Experimental and numerical assessment for HVAC management in an industrial building: a preliminary optimization.

E Stamponi¹, N Lattanzi¹ and E Moretti²,³

¹ CIRIAF (Interuniversity Research Centre on Pollution and the Environment “Mauro Felli”) - University of Perugia, Via G. Duranti 63, Perugia, Italy
² Department of Engineering - University of Perugia, Via G. Duranti 93, Perugia, Italy
³ Author to whom any correspondence should be addressed: elisa.moretti@unipg.it

Abstract. COVID-19 emergency has caused major changes in everyday life in the last months, and it also affected the management of buildings. In particular, indoor air quality and ventilation have been considered to play a key role in the spreading of the infection, causing national and international subjects to draw up specific guidelines on ventilation and air recirculation rate in AHUs. The paper deals with the “Loccioni Leaf Lab”, an industrial building that hosts offices and workers operating on test benches. The building features high performance envelope, solar photovoltaic systems, groundwater heat pumps and a high-technology control and monitoring system and it is connected to a thermal and electric smart grid. A validated model of the building, implemented with the software DesignBuilder and EnergyPlus, was used to carry out numerical simulations to optimize the management of the HVAC through the Building Management System. Different working conditions have been simulated, and the numerical output has been used together with experimental data collected from the Company monitoring system. It has been possible to investigate how the extra ventilation required by the new guidelines would affect the total energy consumption and to compare, in terms of energy efficiency, the different HVAC management strategies that could be used to ensure occupants health safety and indoor air quality.

1. Introduction
In the last few years, the European Union (EU) has set goals to cut greenhouse gas emissions significantly due to the climate change emergency. The building sector accounts for approximately 40% of energy consumption and 36% of CO₂ emissions in the EU [1]. For this reason, sustainable climate-proofed buildings are needed – on a massive scale - to meet the environmental targets imposed by international agreements by 2030, and the European Union has developed strict regulations on nearly-Zero Energy Buildings with the purpose of a climate-neutral Europe by 2050 [2].

The objective of the present paper is to analyze the energy performance of a high-efficiency industrial building, through experimental data and numerical analysis [3-4]. In order to do that, the activity of the air handling units (AHUs) was investigated in detail. The management of indoor air recirculation was analysed in relation to the COVID-19 emergency and the effects on energy demand [5]. Furthermore, through numerical analysis, the impact of different scheduling was evaluated and, finally, a new
scheduling, based on an adaptive logic, has been assessed in order to reduce energy consumption but still ensuring the occupants' wellbeing.

2. Case Study

The headquarters of Loccioni Company is a Campus placed in an area of about 11 hectares, which develops along River Esino, nearby Angeli di Rosora (AN), a small town in the centre of Italy. The campus consists of six different productive buildings, partially dedicated to offices. What is interesting about it is that not only they are served by renewable energy plants (photovoltaic and micro-hydroelectric) but they are also connected by an electric smart grid which allows to better manage consumption and production, also thanks to battery energy system (BES) [6]. Furthermore, the buildings are connected by a thermal smart grid that delivers heat produced by the recently installed combined heat and power system (CHP) [7]. Since 2019, consumption of natural gas has been reduced to zero and all utilities, including heating, ventilation and air conditioning (HVAC) systems, are powered by electricity. The smart grid is also used to power the charging stations of the electric cars of the company fleet. All the Loccioni Campus buildings and power plants are connected to the national power grid by one single point of delivery (POD), produced energy leaves the Campus to enter the national network only if BES is fully charged and no internal user is claiming it. On the other hand, during hours of insufficient production, energy stored in the BES is used before buying it.

The Campus annual energy consumption in 2020 was 2501 MWhe: 38,5% for the HVAC systems, 11,6% for lighting and 49,9% for offices and laboratories. In 2020, the self-consumption of renewable energy produced was 87%, while self-sufficiency was 43%.

2.1. The Leaf Lab building (L4)

This paper focuses on the Leaf Lab building, an industrial building of 6000 m² total floor area, Figure 1, with an occupancy rate of about 80 people per day. The envelope is highly insulated while the edifice itself features an elevated level of building automation and control systems (BACS) [8]. LED lights are installed in all indoor and outdoor spaces. Lighting control is automatic with presence sensors and illumination sensors, to exploit the contribution of daylight. Some windows open automatically, controlled by the management system, to obtain natural cooling during the night [9]. The roof hosts a photovoltaic generator system of 236 kWP, connected with the Campus grid. A full description of the Leaf Lab is reported in [10].

The HVAC system is composed of ground water source heat pumps (COP 4.8, EER 6.2). The HVAC is coupled to a thermal storage water tank of about 450 m³, to store the thermal energy surplus, especially in medium seasons. The building is then equipped with 4 air handling units (AUHs): two of them serve the offices, the meeting room, the canteen and the reception, each one of 12000 m³/h of airflow. They can handling outdoor air or recirculate indoor air and are equipped with a heat recovery device. The two
other AUHs (40000 m$^3$/h + 16500 m$^3$/h) handle only indoor air and serve the central part of the building, a full-height space where the laboratory and the warehouse are. The L4 annual electric consumption in 2020 was 536 MWh: 204 MWh for the HVAC systems, 62 MWh for lighting and 270 MWh for offices and laboratories.

**Figure 2.** AHU 2 (Office East) - Building Management System (BMS) screenshot.

3. Methods

To evaluate the energy performance improvement related to the impact of the proposed strategies, dynamic energy simulations of the case-study building were carried out. Consumption data has been obtained from an online platform called myLeaf [13]. The collected data has been used to create a model of the building, using the software DesignBuilder and EnergyPlus [11]. Firstly, the building performance was validated on the basis of internal air temperatures for representative zones, using ASHRAE guidelines 14-2014 [12]. Then, with the same guidelines, the whole building-system model was validated based on the energy consumption for the air conditioning.

The validated model has then been used to evaluate the impact of interventions proposed during the analysis phase. Results were compared in terms of cooling and heating energy demands.

3.1. Data collection

For the present work, it has not been possible to collect internal data through experimental campaigns, due to Covid-19 emergency. All the necessary information has been obtained from myLeaf, that stores all the data collected through the monitoring system installed in the buildings. Thanks to this platform, it has been possible to obtain information regarding the power and thermal energy consumption of the building in 2019 and 2020, indoor air temperatures, hours of operations of the HVAC system, and weather data. Furthermore, the quantity of CO$_2$ (ppm) is measured in the exhaust air channel of the 2 office AHUs, outlined in Figure 2. The monitoring system did not work correctly on some days, and these periods had not been taken into account to determine validation indexes.

3.2. Thermodynamic model

The case study has been modelled through the software DesignBuilder and EnergyPlus. Initially, thanks to weather data provided by ASSAM [18], the EnergyPlus Weather Format Data files for 2019 and 2020 were created using the tool “Weather Statistics and Conversions”. After modelling the building envelope, all the data collected has been used to model other information like occupancy, internal loads, HVAC system, hours of operations, natural and mechanical ventilation, and solar shading management. A high number of simulations has been carried out to adjust the parameters implemented in the model and ensure that they could reasonably represent the real working conditions of the building.
Data from myLeaf database were analysed in order to highlight the impact of the HVAC system in terms of electric energy consumptions. The model has been validated on monthly basis according to ASHRAE guidelines [14].

4. Results and discussion

During the first phase of the work, the energy analysis of the building led to some considerations regarding aspects of management that could be improved and optimized. The case study is a smart building with a complex HVAC system and an efficient envelope; for these reasons, only interventions on the management aspects have been proposed. Indeed, due to the building's high level of automation, optimising the operation logics is a zero-cost intervention, while, due to the building’s features, other types of intervention would have a too high payback period.

4.1. Recirculation strategies.

At first, the energy saving due to the closing of the AHU's external damper was analyzed. To do this, a Monday and a Tuesday of two consecutive weeks which presented a similar trend in internal and external temperatures were chosen. Even if the external temperatures were lower in the week in which the internal air was recirculated, the consumption trend of the graph in Figure 3 shows that the heat demand of the AHU’s air coils and the cold beam system was lower.

![Figure 3. Week 1: all external air (black); week 2: recirculating indoor air (grey).](image_url)

To evaluate the savings regardless of the external temperature, the kWh saved were normalized on the heating design hours (HDH) [15] calculated as the hourly sum of the differences between the setpoint temperature and the external temperature (Table 1).

On week 2 Monday, the results show a consumption 45% lower than on week 1, while on Tuesday the gap is about 30%. On Monday morning the building is in the most unfavourable condition because the HVAC was off in the previous two days and the indoor temperature is the lowest of the week. For this reason, every Monday the HVAC system has a higher consumption than the other days of the week, in general minimum on Friday. Therefore, the savings resulting from the use of recirculation is greater on Mondays and gradually decreases in the following days.
Table 1. Normalized thermal consumption on HDH in two different conditions.

|                     | Indoor air recirculation | Monday | Tuesday | Total |
|---------------------|--------------------------|--------|---------|-------|
| Thermal energy demand [kWh] | No                       | 2'227  | 1'438   | 3'665 |
|                     | Yes                      | 1'856  | 1'406   | 3'262 |
| Heating degree hours (HDH)  | No                       | 202    | 203     | 405   |
|                     | Yes                      | 311    | 282     | 593   |
| kWh / HDH           | No                       | 11     | 7       | 18    |
|                     | Yes                      | 6      | 5       | 11    |

The CO$_2$ trend is quite stable during the week. It is constant on Sunday when the HVAC system is off, and grow up to 600 ppm (setpoint). If we manually force the opening of external damper the recirculation damper closes automatically (0%) and the CO$_2$ goes down quickly as shown in Figure 4.

![Figure 4. CO$_2$ trend and recirculation damper percentage of opening.](image)

The CO$_2$ never exceeds 600 ppm because the system is already equipped with a proportional–integral–derivative (PID) control algorithm [16] that keep the CO$_2$ at the chosen setpoint, or below, by regulating recirculation and external air damper. Furthermore, the building has a low occupancy rate (about 75m$^2$ per person) and the AHUs are able to exchange 24’000m$^3$/h with the outdoor, which is equivalent to 300m$^3$/h per person. Therefore, the AUHs widely ensured the daily air exchange and that in "standard" conditions a simple algorithm could be enough to guarantee an excellent level of air quality and, at the same time, a high percentage of recirculation. Unfortunately, today the health situation does not allow the HVAC system to work with this type of logic. The AICARR regulations [17] provide that the air conditioning systems must operate during working hours with all external air, throughout the pandemic situation. On the other hand, the HVAC system turns on before the working hours (8:00 AM), based on an algorithm that takes into account indoor and outdoor temperatures (described in the next section). This ensures an early start to reach the setpoint temperature at the beginning of working time. For this reason, during the first part of the day, in absence of people, the recirculation of indoor air could be done, thus reaching the setpoint conditions with less energy consumption and with no risk of a negative impact on inside comfort conditions.

According to the numerical model simulation, this intervention can lead to a thermal energy saving of 9’340 kWh during the heating period, 5.7% of the total consumption of 162’660 kWh.
4.2. HVAC optimal scheduling

In the first months of 2019, the daily starting of the HVAC system was set to a fixed schedule, while in 2020 the schedule was modified using an algorithm that regulated the daily starting time of HVAC. In particular, the algorithm (which is still active) uses the indoor temperature and a fixed temperature gradient of the building to predict the necessary time to reach the thermal comfort conditions, turning on the HVAC system at the right time to avoid energy losses. Figure 5 shows the uselessness of 2019 earlier starting than 2020 to reach the set point at 8 am.

![Figure 5. HVAC starting time in 2019 (grey) and 2020 (black).](image)

For this reason, it has been necessary to modify the validated model, changing the schedule of the first months of 2019 according to the new algorithm. A numerical simulation has been carried out to compare the energy consumption of the two different models with the same climatic conditions (2020 weather file). The difference between the first and the second model in Figure 6 represents the energy saving (10.1%) that could be achieved with the new algorithm.

![Figure 6. The monthly energy demand of the HVAC system.](image)

To further optimize the starting time, a new algorithm relating to the building's thermal gradient was proposed. Instead of using a fixed value for the building gradient (2020 logic), it was assumed to calculate from data of the previous day and use it to regulate the scheduling of the following day. The new algorithm sketched in Figure 7 will be used for 2021.
Figure 7. The new HVAC control algorithm.

Based on the above, this algorithm optimizes the starting time of the HVAC system, reducing energy waste, without affecting occupant’s wellbeing at the beginning of the working day. Finally, although this method of operation may not be the optimal strategy, it is certainly a low-cost solution with a high level of replicability in other buildings in the campus and in general in all the buildings equipped with an energy management system (EMS).

5. Conclusion and future development
In this work, the "Leaf Lab" building of the Loccioni Company was investigated. The preliminary impact of some interventions was analyzed through a validated numerical model.

The first intervention concerns the air recirculation control strategies, through the analysis of the CO$_2$ trend and the use of PID algorithms to management. After an initial analysis of the savings achievable by optimizing air recirculation, we had to face the reality of the pandemic and prefer the health aspect over the energy/economic one. For this reason, as long as we are in a pandemic regime, the recirculation optimization strategies cannot concern the working hours where the operation of the AHUs with all outside air must be guaranteed.

The second part of the proposed interventions is about the historical analysis of the different schedules and logics that over the years have regulated the start-up time of the HVAC systems. Based on historical data, and even in this case through numerical simulations, an adaptive control algorithm based on the thermal inertia of the building and the recorded data of the previous days was proposed.

Overall, the proposed interventions will not produce significant economic savings, but this derives from the investigated building which is designed and built to allow maximum energy savings. However, the proposed interventions can be considered cost-free and therefore reasonable despite of the low impact in absolute terms. It is important to note that, since the building is linked with a thermal and an electric smart grid, even the slightest savings can have a positive impact on the management of the entire
grid. Furthermore, some of the recommended interventions can be extended to all the other buildings of the Loccioni Campus, thus increasing the total savings.

Acknowledgments
The authors wish to thank Loccioni group (https://www.loccioni.com) for the willingness to provide information and for the hospitality received during the inspections at Angeli di Rosora. Special thanks to Team Facility for the valuable support provided during the monitoring campaign. The authors would also like to thank the agency for agro-food sector services of the Marche Region (ASSAM) for the willingness to provide weather data.

References
[1] https://ec.europa.eu/easme/en/news/sustainable-buildings-europe-s-climate-neutral-future
[2] International Energy Agency. Available online: https://www.iea.org/topics/buildings (accessed on 11 June 2019).
[3] Athienitis A K and O’Brien W, Modeling, Design, and Optimization of Net-Zero Energy Buildings, Wiley Online Library: Hoboken, NJ, USA, (2015).
[4] Harish V, Kumar A, A review on modelling and simulation of building energy systems. Renew. Sustain. Energy Rev. (2016). 56, 1272–1292.
[5] IEA. Global Energy Review 2020: The impacts of the Covid-19 crisis on global energy demand and CO2 emissions, International Energy Agency (IEA), Paris; 2020, https://www.iea.org/reports/global-energy-review-2020.
[6] Provata E, Kolokotsa D, Papantoniou S, Pietrini M, Giovannelli A and Romiti G, Development of optimization algorithms for the Leaf Community microgrid. Renew. Energy (2015), 74, 782–795.
[7] Stamponi E, Giorgini F, Cotana F and Moretti E, Preliminary assessment of a microgrid integrated with a biomass gasification CHP system for a production facility in Central Italy, 100RES 2020, E3S Web of Conferences 238, 01012 (2021), DOI: 10.1051/e3sconf/202123801012
[8] EN 15232-1 2017. Energy Performance of Buildings - Energy performance of buildings - Part 1: Impact of Building Automation, Controls and Building Management.
[9] Ghiaus C and Allard F, Potential for free-cooling by ventilation. Sol Energy (2006), 80, 402-413.
[10] Kampelis K, Gobakis K, Vagias V, et al. Evaluation of the performance gap in industrial, residential & tertiary near-Zero energy buildings. Energy Build. (2017), 148, 58–73.
[11] EnergyPlusTM, Engineering Reference Documentation Version 9.1.0, National Renewable Energy Laboratory, 2019. Available at: https://energyplus.net (accessed on 12 August 2019).
[12] M & V Guidelines: Measurement and Verification for Performance-Based Contracts Version 4.0. Available online: https://www.energy.gov/sites/prod/files/2016/01/f28/mv_guide_4_0.pdf
[13] MyLeaf Platform - Loccioni Group. Available online: https://https://myleaf2.loccioni.com
[14] Stamponi E et al., Energy analysis, numerical simulations and intervention proposals for a NZEB industrial building: the “Loccioni Leaf Lab” case study, 100RES 2020, E3S Web of Conferences 238, 06014 (2021), DOI: 10.1051/e3sconf/202123806004.
[15] ASHRAE. ASHRAE handbook: fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Atlanta, GA (USA); 2009.
[16] Wemhoff A P, Calibration of HVAC equipment PID coefficients for energy conservation, Energy Build. 45 (2012) 60-66.
[17] AICARR. Protocol for risk reduction of SARS-CoV2-19 diffusion with the aid of existing air conditioning and ventilation systems. Available online: https://www.aicarr.org/Pages/Normative/FOCUS_COVID-19_EN.aspx
[18] Agency for Agro-food Sector Services of the Marche Region (ASSAM), http://www.assam.marche.it/en/