A modular, open system for testing ventilation and cooling strategies in extremely low energy lecture rooms

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ABSTRACT

Lecture rooms with their high, quickly fluctuating internal gains, e.g. changing from no occupation to full occupation within some minutes, are quite challenging when good indoor air-quality and thermal comfort is required in an extremely low energy building context.

One essential aspect is the perfect control of air flow and temperature based on reliable, continuous measurement in all relevant parts of the ventilation system.

This paper describes a case study that combines real building operation on a university campus with an advanced, modular test platform covering all aspects of the real operational performance of extremely low energy lecture rooms.

A full-scale Passive House test facility was constructed at Technology Campus Gent, KU Leuven, Belgium. The building is part of the campus and has two lecture rooms for 80 students each. Designed and certified according to the Passive House standard, the new facility consists of two levels, constructed on top of an existing building (ground-floor only).

Thermal insulation was placed also in-between the two lecture rooms and in the internal walls towards the staircase. This results in a layout with two identical, box-shaped volumes with different thermal mass (one with a timber-frame structure, one with brick-walls).

The facility includes a high performance AHU, with frequency controlled fans and two sets of VAV-boxes, providing ventilation, heating and cooling, a wood pellet boiler, motor-controlled exterior sun-shading and windows and high performance lighting fixtures with daylight control.

A key feature is the integrated system for monitoring and control based on open standards: BACnet for communication with the AHU, KNX, DALI and EtherCAT to link decentralized IO-units with the Building controller. This PLC based, distributed PC environment provides detailed control of the building equipment and real-time, long-term monitoring of all building parameters and the outdoor climate.

It provides also a very flexible and powerful platform for the implementation and testing of new strategies for model based predictive control (MPC) and fault detection and diagnosis (FDD). The Modelica language is used for building simulation during operation.

A detailed Building Information Model (BIM) was created and all relevant elements of the equipment and the BMS will be added. The BIM will be used to manage measured data and provide integration between simulation and measurement.

Results from detailed air flow measurements at different fan speeds are provided. These initial measurements show good general agreement and provide deeper insight in the dynamic behaviour of the ventilation system. Beside the air flow sensors of the AHU and the VAV boxes, Venturi tubes are integrated in the supply- and return-air duct of each lecture room. The modular monitoring system provides the possibility of easy integration of additional sensors (e.g. thermo-anemometers for temporary measurement of velocities and calculation of the air flow based on the Log-Chebychev method)..

KEYWORDS

nZEB, case study, building monitoring system, air flow measurement

1 INTRODUCTION

Indoor air quality (IAQ) and thermal comfort are essential parameters to ensure an optimal indoor environment for people living or working in buildings. This emphasizes the importance of an adequate ventilation strategy where the main purpose is to provide fresh and clean air while removing harmful air contaminant (Dimitroulopoulou, 2012). This aspect of ventilation is of importance as a correlation between occupant's health and IAQ has been established. The association of ventilation rate and occupants health in commercial buildings was investigated (Seppänen, Fisk, & Mendell, 1999; Seppänen & Fisk, 2004). These studies concluded that at low ventilation rate, building occupants show the symptoms of the sick building syndrome (SBS) which is due to the high concentration of carbon dioxide within the environment. Moreover, (Emenius et al., 2004) examined the impact of building characteristics and IAQ on infants in Stockholm, during the first 2 years of their life. They concluded that indoor humidity superior to 45% and the age of the building are related to a recurrent wheezing in children. Dimitroulopoulou (Dimitroulopoulou, 2012) summarizes in his review study, the likely health effects (asthma, allergies, inflammation) on vulnerable persons such as infants and elderly of an inadequate ventilation system in buildings.

Alongside of maintaining an optimal air quality, the ventilation system is also used for cooling purposes to achieve an optimal indoor thermal comfort (Emmerich, Dols, & Axley, 2001). It can be used to cool directly building interiors by replacing the warm indoor air with cooler outdoor air or to cool directly building occupants by directing cool outdoor air over building occupants at sufficient velocity. Another ventilation aspect is the night ventilation which constitutes an indirect way of cooling building interiors by pre-cooling thermally massive components of the building with cool nighttime outdoor air.

Two main ventilation technologies are currently used: the passive, natural ventilation and the mechanical ventilation. The choice of technology depends on miscellaneous factors ranging from the local climate to the building characteristics and the envelope's air tightness.

Natural ventilation is defined as ventilation provided by thermal, wind or diffusion effects through doors, windows, or other intentional openings in the building. It has the potential to significantly reduce the energy cost required for mechanical ventilation and constitutes the primary choice for building ventilation as long as the building characteristics and local conditions permit its safe and (energy-) efficient implementation.

Three (3) fundamental approaches of natural ventilation are to be considered (Emmerich et al., 2001):

- The wind-driven cross ventilation which occurs while openings on opposite sides are kept open
- The buoyancy driven stack ventilation which relies on the temperature differences of indoor vertical air layer stratification to draw cool outside air.
- The single sided ventilation where the openings from one side of the room are used.

Most of the currently used natural ventilation strategies are variants of the above-mentioned approaches and are enhanced by using controlled openings.

On the other hand, mechanical ventilation implies the use of mechanical fans connected to ductworks to supply fresh outdoor air to the building interiors. An obvious and major drawback of these kind of systems is the high use of energy to run the mechanical components. According to (Pérez-Lombard, Ortiz, & Pout, 2008), about 50% of the total primary energy used within buildings are used for mechanical ventilation systems. This situation points out the necessity of energy efficient ventilation strategies which leads to an intensive research for optimised design and control of mechanical ventilation systems and their integration into the building context. Three basic types of mechanical ventilation strategy are to be considered (Roberson et al., 1995):

- The exhaust only ventilation where fans are used to extract indoor air from the building while outdoor air is entering through openings and buildings leakage.
- The supply only ventilation where fans are used to push air into the building and induce a positive pressure. This constitutes the main advantage of this strategy as it prevents outdoor pollutants to flow into the building.
- The balanced ventilation strategy where the supply and exhaust fans provide similar volume flows. This type of ventilation system is typically equipped with heat recovery to improve indoor thermal comfort and energy efficiency.

Considering these fundamental approaches for natural and mechanical ventilation strategies, a large range of combination and hybrid ventilation strategies can be implemented. However, prior to any implementation in real buildings of any strategy, a thorough study needs to be undertaken to find out its suitability considering local climate and building characteristics and its efficiency in term of health, comfort and energy use. Moreover, alongside an in depth theoretical study, an experimental validation and testing is a mandatory step to investigate the effectiveness of a strategy in the real world. This situation emphasizes the need for an experimental facility having the capability to provide an adequate environment such as an accurate and reliable air flow measurement system to carry out such experimentation.

This work presents a high performance test facility having the capability to host such testing and experimentation due to its unique features. The building is a passive house located in a temperate climate and fully equipped to perform natural ventilation, as well as mechanical ventilation strategy testing. Four main features are:

- Its highly insulated and air-tight building envelop and motorized windows and exterior shading provide a unique environment for natural ventilation scenario testing.
- Its integrated computer based monitoring and control system provide a modular, real time testing framework.
- Its high performance airflow measurement system provides continuous and reliable airflow data of the mechanical ventilation system's key components as well as the indoor and outdoor air velocity and direction.
- Its comprehensive set of installed sensors which covers all key aspects of buildings.

Within a first section, the main characteristics of the facility will be presented. The focus will be set on the facility's unique features related to ventilation testing. A particularly relevant point is the choice of a continuous air flow measurement system. As velocity based air flow measurement technologies such as the log Chebyshev method are strongly influenced by local perturbancies (fans, bends, …) and less convenient to set up (De Zutter & De Bock, 2014), the facility is equipped with Venturi-tubes (ISO 5167-4) with differential pressure sensors to measure air flow within the ducts of the ventilation system. Their measurement performance will be emphasized by showing their behavior towards an identical and controlled excitation and results are checked against the values provided by the sensors of the Air Handling Unit (AHU) and the Variable Air Volume (VAV) boxes.

A second section will be dedicated to the prospective ventilation strategy experimentation possibilities that will be implemented by using the presented facility as test case. A non-exhaustive review of existing studies and research will be used to demonstrate the facility's capabilities towards ventilation strategy implementation.

2 TEST FACILITY ASSETS FOR VENTILATION STRATEGIES DEVELOPPMENT AND OPTIMISATION

The facility is part of the civil engineering department of the Technology campus Gent of Leuven University (Belgium) and consists of two lecture rooms for 80 students each (lecture room E220 and E120) (see figure 1). The building was designed and certified according to the passive house standard with a total energy demand of 11 kWh/m^{2}y and 6.10 kWh/m^{2}y respectively for space heating and cooling. Moreover, the air tightness of the lecture rooms reaches a value of $n_{50} \leq 0.6$ h^{-1}. Alongside of being used as normal lecture room for courses, the facility is also used by students, researchers and projects for research on building energy-efficiency strategies development in a “real use” environment. Its main components which are the building envelop, the Air Handling Unit and the integrated monitoring and control system have specific features which facilitate the testing of such strategies and especially ventilation strategies.

2.1 Facility envelope features for ventilation strategy implementation

The test facility was constructed on top of an existing university building (see Figure 1.a) and has four zones which are: the two lecture rooms (E120 and E220), the staircase and the technical room. The lecture rooms form two cuboids with a volume of 380 m^3 each and are thermally insulated from the outside and the neighbouring zones. The E120 room’s external wall was designed as brick wall with exterior insulation (cellulose fibre) with an average u-value of 0.148 w/m^{2}K while the lecture room E220 was designed with an 0.346 m thick insulated lightweight timber frame wall with an u-value of 0.155 w/m^{2}K. This design of the lecture rooms leads to two identical box shaped zones with different thermal mass. Such characteristic could be emphasized in a ventilation strategy where the thermal mass plays an important role (e.g: Night ventilation). Moreover, for ventilation strategy study involving numerical modelling, the simple architectural shape of the building and the thermal separation of the lecture rooms facilitates the model implementation and calibration.

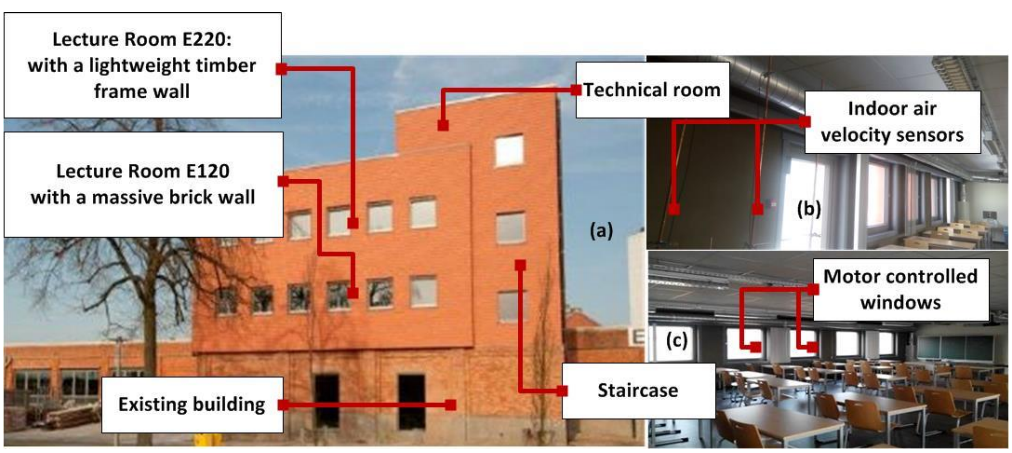

Figure 1: Building envelop presentation and brief description

Each classroom has the same surface and type of windows which are high performance triple glazing windows filled with argon with a solar heat gain value g-value of 0.52 and an u-value of 0.6 w/m^{2}K (see Figure 1.c). Each window’s opening rate is driven by motors controlled by the computer based control system and can be opened or closed automatically and independently.

Electricity counters monitor also the energy consumption of these motors. Such feature constitutes an important asset for natural ventilation scenario study and implementation.
A set of sensors has been installed to monitor indoor and outdoor conditions. The facility has its own weather station which monitors the main outdoor parameters such as the solar radiation, the outdoor temperature, the outdoor humidity and the wind speed and direction. For the indoor conditions, the indoor temperature, the CO_2 concentration and the indoor humidity are continuously monitored. However, a set of indoor high precision air velocity sensors is available to monitor the distribution of indoor air velocity and direction (figure 1.b). The data from these sensors are displayed in real time and recorded within the computer based monitoring and control system. Among the above mentioned sensors, those of interest for ventilation strategy implementation are the outdoor wind speed and direction sensors and the indoor air velocity sensors. These sensors are to be used to investigate the outdoor and indoor air speed and motion. Moreover, as the knowledge of the occupancy's level is an important parameter for mechanical ventilation control, the facility, alongside of the CO_2 sensors, has motion detection sensors and high definition camera with face recognition installed within each classroom. They provide the occupancy level in real time.

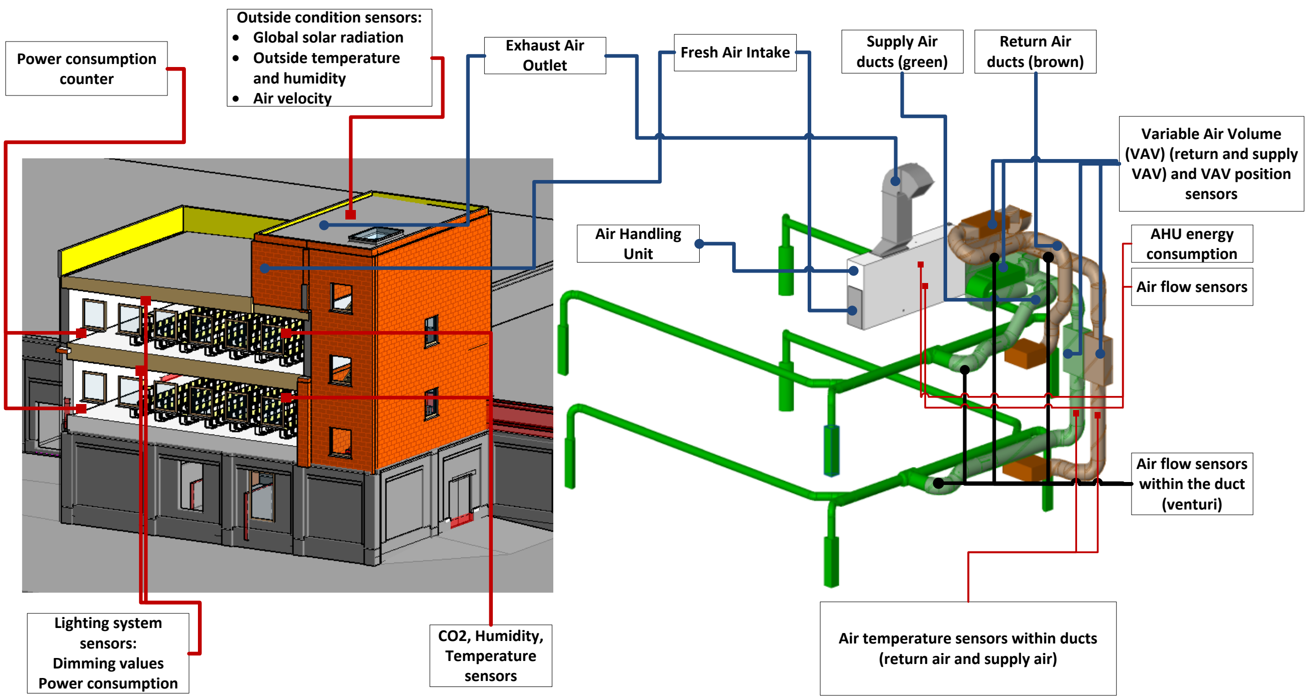

Figure 2: Ventilation system description and sensors placement description

2.2 Air Handling Unit (AHU) features for ventilation strategy implementation

The AHU is a high-performance unit capable of a maximum air flow rate of 5100 m^3/h and has an air flow of 4000 m^3/h at normal condition (see figure 2). It has a coefficient of power efficiency of 72 % (EN 13053:2012) (European Standard, 2012) and is equipped with a double heat exchanger in polypropylene and an Indirect Evaporative Cooling (IEC) system. The heat recovery system can reach an efficiency superior to 75% and is categorized as H1 class (EN 13053:2012). The AHU unit is powered by two energy-efficient fan units with respectively a

Specific Fan Power (SFP) category 1 for the air supply fan and category 2 for the Return Air (RA). The fans' speed can be controlled externally and independently to one another by introducing the fans' motor desired angular frequency. Figure 3 (left curve) presents a fan speed control test which emphasizes two distinct periods. A first period where the supply air fan is controlled and a second period where the return air fan is controlled. One can notice the stair shape curve of the controlled air flow which testify the change in angular frequency operated by the controller during the test. This control feature shows a large range of possibilities for mechanical ventilation strategies testing and implementation as it can mimic an over pressurization and a depressurization phenomenon within the lecture rooms.
To regulate the supply and return airflow rates of the two lecture rooms separately, the ventilation system is equipped with (4) four Variable Air Volume (VAV) where the dampers' position can be controlled by the BMS through the BACnet interface of the AHU. Hence, by closing both return and supply VAV of a lecture room, we can implement natural ventilation testing in one room while using the other room for mechanical or hybrid ventilation.
Knowing the importance of airflow within ventilation strategies, two distinct airflow measurement processes are present within the ventilation system:

- An airflow measurement system embedded within the AHU provides the total supply and return volume flow from the AHU (figure 3, left curve) and the linear position of the four VAV. The combination of these parameters allows us to compute the air flow entering and outgoing the lecture rooms.
- A second airflow measurement system is composed by four differential pressure sensors installed into Venturi tubes which are integrated into the supply- and return-air duct of each lecture room (see figure 2 black lines). These additional sensors are installed to continuously monitor the air flow rates of both lecture rooms. The figure 3 (red and blue curves) shows the supply air entering the lecture rooms (E120 and E220) recorded with the "Venturi sensors" while the black curves present a comparison of the supply flow rate values monitored with the two distinct systems. One can notice the good agreement between the two airflow measurement systems.

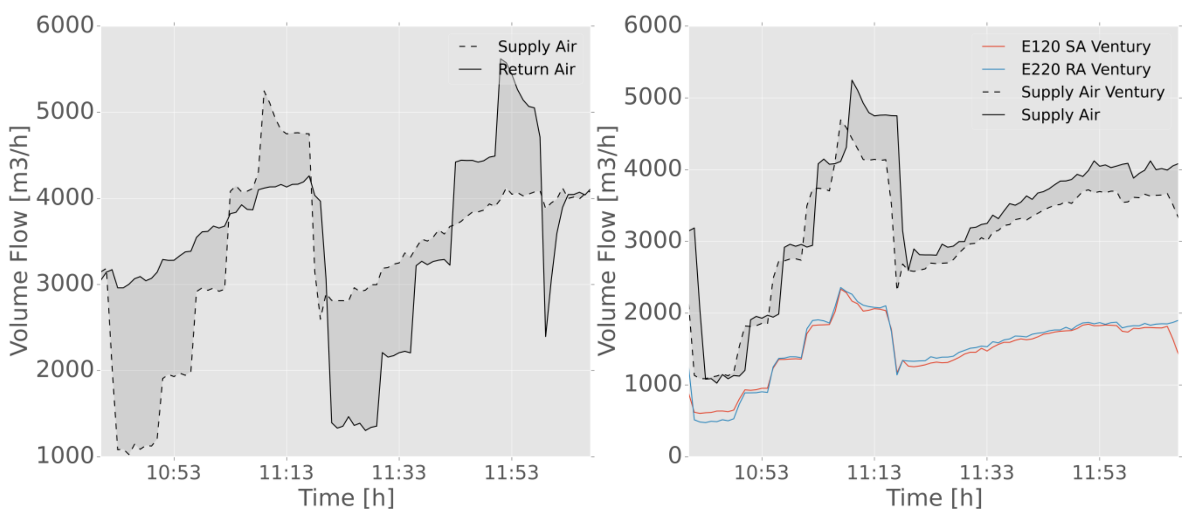

Figure 3: Airflow measurement system comparison

Separate electricity counters are also installed to monitor the energy consumption of the Air Handling Unit.

2.3 Monitoring system features

The monitoring and control system is one of the main assets of the facility. The system relies on the use of open and standard protocols to establish the communication between the main computer based Programmable Logic Controller (PLC) and the system components such as the sensors, the Air Handling Unit and the controllable devices. The open protocol BACnet is used for the fan speed and VAV position control and to communicate with the AHU's embedded sensors while the KNX standard and the EtherCAT protocol are respectively used for controllable devices and decentralised input/output (sensors) in the facility. The monitoring system and control structure can be represented as a two layers structure (see figure 4).

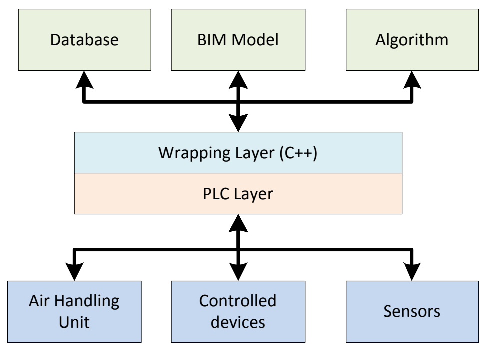

Figure 4: Simplified scheme of the monitoring system

The main task of the bottom real-time PLC layer is to establish and coordinate the communication between the hardware components and the upper software layer while the wrapping layer which is mainly coded in C++ has three (3) main tasks: (1) It establishes the communication between the bottom layer and the database where the monitored data is recorded with a one minute time resolution. (2) It constitutes the link between the system and the Building Information Model (BIM) of the facility. To improve measured data management, the monitoring system was coupled with the existing BIM model of the facility (figure 2 shows a screenshot of the BIM). Each physical sensor is represented within the BIM by its own virtual representation and BIM characteristics are used to couple the virtual sensor with its corresponding measured data to facilitate data access. This method enhances the measured data access for numerical simulation validation. (3) It constitutes a link between the system and the user's control algorithm. Hence, users and researchers have access to real time measured data and control. The system was designed in a way that users can implement their algorithm or scenario using their "favourite" programming language for control. Such configuration confers to the users a large panel of possibility for ventilation cooling strategy implementation testing.

3 PROSPECTIVE CONTRIBUTION TOWARDS VENTILATION STRATEGY TESTING

Considering its features, the test facility provides an optimal, controlled laboratory environment to perform ventilation strategies. The following section emphasizes the advantages provided by the facility characteristics towards ventilation strategies implementation based on a non-exhaustive literature review.

Within the last decade, the high energy use in mechanical ventilation system has raised concern and leads to a regain of attention towards the natural ventilation systems. Passive ventilation could be used either as the main ventilation system or coupled with mechanical ventilation system to reduce energy use. Research involving experimental investigation as well as numerical study of natural ventilation has been undertaken to enhance its efficiency. Among them, (Heiselberg & Perino, 2010) evaluate the airing performance of buoyancy driven and single-sided natural ventilation in terms of ventilation characteristics, IAQ and thermal comfort. They investigate the consequences of opening time, opening frequency, opening area, ventilation efficiency and thermal comfort within a fully monitored test facility equipped with controlled windows located in Aalborg (Denmark). The importance of these parameters has been confirmed by (Karava, Stathopoulos, & Athienitis, 2007). In their work they also point out the necessity of further experimental work before generalization of the conclusions. In this scope, the presented facility has the required technical features to host such experiments. As the facility is equipped with motor driven windows located on the two opposite façades of each lecture room, one can investigate various combination of windows opening rate of the windows while their effect is recorded and monitored by the indoor sensors installed. Hence the facility provides an ideal environment to perform such test.

Alongside experimental studies, numerical modelling and especially computational fluid dynamics modelling is widely used for natural ventilation performance study (Hu, Ohba, & Yoshie, 2008; Jiang & Chen, 2001; Ramponi & Blocken, 2012). This implies the need of high precision monitoring of the indoor air velocity and direction for model validation. For this purpose, as the sensors are already available, air velocity and air temperature at various heights within the rooms can be measured as needed. The modularity and flexibility of the computer based system allows to easily install, remove or change sensors for a specific test.

Being a major energy use item within buildings, the enhancement of mechanical ventilation systems efficiency has drawn researcher's attention. Due to the control of the fan speed and VAV position of the Air Handling Unit of the presented facility, one can test and investigate the performance of mechanical ventilation strategies by creating similar environment such as over pressurization for supply only ventilation strategy or under pressurization for exhaust only. The facility features fulfill all technical requirements to investigate the advantageous and disadvantageous aspects of these fundamental approaches of mechanical ventilation. However, although testing and implementing new mechanical ventilation strategies is possible within the facility, the current focus within this field is set on the enhancement of the control strategy. (Erickson & Cerpa, 2010; Karava et al., 2007) propose a demand response HVAC control strategy that uses real time occupancy monitoring to achieve efficient conditioning. They conclude that such control can reach a 14% to 20% energy usage reduction of the Air Handling Unit system. An important challenge in the implementation of such method is the real time occupancy detection method. Having CO2 sensors, motion detection sensors, camera with face recognition installed within each lecture rooms and two air flow measurement system, the test facility has the capability to provide the real time occupancy level. Therefore, it can be used to

implement the existing methods or improve their efficiency by investigating the possibility of an enhanced control of the AHU coupled with (controlled) natural ventilation.
Another ventilation aspect with promising implementation within buildings is the night ventilation process. This process relies on the use of the cool ambient air as a heat sink, to decrease the indoor air temperature and the temperature of the building's structure. The cooling efficiency of this technique is mainly based on the air flow rate as well as on the thermal capacity of the building and the efficient coupling of air flow and thermal mass (Geros, Santamouris, Tsangrasoulis, & Guarracino, 1999). The importance of air flow within this method and thus air flow measurement constitutes one of reasons of the special attention given to the air flow measurement system within the facility. Night ventilation could be coupled with natural ventilation, mechanical ventilation or hybrid strategies. The importance of thermal mass for night ventilation is emphasized by (Givoni, 1998) within his study where he investigates the effect of thermal mass on night ventilation by considering three houses with different thermal mass located in Pala, South California (USA). He concludes that night ventilation is efficient for buildings with high thermal mass during the summer. As the two classrooms of the facility has different thermal mass, such experiments initiated by (Givoni, 1998) could be undertaken to investigate the effect of the thermal mass difference between the two classroom in a temperate climate especially during summer periods with high occupation and high outdoor temperature during day time.
In addition to the above-mentioned non exhaustive list of possibilities, one of the most important characteristic of the system is its open, integrated and modular monitoring and control system, implemented as soft-PLC in a standard computer environment (IPC) . This feature allows users to interact directly with the control features and real time monitored data and avoid the time consuming process of learning new software and languages to communicate with the control system and software limitations of a traditional hardware PLC.
Being a recently built facility, a set of measurements and studies need to be initiate on the facility either within the ventilation strategies implementation field or building physics field. However, some projects such as the "Optimization of demand control ventilation in tertiary buildings nZEB project" already use the facility as test case (VraagVent, n.d.).

4 CONCLUSION

The constant evolution of research on buildings performance efficiency raises the need for full-scale test facilities case for experimentation, method testing and validation. This work presents a test facility with dedicated features for natural ventilation as well as for mechanical ventilation strategy implementation and control. Its main characteristics lie in its envelope features, AHU controllability and air flow measurement system, and its modular, flexible and integrated monitoring and control system. Special attention was paid to airflow measurement where a first experiment considering various imposed steps of constant airflow testified the accuracy of the measurement process. A non-exhaustive review of the testing possibility that can be carried out within the facility has been presented based on existing studies and research on ventilation strategies. Regarding its characteristics, this demonstrated the large range of experiments that can be hosted by the facility and open new perspectives and possibilities for ventilation strategy implementation using the facility as a test case.

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