motors. Figure 5 shows the architecture for the control of this sub-system. The sub-system communicates with the iBEMS hardware using the available open protocol (LonWorks).
The operation of the motors for natural ventilation uses information from sensors located in the common area. Thus, the information required for the operation of this sub-system are under the same hardware installation.

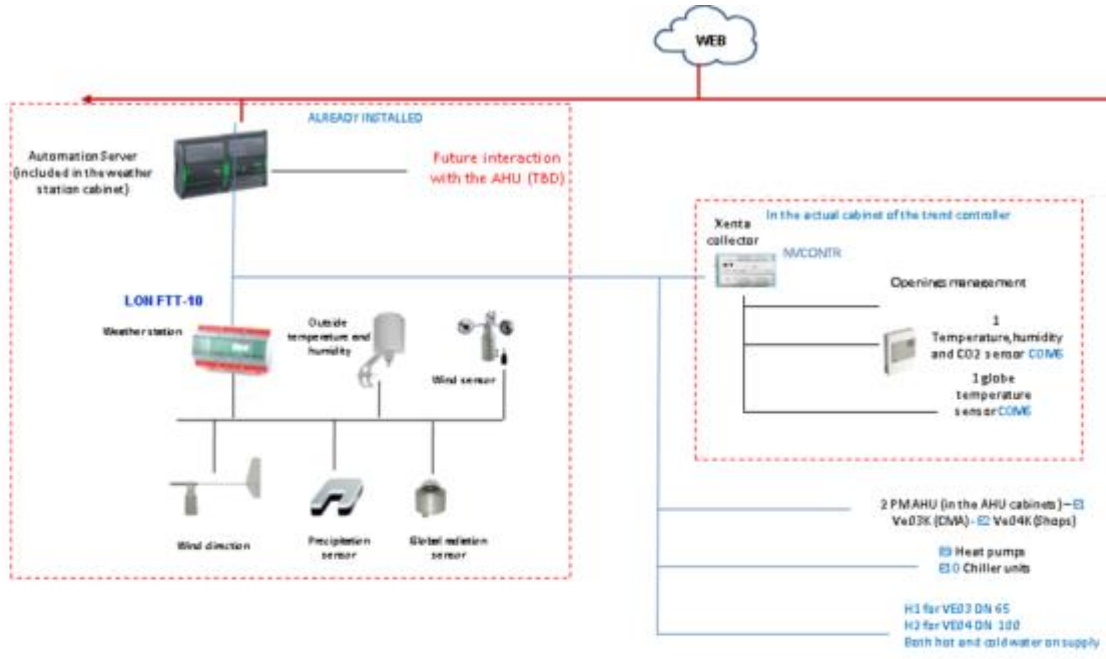

Figure 5: iBEMS architecture for openings automation.

4.2 Monitoring layout

Besides its role in the natural ventilation control rules, the common area monitoring aims at evaluating the overall performance of the natural ventilation.
Indoor air temperature, radiant temperature, relative humidity and CO_2 concentration sensors are installed in seven positions within the two floors of the common areas, as shown in Figure 6. Point 6 is located in the cafeteria in the mezzanine floor. The signals collected in the building are being saved in the iBEMS.

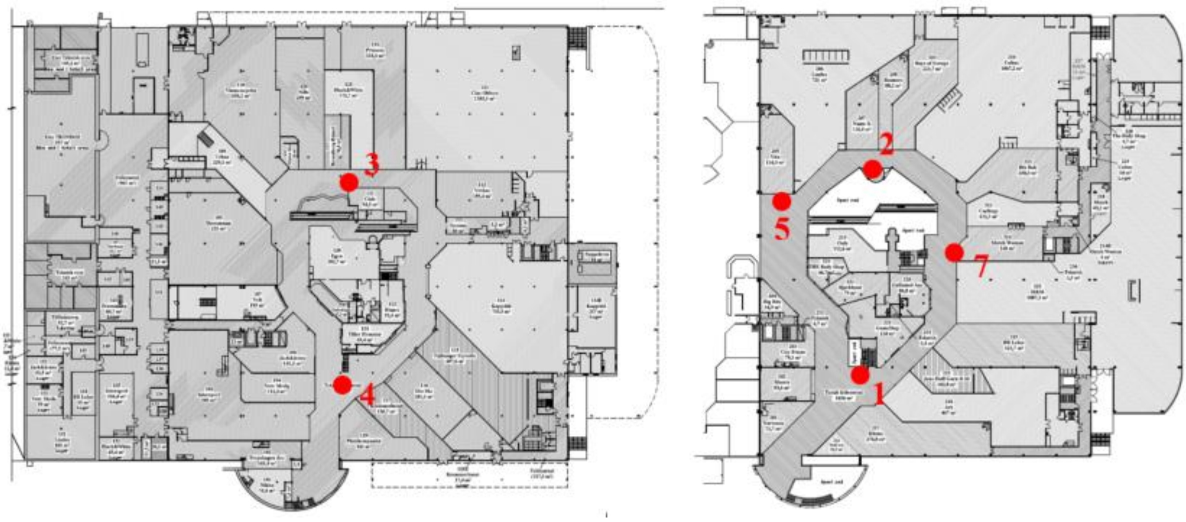

Figure 6: Sensors position in the common areas

4.3 Interaction between simulation model and iBEMS

The energy model of the building was developed within the Integrated Modelling Environment (Dipasquale, Belleri & Lollini 2016), a pre-casted simulation environment representing the building and its subsystems in a modular structure making more effective the development of a shopping mall model. We set up an airflow network model and coupled it with the energy model of the building (Haase et al. 2015).

Baseline simulations were run in unlimited power mode, where the generation system is assumed to always have the power necessary to keep indoor temperatures within 20°C (heating setpoint) and 25°C (cooling setpoint) during the opening time of the shopping centre (h 09:00-19:00). The mechanical ventilation is always on during opening time and provides the minimum required air change rates, which are assumed 20’835 m³/hr (circa 1 ach).
Then, we compared the baseline simulation results with the results of the energy simulation model where we implemented the natural ventilation strategy. The graph in Figure 7 shows the percentage of opening time when natural ventilation is activated and effective (MODE 1), when natural ventilation is activated but the minimum airflow rates are not met (MODE 2) and when mechanical ventilation is needed (MODE 3). Due to the low outdoor temperatures, natural ventilation is activated mainly during the summer season.

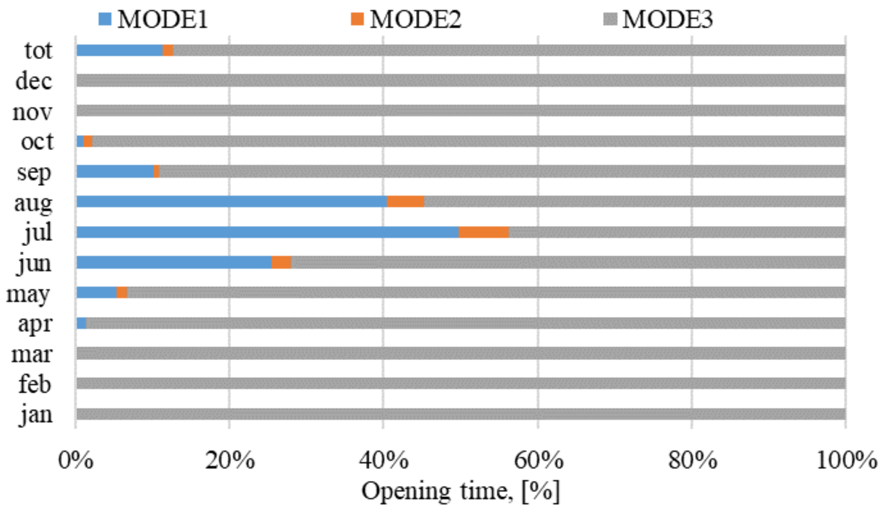

Figure 7: Percentage of opening time when natural ventilation is activated and minimum required airflow rates are met (MODE 1), minimum required airflow rates are not met (MODE 2) and mechanical ventilation is needed (MODE 3).

Since the HVAC model is ideal, the following efficiencies were considered for the estimation of the electricity consumption due to heating, cooling and ventilation: COP = 2.36; SPF = 0.45 Wh/m³.

Table 3: Estimated energy consumption and cost savings for the mixed mode ventilation strategy (natural and mechanical ventilation) compared to the energy performance of the building with mechanical ventilation only.

		Mechanical ventilation only	**Mixed mode ventilation**
Daytime natural ventilation operating hours	[hr/y]	0	513
Mechanical ventilation operating hours	[hr/y]	4,538	4,025
Electric energy consumed for ventilation	[MWh/y]	43	38
Electric energy consumed for cooling	[MWh/y]	28	19
Tot electric energy consumption	[MWh/y]	71	57
Operating costs saving[1]	[€/y]	-	1,748

Table 3 summarizes the outcomes of the building energy simulation. The total electricity consumption for cooling and ventilation of the common areas over the whole reference year decreases by an 11% thanks to the exploitation of natural ventilation. Simulation results also showed that natural ventilation is effective in providing the minimum required air change rates for 98% of its activation time. The operating cost savings are approximately 1,750 €.

[1] The cost of electricity in Norway is 0.12 €/kWh.

The building energy model also supported the monitoring based-commissioning phase by providing a set of benchmarking scenarios. The control output of the benchmarking scenarios was then compared to the iBEMS control output by setting the same boundary conditions.

5 MEASURED PERFORMANCE

The proposed solution is active in the demo case since summer 2016. The graphs in Figure 8 and Figure 9 report the monitored data recorded in August 2016 about outdoor (T_EXT) and indoor (T_IN) temperatures and doors and windows position (OF_DR = opening factor of doors, OF_SK = opening factor of skylight windows).
The graphs show that, when natural ventilation is activated, indoor temperatures stay below 26°C. Indoor temperatures can increase up to 28°C in the cafeteria area (T_IN_6) when natural ventilation is not activated (e.g. on 07.08.2016 or 21.08.2016 or 28.08.2016).
The data clearly highlights room for improvement of the implemented control strategy. Indoor temperature peaks in the cafeteria could be reduced by exploiting ventilative cooling.

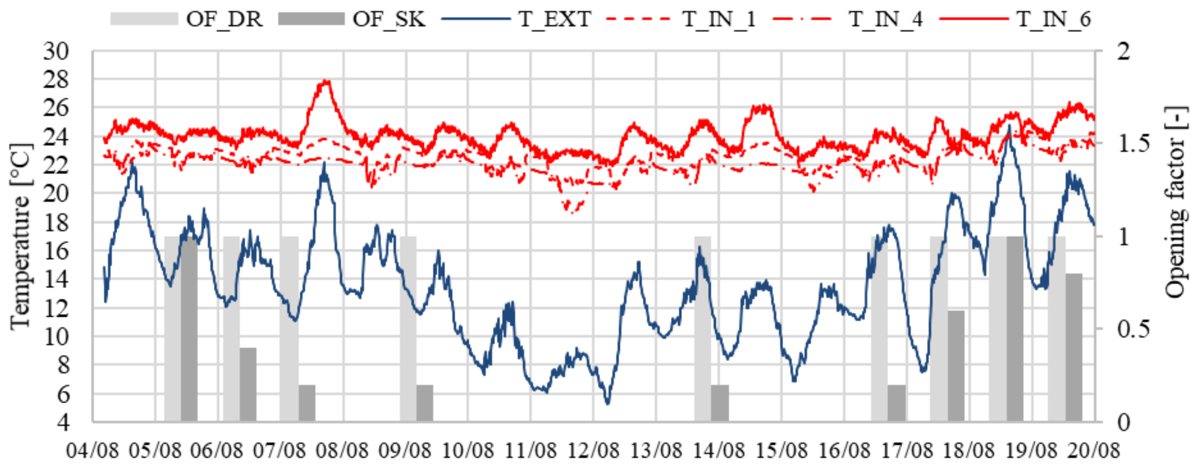

Figure 8: Monitored indoor and outdoor temperatures and opening factors from August 4th until August 20th 2016.

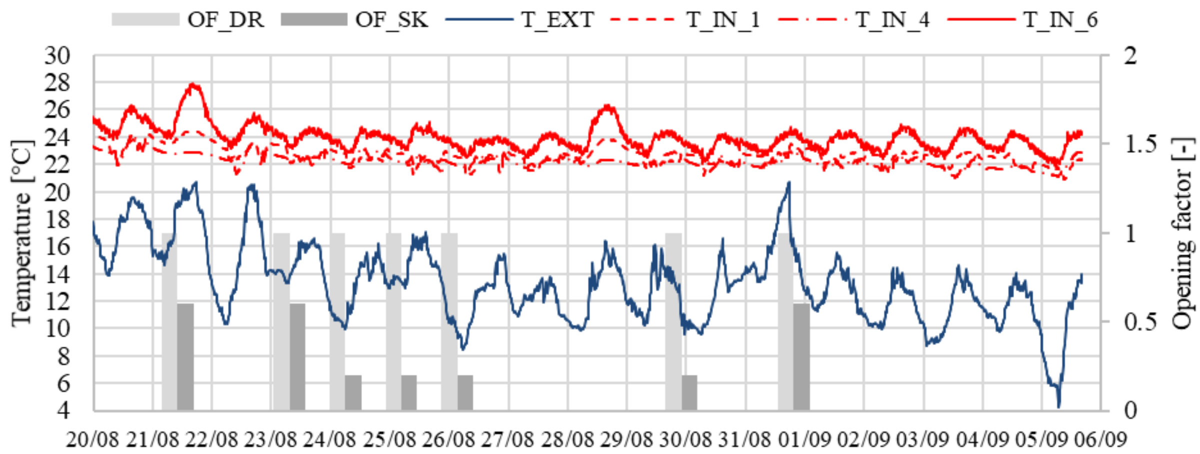

Figure 9: Monitored indoor and outdoor temperatures and opening factors from August 20th until September 6th 2016.

6 CONCLUSIONS

The demo case is suitable for the application of enhanced stack ventilation through the atrium. The natural ventilation strategy combines the effect of opened sliding doors and skylight openings to enhance stack ventilation and ventilate/cool the common areas. In order to prevent cold draughts, skylights windows groups are controlled separately and the opening angle of the skylight windows is modulated according to the outdoor temperature and the indoor temperatures measured by sensors distributed within the common areas.

Potential energy savings are estimated by building energy simulations. The total electricity consumption for heating, cooling and ventilation of the common areas over the whole reference year is reduced by an 11% thanks to the exploitation of natural ventilation. Simulation results also showed that, with the control strategy defined, natural ventilation is effective in providing the minimum required air change rates for 98% of its activation time.

The energy savings predicted by the simulation models are going to be validated by calibrating the building energy simulation models with dedicated measurements.

The proposed solution is active in the shopping centre since summer 2016. First monitored data showed that, when natural ventilation is activated, indoor temperatures stay below 26°C. When natural ventilation is not activated, indoor temperatures can increase up to 28°C. The first measured data clearly highlighted room for improvement of the implemented control strategy and continuous commissioning is ongoing.

7 ACKNOWLEDGEMENTS

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