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The design of safe classrooms of educational buildings for facing contagions and transmission of diseases: A novel approach combining audits, calibrated energy models, building performance (BPS) and computational fluid dynamic (CFD) simulations

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Abstract

The proposed investigation is aimed at providing useful suggestions and guidelines for the renovation of educational buildings, in order to do University classrooms safe and sustainable indoor places, with respect to the 2020 SARS-CoV-2 global pandemic. Classrooms and common spaces have to be thought again, for a new "in-presence" life, after the recent worldwide emergency following the spring 2020 pandemic diffusion of COVID-19. In this paper, starting from a real case study, and thus the architectural and technological refurbishment of an Italian University building (Campobasso, South Italy, cold climate), with the aims of improving the classrooms’ quality and safety, a comprehensive approach for the retrofit design is proposed. By taking into account the necessary come back to classrooms starting, hopefully, from the next months (Autumn 2020), experimental studies (monitoring and investigations of the current energy performances) are followed by the coupling of different numerical methods of investigations, and thus building performance simulations, under transient conditions of heat transfer, and computational fluid dynamics studies, to evidence criticalities and potentialities to designers involved in the re-thinking of indoor spaces hosting multiple persons, with quite high occupancy patterns. Both energy impacts, in terms of monthly and annual increase of energy demands due to higher mechanical ventilation, and indoor distribution of microclimatic parameters (i.e., temperature, airspeed, age of air) are here investigated, by proposing new scenarios and evidencing the usefulness of HVAC systems, equipment (e.g., sensible heat recovery, without flows’ contamination) and suitability of some strategies for the air distribution systems (ceiling squared and linear slot diffusers) compared to traditional ones.

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1. Introduction: State of the art and research significance

1.1. Motivation for a new study and organization of the manuscript

During the first months of 2020, our lives have been shaken up by the pandemic diffusion of the Severe Acute Respiratory Syndrome CoronaVirus 2 (SARS-CoV-2) that, really at a global level, has had an exponential diffusion, by involving heavily quite all countries, with around 33 million of global cases, almost 1 million global deaths, about 204’700 victims in the U.S., 141’700 in Brazil, 94’600 in India, 76’400 in Mexico, around 42’100 in U.K. (COVID-19 Dashboard, at Johns Hopkins University, 28 September 2020). Both contagions and deaths are probably many more than those of official data. The World learned a new word: lockdown. A large part of the population had to change, suddenly, habits, daily activities, sport, and hobbies, besides new modalities for working and learning and, where the lockdown has been too light, tardive, short, or uncoordinated, the pandemic resumed or did not slow down its spread, so that diffusion and complications, especially in the older segment of the population, have had a serious impact on society. The pandemic COVID-19 heavily destabilized all aspects of normal life, with a violent and sudden re-organization of every-day activities in “remote mode”, from the smart working to the educational (i.e., scholastic and university) web-learning.

In this investigation, only a small part of the global issue can be addressed, a huge problem that concerns our future normality, the sustainability of our lives, the need to renew economies, incomes,
lost jobs, and salaries. Even before the COVID-19, the World had big and unacceptable differences of possibilities among countries and persons of the same nations, cities, and districts. Now, everything has been exasperated, and the digital divide, for instance, is only a new and terrible face of the 2020 energy poverty.

The aim of this study is the proposition of a novel contribute toward the recovery of normal life, and then try to rethink what we do every day: teaching in the presence of students, learning in presence of teachers, by guaranteeing the reciprocal safety in the place in which family and society invest in the future. In particular, the study here proposed deals with the issue of ventilation in university classrooms of a real educational building and its impact on energy demands, costs, and emissions for the micro-climatic control. We are presenting the results of a research that involved us closely, the redevelopment of an educational building that, in the second half of 2019, was involved by the re-design of indoor spaces, to create new classrooms and which, in the midst of the pandemic, is currently designed again, with a series of reflections.

New systems and equipment were planned to allow safety, comfort, flexibility, airflows compatible with the need of containing the transmission of the virus, and, if possible, also with a view to energy savings, linked to lower polluting and climate-changing emissions and thus to a cleaner ambient.

The investigation concerns a building of the University of Molise (South Italy, city of Campobasso, Apennines backcountry), namely some large spaces of the Faculty of Agriculture, and, in particular, it begins with the calibration of a calculation model, deeply defined with regard to input data (i.e., direct inspections and surveys on building components, thermal images, etc.) derived from in-field surveys. Then, the outcomes of the transient energy simulation (BPS) have been compared to the monitored energy consumptions, through the organization and comparisons of historical bills of the energy supply contracts (natural gas and electricity). Furthermore, by correcting some input when necessary, the model has been calibrated. Once available a reliable numerical model of the whole building, to reduce the computational effort, a deepening on the air diffusion performances in one of the architectural and space computational domains; in Section 3, the architectural and technological refurbishment of one of the main buildings of the University of Molise is presented. The need of flexibility and management of increased outdoor air, that emerged during the last months, has implied the energy, economic and environmental study, a deepening concerned one of the new classrooms of the building: in particular, one of the possible and suitable HVAC (Heating, Ventilating and Air Conditioning) configuration, deeply analyzed through BPS (building performance simulation, in the domain of the time), was modeled also for what concerns the air diffusion performance of several strategies of supply and extraction of the air in the room. Thus, several air diffusers configurations and air distribution strategies were designed and simulated in a suitable CFD environment (Computation Fluid Dynamics, in the domain of the space). Various configuration of inlet systems of ceiling (square, linear) and wall-mounted (grilles and nozzles) diffusers, as well as different types of extraction grilles, were firstly designed according to the ASHRAE ADPI method, and then analyzed as regards the implications on the indoor environment, in terms of thermal and flow fields, air velocity, mean age of air.

The paper is organized as follows: the introduction (Section 1), with recent referenced studies in the matter of measures and habits for limiting contagions, with a special focus on the role of the HVAC systems and thus heating, cooling, and ventilation; Section 2 introduces the study methodology and the advanced modeling of building energy performance, with reference to both time and space computational domains; in Section 3, the architectural and technological refurbishment of one of the main buildings of the University of Molise is presented. The need of flexibility and management of increased outdoor air, that emerged during the last months, has implied the energy, economic and environmental tests of HVAC systems' alternatives, shown in Section 4, evaluated with hourly energy studies, according to transient energy simulations, with a deepening on the air diffusion performances in one of the new classrooms, by means of a CFD investigation (Section 5), firstly by establishing the social distancing. Some additional remarks and future topics to develop are proposed in Section 6.

The main objective and novelty of this study, from the point of view of technicians involved in the architectural engineering and the energy efficiency of buildings, is to propose a comprehensive approach and methodology for sustainable and safe educational...
activities, by renovating spaces, air conditioning, and ventilation systems, also with consideration of the air distribution strategy in classrooms.

1.2. COVID-19 and role of Heating, Ventilating and Air Conditioning in Buildings

COVID-19 is an abbreviation of Coronavirus Disease 2019, appeared in China at the end of 2019 and, in few weeks, diffused in the entire world, with millions of contagions, hundreds of thousands of deaths, many of these not calculated in statistics. COVID-19 can have many different evolutions in different persons, given the large variability of the reaction of the human body, and thus it can imply quite light infections not showing symptoms or, on the opposite extreme, very heavy complications, illness, respiratory acute affections, cardiac pathologies and, often, mortality. All possible effects (and affected organs, e.g., lungs, kidneys, heart, brain) are probably still unknown. Surely, the mortality rate is high, and the risk of severe complications for a huge part of infected people is common as well. In general, from available data, it results that the weakest part of the population is constituted by the older persons, with an age higher than 60 years, even if often also young and very young persons can be seriously affected with dramatic implications. The SARS-CoV-2 is highly contagious, with a high rate of reproducing itself. The mathematical indicator more common for evaluating a pandemic risk is the parameter R0, the so-called “basic reproduction number”. This index counts how many persons, starting from one infected case, become infected: an R0 higher than 1 means that the infection is outbreaking, and this can lead to a pandemic. An analogous meaning is expressed by Rt, even if this is dynamic and thus, differently from R0, is referred to the second phase of the pandemic, after the adoption of anti-contagion policies and measures. SARS-CoV-2 is transmitted from the infected person to another person through infectious agents, disseminated by the airborne transmission via the large droplets emitted with coughing, sneezing, the act of speaking, and given the close contacts among persons. For what concerns the airborne transmission due to the exhaled air and thus related to tiny droplets, there is a large debate among scientists, still in summer 2020. Indeed, small particles and droplets, in the respirable size, remain in the air or can be transported by the air movements or by other solid suspended contaminants and, in this way, can reach other persons: presently, the airborne transmission route is under investigation and requires a better understanding. The contagion requires direct contact from pathogens, coming from an infected person to another person. These pathogens are the microorganisms, transmitted with airborne droplets, aerosols, or present on a surface that, after contact with mouth and nose, enter into the respiratory tract of the person that could become infected. Eyes can be also a route for the virus. Thus, some key factors must be taken into account for limiting contagions, and these involve many behaviors and practices.

In this paper, only the HVAC-related operations for reducing the transmission are investigated. On the other hand, non-HVAC-related good practices and measures (e.g., the necessary social distancing, frequent sanitizing of rooms and surfaces, cleaned hands, use of surgical, FFP2, or KN95 facial filters, frequent opening of windows for removing pathogens in naturally ventilated buildings) here are not discussed. These habits, behaviors and practices - first of all the avoiding of too-close contacts, i.e., less than 1-2 m, for achieving the so-called social distancing - must be suitable and correct.

In the view of restarting in-presence activities, among which the educational ones, one common question among the technicians involved in the topic of building engineering but also very common among persons and workers, was the following one: Which can be the impact of HVAC systems as regards the spreading of the virus, with the risk of contagious and contamination by the SARS-CoV-2? Worldwide, many associations of technicians involved in the building energy study and design of building systems and equipment, for instance, ASHRAE (the Position Document on Infectious Aerosols [1]) in the USA, REHVA (COVID-19 guidance document [2]) in Europe, AiCARR [3,4] in Italy answered to the first questions. Several useful documents and guidelines were published from the Indoor Environmental Quality – Global Alliance (IEQ-GA), that join many world associations involved in study and researches concerning the indoor environmental comfort. At the IEQ website, several documents are suggested for understanding the role of ventilation and HVAC systems about the containment of COVID-19 transmission (https://ieq-ga.net/covid-19/information-center/).

Epidemiology Science has underlined that closed environments (i.e., the indoor spaces) are much more dangerous, in terms of risks of contagions, compared to open spaces, first of all given the lack of spacing among people. Really, ventilation, and thus a suitable renovation of air inside buildings, is an efficient strategy to fight the indoor contamination. Indeed, ventilation is a way of diluting the concentration of pathogens. There are no doubts that the building ventilation is necessary and, mainly in overcrowded indoor environments (i.e., high occupancy, such as common in working or studying places), air change rates have to be intense, even if, of course, this implies a higher ventilation thermal load and thus higher air-conditioning-related energy and economic (and even “environmental”) costs.

Common events (breathing and sneezing, toilet flushing, or, for instance, during the use of medical equipment, like in a dental clinic) spread pathogens into the indoor air, in form of large droplets and aerosols, characterized by a different behavior [1]. Large respiratory droplets are responsible for the short-range transmission, while the smaller aerosols, due to the evaporation of droplets, can infect secondary persons without direct contact with the primary one, also traveling for long distances:

- “respiratory droplets” are those with a diameter > 5–10 μm, and these tend to fall on pavement or surfaces because of gravity so that the infection can be limited by maintaining a threshold distance among people. This is why social distancing is necessary for limiting the contagions due to close contacts (probably, the main cause of contagions).
- “droplet nuclei”, with a less than 5 μm diameter, and thus the dried residua of droplets, and aerosols can settle and travel in the air for a long time and distances; these are responsible for the airborne transmission, can remain suspended in the air and also can travel for several meters, with the related risk of transmission. This is why indoor ventilation is important.

The World Health Organization [5] considers the respiratory droplets and the direct contact as the primary via for the virus transmission. Moreover, the WHO considers the airborne transmission possible, mainly under circumstances related to activities generating aerosols (i.e., some medical procedures cited in [5]).

According to the American ASHRAE, “Ventilation and filtration provided by heating, ventilating, and air-conditioning systems can reduce the airborne concentration of SARS-CoV-2 and thus the risk of transmission through the air. Unconditioned spaces can cause thermal stress to people that may be directly life-threatening and that may also lower resistance to infection. In general, disabling of heating, ventilating, and air-conditioning systems is not a recommended measure to reduce the transmission of the virus” (literally, from the ASHRAE website https://www.ashrae.org/technical-resources/resources). Thus, three facts can be evidenced:
• ventilation is suitable for diluting and for removing the indoor infection pathogens;
• filtration can reduce the indoor contamination, of course, it requires suitable positions, maintenance, and replacement of proper High-Efficiency Particulate Air (HEPA) filters.
• a suitable thermal and hygrometric environment can reduce the thermal stress, and thus it can allow the strengthening of the individual resistance to infections.

Finally, waiting for effective universal therapy and vaccines, besides the aforementioned good practices, surely flexible and suitable air-conditioning and ventilation systems must be commissioned, designed and managed for reducing the risk of contaminations. Really, HVAC systems can be an important partner to contrast the infections and the ASHRAE position paper [1] underlines the need of perfect design and maintenance of these, by respecting for instance the requirements of relevant design standards and handbooks (ASHRAE Fundamentals [6], Application [7], Systems and Equipment 2020 [8]). This document specifies - besides the need of suitable air changes for dilutions – the importance of suitable airflow patterns, thermal and hygrometric fields in the indoor environment (temperature and humidity distribution) and filtration, also through the ultraviolet germicidal irradiation (UVGI). Minimum standards to fulfill are the ANSI/ASHRAE Standards 62.1 [9] (in the matter of Indoor Air Quality – IAQ), ANSI/ASHRAE Standards 62.2 [10] (IAQ in residential low-rise buildings), ANSI/ASHRAE/ASHE Standard 170 [11] (ventilation in Healthcare facilities).

The following two statements have been approved by the ASHRAE, specifically for what concerns the transmission of SARS-CoV-2, and thus:

• concerning the airborne transmission, a suitable operation of building and facility, that includes proper management and use of air-conditioning, can limit and reduce the airborne exposure, and thus it can contribute in controlling the virus transmission.
• about the airborne concentration, specifically, ventilation and filtration can have a positive effect in reducing the concentration of virus in the air and thus in reducing the risk of transmission through the air.

According to several papers, among which [1] and the recent study of Correia et al. [12], large droplets, with a diameter > 10 μm and emitted as a consequence of coughing and sneezing, fall to the floor and on surfaces in a distance of about 1–2 m from the infected person. This is why close contacts must be avoided, just for reducing such modality of respiratory infection, as discussed by Chen et al. [13]. Of course, large droplets, once emitted, evaporate too, by becoming an aerosol, and, to control the virus transmission, the management of the aerosol is different being capable of traveling for meters and tens of meters, as stated by Morawska and Cao [14]. The authors, during the first phase of studies in the matter of COVID-19, underlined that the predecessor of SARS-CoV-2 (i.e., the SARS-CoV-1) has had the main transmissibility of virus in the air.

As cited, large droplets are affected by gravity, and thus the via of the infections related to these is the close contact, directly from person to person. On the other hand, ventilation and air conditioning operations may affect the diffusion and distribution of droplet nuclei and aerosol. As evidenced by Correia et al. [12], the infection route via aerosol connected to the use of centralized air-conditioning systems may be possible and requires attention, so proper HEPA filters, that can remove pathogens, must be adopted. In this regard, air handling units can have a positive effect because of air filtration, which improves the quality of air supplied into the indoor spaces. Differently, channels and air ducts, without HEPA filters, may spread the virus. In the same study [12], the example of the Diamond Princess Cruise Ship was inferred. Finally, the wrong management of ventilation systems can be dangerous.

In the study of Yao et al. [15], it has been shown, on large statistics, a negative association between confirmed COVID-19 and ambient levels of ozone and a positive association between the confirmed COVID-19 and the average ambient relative humidity. The same investigation, also based on previous studies, evaluated that large droplets in closed environments evaporate fast into fine aerosols. Finally, fine aerosols require deep attention, to manage viral particles. Here again it is underlined the important role that HVAC systems can play.

According to [1]: “Directional airflow can create clean-to-dirty flow patterns and move infectious aerosols to be captured or exhausted”. This is what we will purpose in the second part of this study, by accurately designing air distribution systems (method ASHRAE ADPI – Air Diffusion Performance Index), by evaluating thermal and flow fields inside the classrooms, together with other parameters related to thermal comfort and air diffusion performance (e.g., local age of air).

In a matter of the role of ventilation systems and airflow purification and directions for controlling the transmission of diseases and viruses, some authoritative studies are here briefly cited. First studies in a matter of management of ventilation in buildings to face contagions and spread of COVID-19 are, obviously, related to health care facilities, hospitals, and special buildings.

Firstly, the variation of indoor pressure can be a lever for protecting an indoor space from surrounding spaces:

• a positive pressure, for instance, can be designed where immunodeficient persons are hosted;
• a negative pressure, conversely, is suitable for spaces hosting infectious patients.

Finally, negative and positive pressures are important strategies that can be adopted in designing particular building wards. About it, authoritative indications, worldwide, were already inferred in previous studies, among which [16,17].

In 2018, a wide review proposed by Quian and Zheng [18] testified the importance of ventilation, both natural and mechanical, to dilute contaminants. The study refers to the most known respiratory affections from 2003 to 2013 (e.g., SARS, H1N1, MERS). As testified by the many cited studies, even if natural ventilation, enhanced by enlarging the size of the windows, can improve the indoor air quality, the ventilation system of a hospital, general wards or, even negative pressure wards, has to both dilute contaminants and, at the same time, allow the supply of pathogen-free air into the indoor environments. At the same time, the airflow direction has to be controlled, from the clean zones to the dirty areas and this is fundamental to reduce the transmission of contaminated aerosols between rooms. This study is referred to hospitals but, the same notes can be transferred also to other spaces, especially those with a high occupancy rate.

Linch and Goring [19] outlined, for the long-term care facilities, some points for improving the safety of the environments against possible transmission of the Sars-CoV-2, and these involve the modification of patients’ rooms to negative pressure, for limiting the contamination of other spaces. These key points concern the suitable evaluation of space volumes, ventilation requirements and differential pressure, the installation of additional exhaust fans, the increment of the overall air filtration efficiency, the correct management of doors (i.e., closed doors between corridors and wards, open doors between wards and bathroom, if here the exhaust air is extracted), the respecting of all guidelines for the
prevention of infections as proposed by the dedicated Centres for Disease Control and Prevention (CDC).

Still on the matter of hospital settings, Zhao et al. [20] cited an important study of the WHO [21], in which a ventilation flow rate of 288 m³/h per person is recommended to control the airborne transmission. Really, [21], in the matter of natural ventilation in hospitals, proposes an average ventilation rate of 160 l/s/patient for airborne precaution rooms, with a minimum value of 80 l/s/person, while lower values are needed for general wards (i.e., 60 l/s/patient); regarding corridors and spaces without a fixed number of the persons, a ventilation rate of 2.5 l/s/m² is cited. According to [20], natural ventilation is dependent by weather and architectural features and, existing ventilation systems often are not capable in providing such ventilation rates: therefore, they underlined that the use of indoor purifiers provided with HEPA filters is recommended, because such systems generally are enough efficient for removing such virus-laden aerosols, given their size range (the peak concentration of Sars-CoV-2 aerosols is in two size range, sub-micron between 0.25 µm and 1.0 µm, and super-micron on > 2.5 µm). The efficiency of filtration of HEPA is higher than 95% and around 100% concerning the aforementioned particles’ ranges. Such air purifiers can be used also in dwellings, in which quarantined persons are hosted. Specifically as regards to the COVID-19 hospitals created in Wuhan just during the peak of the pandemic (January 2020) and thus the Huoshenshan and Leishenshan hospitals, Luo et al. [22] presented the lesson learned from these design and construction, ultra-rapid to be ready in less than 12 days for facing the sanitary emergency in Hubei. By means of a BIM approach, and thus an integrated, architectural, engineering and service design, the Leishenshan Hospital was designed for having wards in negative pressure compared to the surroundings, to isolate the pathogens. Mechanical ventilation was largely used to dilute the contamination, and the air circulation was carefully designed for fulfilling relevant standards. In the same vein proposed in our paper (in the next sections), also regarding the Leishenshan Hospital, various solutions of air supply and extraction were simulated, during the design phase, to select the air distribution and return strategy most suitable for preventing the contagions. This design is very interesting also for the high care to the issue of discharging the filtered exhaust air into the surrounding environment, aimed at avoiding secondary pollution.

Concerning dental clinics, using accurate CFD simulations, Chen et al. [23] studied the capability of the air cleaner in controlling the dispersions of droplets and aerosol particles, emitted by patients and exposing the dental healthcare workers at high risks. All boundary conditions were properly modeled, by taking into account the kind of ventilation systems, and thus even the airflow, temperature, and supply velocity, to evaluate the efficiency of air cleaners. The simulations results revealed that the use of air cleaners can be effective for reducing the exposure of workers to both airborne droplets and aerosol particles. Also the directions of airflow and the relative location between positions of the air cleaner and sources of droplets/aerosol are important. Dental settings are extremely serious environments, with a high risk of cross infections between dentists, operators, and patients, because of aerosols and droplets, and this is evidenced in the wide review of Shah [24], in which available studies are discussed, about new protocols and guidelines for the management of patients, the dental activities, new organization models and practices for facing the risks of transmission during the COVID-19 pandemic. On the other hand, poor indoor ventilation can be a factor of contagions. In this regard, for several countries of the Middle East, a deep review of Amoatey et al. [25] revealed that the indoor ventilation in buildings is often not sufficient, and the indoor pollution can have various health effects, and thus respiratory affections and sick syndrome buildings. More in-depth, ventilation levels not fulfilling the ASHRAE standards are verified in most buildings and, as cited in [26] (some of the same authors), this can have effects also on the transmission of COVID-19, so that specific studies are required. Really, where ambient temperatures and relative humidity are extreme, often ventilation in the building is limited, for reducing the consumption of the HVAC systems, usually working with very low setpoint temperatures. These two conditions, and thus a poor air change rate (around 5 L per second per person, instead of 8, as suggested by ASHARE) and the low indoor air temperature can favor the transmission of respiratory diseases, as the COVID-19. This can happen in airports, shopping malls, mosques, offices, and residential buildings and, to acquire scientific data and knowledge, the authors underline the necessity of study concerning the building ventilation rate for avoiding virus transmission via respiratory droplets and maybe aerosols. A deep study in the matter of university classrooms is not available in the literature and, in this vein, the paper here proposed is our first contribution to the field.

Again concerning the filtration importance, it is very interesting the notion of Shiu et al. [27], that underline, in the case of measles, the necessity of protecting from nosocomial infections, and thus the necessity of adoption of HEPA filters also in the outlet exhaust ducts. This is a very interesting notion also in the matter of studies concerning air-conditioning operation for reducing the COVID-19 transmission. About the airflow purifications, the role of ultraviolet germicidal disinfection, and its contribution was deeply investigated by Memarzadeh et al. [28] and testing procedures are provided in [29].

Really, as cited, to limit and nullify the risk of contagious, the HVAC-related strategies must be, obviously, complementary to non-HVAC containment operations, and the most important are the social distancing, a frequent cleaning of surfaces, correct behaviors of persons, and thus the use of facial winters, the avoiding of contact of hands with mouth, nose, eyes and of each self-inoculation into mucous membranes. These aspects are deepened by Morawska et al. [30]. The need for precautions, suitable behaviors, practices, and systems for avoiding transmission is evidenced also by Faridi et al. [31]. The authors collected air samples in hospital wards hosting persons affected by COVID-19, at distances of 2 to 5 m from beds, and the samples resulted in negative. Therefore, the study evidenced that close contacts are those very dangerous, and thus the healthcare workers must be surely equipped with stringent levels of personal protection systems. Future developments of medical knowledge, concerning the risks of airborne exposure, are really necessary. Kumar and Morawska [32] evidence also the necessity, for indoor environments characterized by a high density of occupancy, to minimize the virus-laden as possible, and thus ventilation is an important strategy. The risk of infection rises if the indoor air is stagnant and this happens when the ventilation is not efficient. The study specifically cites the case of hospitals, malls, shops, schools, public transport, and others. On the other hand, mechanical ventilation must be effective, because in some cases this can also induce a worsening of stagnancy in some zones. Once again, the importance of HVAC systems for effective indoor-outdoor air exchange is underlined, together with other individual good practices.

The risks related to a crowded indoor environment, for instance, classrooms and educational buildings, are evidenced by Franco and Leccese [33] and, in the view of starting with the in-presence activities (September 2020), a punctual evaluation of the occupancy is important. The authors proposed a study in which, at the University of Pisa, the CO₂ concentration was measured to evaluate the real number of occupants, and thus to manage the ventilation strategy in terms of DCV (demand control ventilation); this can be useful for controlling both thermal comfort and energy costs. Besides direct measurements of contaminants, also the numerical modeling of indoor environments, through advanced studies, such
as the Computational Fluid Dynamic (CFD) analyses, can be useful in sensible buildings. A wide discussion about the potentialities of CFD for understanding the mechanisms of transmission of pathogens (virus and bacteria) and the role of ventilation, with reference to different buildings (among which hospitals and teaching applications), is proposed in the recent study of Peng et al. [34], with a wide review of many papers involving different applications of CFD analyses.

Our investigation, by taking into account all these studies and the available literature, proposes a novel overview in the matter of increased outside flowrate and total supply mass flowrate supplied into classrooms, by evaluating the impacts on energy demands, costs, emissions and analyzing the indoor spatial distribution of microclimatic parameters, with an original contribution coupling different numerical methodologies.

2. Materials and method

2.1. A coupled approach: Building Energy Simulations and Computational Fluid Dynamics Simulations

This paper proposes a coupled approach of two complementary numerical investigations on building energy performances, and thus a time-dependent study (BES – Building Performance Simulation, based on transient energy balances, performed by assuming sub-hourly time steps) and a space-dependent investigation (CFD – Computational Fluid Dynamic, based on the solution of conservation equations and adoption of turbulence model concerning a 3D discretization of the spatial domain).

The coupling a CFD simulation with a BES provides more detailed information on the building indoor air conditions and improves the accuracy of the energy results [35]. A BES allows the evaluation of the building energy demand, on an hourly or sub-hourly basis for a reference period or even the whole year. Therefore, an analysis of the cooling, heating, and ventilation systems and the indoor environmental conditions is performed, with the assumption that the air is in conditions of ‘perfect mixing’, i.e., one computational node is representative of the whole zone. Conversely, by taking into account the real volume of the zone, a CFD simulation makes a prevision of the indoor temperature distribution, of the air velocity, humidity, and contaminant concentration, and it allows the evaluation of the local thermal comfort, usually with reference to a specific instant. The possible coupling strategies between CFD and BE simulations are described by Zhai et al. [36], who detected static and dynamic coupling strategies. In the first case, the data exchange between the two simulations occurs in one-step or two-steps depending on the accuracy of the simulation, while - in the second case - the data exchange is continuous and dynamic. The set of data exchanged between BES and CFD simulation can be classified into “interface data” and “state data” [37]. The first ones are the data at the boundaries of the two different physical domains (examples are the surfaces’ temperature, heat fluxes, airflow rates, supply temperatures, and so on). The state data, conversely (e.g. PPD, PMV, indoor air temperatures, relative humidity, and air velocity), belong to one of the physical domains, and thus, by having a non-uniform distribution, after the evaluation through the CFD analysis, these can be transferred to the BES. The reading of [37] is suggested for a deepening.

The studies about the coupled approach of BES and CFD are various; some authors, for example, focused on the evaluation of double skin façade performances [38], or of advanced air-conditioning control strategies [39]. On a larger scale, the study of Gobakis & Kolokotsa [40] focused on the correlation between the external conditions and the indoor environmental quality in the Campus of the Technical University of Crete. Furthermore, Ascione et al. [41] investigated the energy refurbishment of a historical University building in Naples, through a coupled approach, in which BES was employed to evaluate possible retrofit scenarios and a CFD simulation was applied to verify the fan coil positioning for a better indoor thermal comfort. Fan & Ito [42] integrated CFD and BES for the evaluation of different types of ventilation systems in an office building. Moreover, Alnusairat et al. [43] applied this for the comparison, in terms of thermal comfort and energy demand, of configurations of sky court in high rise office buildings. Coupling CFD and BES analysis could be necessary for suitable energy-efficient design and the project of comfortable and healthy spaces [36].

The importance of air purification and indoor ventilation is one of the main topics in this serious emergency period. Filtration, ventilation and air conditioning systems could contribute to mitigate the diffusion of particles and droplets, and therefore the infection transmission, especially in crowded buildings. Ventilation systems, properly designed, which provide outdoor air, highly filtered, could reduce the exposure to contaminated air. The use of CFD to verify the indoor conditions of environments at risk of contagion was widely demonstrated, especially in hospital rooms [44 – 45].

Thus, the use of a coupled CFD and BES analysis can be the right approach to investigate the indoor building environment together with the building energy demand. In the proposed investigation, we applied such coupled approach to a case study: this is a University Faculty located in Campobasso (Italy), which hosts the Department of Agriculture, Environment and Food. The investigation starts with the calibration of the building energy model, based on real and measured data, continues with the comparison of different HVAC configurations from the point of view of energy demands, costs, and emissions, and ends with a CFD analysis of a typical classroom, with the aim of limiting the energy request and improving the indoor microclimatic quality (i.e., PMV/PPD, air temperature, flow fields and mean age of air). Methodology and development of the study are shown in Fig. 1, then accurately described in the following sections.

2.2. The Building Energy Simulation

The numerical model for the dynamic energy simulation of the building is here described, through the definition of a 3D model and by collecting information about the building orientation, the location, the thermo-physics of the building envelope, the indoor temperature, and the activities.

With the aim to obtain a detailed characterization of building envelope, HVAC systems and indoor conditions, a deep energy audit has been performed by means of in-situ surveys measurements, as well as interviews with occupants. Materials, lighting and equipment schedules, occupancy, temperature set-point, layers and construction for the opaque and transparent envelopes, use of each thermal zone, operational conditions, heating, cooling, and ventilation systems, and hot water production were the data used to define the building energy model, to simulate in EnergyPlus [46] through the DesignBuilder interface [47] (the detailed description is in Section 3). The numerical model was calibrated by means of a comparison with the energy bills, by using the approach proposed by the authoritative M&V Guideline [48]. Here, the comparison takes place through some statistical indices, such as the mean bias error (MBE) (Equation (1)) and the coefficient of variation of the root mean squared error CV(RMSE). Typically, models can be considered calibrated, and thus these well-represent the present energy demands of the real buildings, if the MBE is lower than ± 5% and CV(RMSE) is within 15%, when monthly data are considered.
In equations (1) and (2):

\[
MBE\% = \frac{\sum_{\text{period}} (M - S)_{\text{month}}}{\sum_{\text{period}} M_{\text{month}}} \times 100
\]

\[
CV\left(\frac{\text{RMSE}_{\text{month}}}{A_{\text{month}}}\right)\% = \frac{\text{RMSE}_{\text{month}}}{A_{\text{month}}} \times 100
\]

and

\[
A_{\text{month}} = \frac{\sum_{\text{year}} M_{\text{month}}}{N_{\text{months}}}
\]

In order to compare the energy performance, common primary energy factors (PEF) were used, and thus 1.95 for the electricity (i.e., the considered non-renewable average efficiency of thermoelectric Italian system is 0.51) and, concerning the natural gas, a PEF equal to 1.05 is chosen, as suggested nationally [49].

Furthermore, in this study:

- emission factor for natural gas is 0.24 tons CO\textsubscript{2}-eq/MWh [50] (LCA approach emission factor);
- emission factor for electric energy is 0.424 tons CO\textsubscript{2}-eq/MWh [50] (LCA approach emission factor);
- electricity cost (including non-recoverable taxes) is 0.16 €/kWh (from real energy bills and contracts);
- natural gas cost (including non-recoverable taxes) is 0.062 €/kWh (from real energy and contracts).

The prices of natural gas and electricity are those paid, averagely, by the University of Molise in 2019. Regarding the energy models, as aforementioned, these are geometrically built in DesignBuilder [47], the same software used also for defining the thermo-physics of the building envelope, HVAC system and lighting equipment. Other specifications and schedules of facility’s plants and HVAC systems have been implemented and/or modified in EnergyPlus [46], the well-known program for the whole building energy simulations, operating under transient conditions of heat transfer, whose capabilities have been discussed in a very wide scientific literature. Before the modeling of the building as renovated, also a simplification of the original model was provided, in order to reduce the computational effort. Obviously, against the billings and the previous calibrated model, also the new simplified model was tested and validated.

The capability of EnergyPlus [46] in predicting real and reliable energy performance of buildings, also concerning HVAC systems and equipment, are here not discussed, being available important reference studies, that investigated these capabilities by taking into account methodologies and indications provided by authoritative sources, such as the Standard ANSI/ASHRAE 140/2011 [51] and the International Energy Agency IEA [52]. In this investigation, among the various alternatives of EnergyPlus – e.g., Conduction Transfer Function (CTF), Conduction Finite Differences (ConFD), Combined Heat And Moisture Finite Element algorithms (HAMI) – the chosen algorithm for solving the transient energy transfer...
was the CTF. Other particular simulation parameters are described in the sub-section 3.2.

2.3. The Computational Fluid Dynamic Simulation

For understanding the thermal and flow fields and the air quality in the breathing zones of the indoor environment, some common configurations for the supply and the extraction of air were designed for a selected typical classroom. In particular, four air distribution configurations referred to the “All Air systems OA 7/14” (Section 5), and thus one of the proposed HVAC solutions, were compared through CFD simulations. These will be described in the following lines.

The CFD is an investigation methodology widely used in many studies to evaluate the indoor thermal conditions of different types of environments and buildings, such as lecture rooms [53], museums [54], residential spaces [55], hospitals, offices and schools. As in our case, Buratti et al. [56] evaluated the indoor thermal comfort in a university classroom, through CFD simulations. Méndez et al. [57] optimized the organization of a hospital room by considering, at the same time, the better ventilation at the patient site and the cost of execution. The authors analyzed the age and the velocity of air inside the room and verified some modifications in the location and geometry of the air inlet and outlets, and the dimension of the partitions.

Our study, conversely, compares some types of supply and extraction systems of the air through CFD simulations in order to bring out differences in terms of thermal comfort and air purity and quality. Following the provisions of Italian Government [58] and therefore to simulate the real situation that will occur at the resumption of the “in presence” educational activities (in the next weeks, in Italy), the number of occupants for the classroom under consideration was halved, to ensure the minimum spacing of 1 m between the students. In non-emergency conditions, and therefore for the calibrated model, the number of occupants considered corresponds to the number of seats in the classroom and to the provisions of the Italian Ministerial Decrease 18-12-1975.

All diffusers’ configurations were designed by taking into account the ADPI (Air Diffusion Performance Index) method [6,59]. This index, developed for evaluating the air diffusion performance in the cooling-mode operation, establishes a relation among the type of diffusers, isothermal throw distances, layout of air terminals, characteristic length of the room, and it is referred to a typical range of cooling loads. Higher is the ADPI, the higher is the achievable performance by the air distribution systems in terms of thermal comfort and reduction of the discomfort due to air draft inside the room. According to ASHRAE Fundamentals 2017 [6,59], most air distribution systems is designed for achieving an ADPI higher than 80%.

For what concerns the CFD simulations, the boundary conditions were directly acquired from the previous BES model, while, convergence criteria, turbulence model, mesh, resolution methods, were defined and implemented in the CFD numerical model. The numerical method to solve the set of partial differential equations (PDEs) describing the transport of momentum, energy and turbulence quantities is the finite volume method (FVM), while the grid which discretized the room space is a computational mesh of non-overlapping adjoining rectilinear cells (finite volume grid), 30 cm spacing. An up-wind discretization scheme was adopted for the convection term and a standard k-ε turbulence model was selected (“k” is the turbulent kinetic energy and ε is its dissipation rate). The convergence criteria were set with a termination residual of 10^-5. All the boundary conditions, and thus the interface data as defined by [37], were automatically assumed by the hourly dynamic simulation of the building. The used code is DesignBuilder [47].

2.4. Thermal comfort and Indoor Air Quality

In order to compare the different air distribution configurations, the thermal comfort and the indoor air quality were deepened. The analysis of the thermal comfort for the indoor environment was performed through the Fanger approach [60], and thus through the PMV and PPD indices, and thus the Predicted Mean Vote and the Predicted Percentage of Dissatisfied. In addition, some other parameters were investigated to evaluate the indoor thermal comfort, namely the vertical temperature stratification and the air velocity. An excessive vertical temperature stratification, indeed, in addition to implying a greater energy consumption in the period of heating, could produce a feeling of discomfort (heat in the head, cold in the feet). The UNI EN ISO 7730 standard [60] provides that this temperature difference, at 0.1 m and 1.1 m (sitting people), must not be above 3 °C. This means accepting one maximum percentage of dissatisfied equal to 5%. To evaluate the temperature uniformity in the indoor environment, the temperature difference (Tmax - Tmin) has been calculated for the central area of the occupied volume, both in the horizontal and vertical sections. The aim was to evaluate both the presence of local thermal discrepancies and the presence of high temperature differences between the lower part and the breathing area of the environment (see Section 5.1).

For what concerns the air velocity, as conventionally assumed in the summer regime, an air movement within 1 m/s was not considered uncomfortable, while, in the winter regime, even an air-speed above 0.20 m/s was considered as a cause of local discomfort (see Section 5.2).

This investigation does not aim to evaluate merely the indoor thermal comfort depending on the adopted air terminal solutions, but also this would evaluate some parameters which affect the local air quality and rate of renewal, such as the movement of the indoor air, flow fields, and mean age of the air which depends on the number of diffusers, their position, the airspeed and the position of the extraction grilles (insights in the Sections 5.2 and 5.3). Obviously, the occupant number affects the air quality, indeed, the human respiration and transpiration release components such as water vapor, bio-effluents and carbon dioxide (CO2) which, in large quantities, makes the air unhealthy. Suitable air changes to ensure the healthiness of the indoor environments have been defined starting from the Italian Standard UNI 10.339 [61] and then were adopted in the energy model of the building. By considering the COVID-19 emergency, as a precaution, different HVAC configurations have been then proposed in the study, in which the outside flow rate was doubled or tripled (Section 4.2). Moreover, as aforementioned, in the CFD simulation, the number of people was halved in compliance with very recent national guidelines [58], to reduce the number of persons, by lowering the spread of pathogens in the air and mainly for allowing the necessary social distancing.

3. The case study: The university building of Campobasso

Campobasso, where the case study University building is located, is a city of Italian backcountry, in the south, near the Apennine Mountains and characterized by a quite cold climate, classified Cfb according to the Köppen-Geiger method. The average annual temperature is of about 12.3 °C; all main information about the statistical weather conditions are provided in Fig. 2.

3.1. Energy audit

The building was built in the early ‘90 s; it is characterized by two blocks (namely, I and II in Fig. 3), with a rectangular shape
and six floors joined by means of an atrium covered with a cupola. The whole surface to volume ratio (S/V) is 0.37 m².

The most important information about the climatic conditions, the thickness (s) and the thermo-physics of the building envelope are summarized in Table 1. Herein, the value of thermal transmittance (U) has been calculated according to [62] and [63] and the periodic thermal transmittance (YIE) according to [64] starting from the available datasheets. During the 2018, accurate thermal images were also acquired in order to check eventual lack of uniformities in thermal characteristics and presence of significant thermal bridges or air infiltrations (Fig. 4).

Regarding the building envelope, it is composed by different types of opaque and transparent components. The main wall types have aerated concrete blocks, with mineral fiber insulation and external aluminum panel (Fig. 4a) or hollow bricks with air gap and external “porfido” stones (Fig. 4b). The structural slabs of ceilings are made with pre-stressed reinforced concrete, with different types of finishing and insulation level. Through a comparison of the values reported in Table 1 and the ones established by Italian legislation for new and refurbished buildings, it results that, currently, the case study building has not optimal U values. Indeed, current reference values of thermal transmittances are 0.28 W/m²K and 0.24 W/m²K for vertical walls and roof slab, respectively. This causes quite high heat losses and then in a negative impact on heating needs and on the comfort conditions for occupants. For YIE, and thus the periodic thermal transmittance, in order to limit the diurnal indoor overheating, the current normative reference values are 0.10 W/m²K and 0.18 W/m²K, for vertical and horizontal building components, respectively. The current building envelope values are suitable. Moreover, because of the high occupancy rate and large windows, during the summer, the building cannot prevent indoor overheating.

Several types of windows have been identified. The first one is a laminated glass-wall, used in the south-west façade, at the entrance (ground floor) and for the hallway of the first floor (Fig. 4c). The second type of transparent envelope consists of glass blocks. Finally, all other windows are clear, double-glazed (6 mm glass/12 mm air/6mm glass), with aluminum frames and most of these has an inner shading system, with vertical white slats.

The occupancy rate of classrooms was established according to provisions of the aforementioned Italian Laws. As regards the air conditioning systems of the building, all offices, lecture rooms,
bar, circulation zones and most classrooms are served by a mixed air/water system, given by a combination of fan-coil and air handling units (AHU). Classrooms and corridors of the ground floor of the II block have heavy cast-iron radiators, and a centralized AHU for balancing latent loads and providing ventilation. The bigger “Mendel” classroom, the library and the main central hall are air-conditioned by an all-air system, which provides both heating, cooling and ventilation necessities. Two traditional boilers with nominal power equal to 766 kW (each one) and two vertical storage boilers (1500 l) allow the hot water generation, also for sanitary use. Moreover, two electrical air-cooled chillers provide the cold water: a first chiller (nominal power of 735 kW, refrigerant
4.2. BES – Building Energy Simulations: Energy analysis of alternative HVAC systems

In order to reduce the risks of contamination from a room to another one of the same building, served by the same HVAC systems, the recirculation in centralized air conditioning systems...
should be avoided. Indeed, recirculation air in a centralized air handling unit, without a correct operation of suitable filters, could provide transportation of pathogens from a contaminated ambient to another one. Moreover, used along with other best practices recommended by the aforementioned and cited Institutions and Centers for Disease Control and Prevention, increasing ventilation, and thus the amount of outdoor air, can be part of a plan to protect occupants by contagions of diseases. Indeed, for reducing every risk of potential airborne viral transmission - by reducing exposure to virus-laden aerosols – and also for reducing the chance for particles to settle and remain on surfaces (desks, chairs, furniture), the main HVAC-related strategy is the increasing of ventilation for removing and diluting the pathogens, as discussed in the previous sections. Finally, with the aim to refurbish both classrooms and didactic activities, a strategic plan is under evaluation, together with technicians of the University of Molise.

For what concerns the HVAC systems, the plan is based on the conversion, for the new 7 classrooms (Fig. 8) of the existing mixed air–water system into an all-air system, with some variants concerning total airflow rate, outside air, kind of handling in the AHU. Of course, the aims are:

- suitable ventilation of the indoor environment;
- high capability in the microclimatic control;
- achievement, when possible, of energy savings;
- reduction of emissions and limitation of the climatic impacts.

The comparison among possible configurations is performed under the points of view of energy, economic and emission savings. In the second phase of this study (i.e., the CFD simulation, Section 5), also a reduction of the number of students, in order to fulfill the need of social distancing, is supposed.

The modification of HVAC operation concerns the classrooms of the block II. One of these is placed on the ground floor (originally, designed for 117 students), the other ones are located at the first floor, with a number of seats ranging from 40 to 120 (Fig. 8). In the original design, these classrooms would be conditioned by an air–water system in which the outdoor ventilation is regulated according to the minimum OA rate required by the Italian Standard UNI 10339 [61] and thus, in each classroom, the ventilation rate is 0.007 m³/s person. More in deep, the designed HVAC system (already described and depicted in Fig. 9) couples fan coils, in a variable number depending on the size of the classroom, to an all-air system without recirculation, equipped with a flat plate sensible heat recovery. The centralized DOAS (Dedicated Outdoor Air System) is the same for all classrooms. The heating and cooling coils, in the Air Handling Unit, are fueled by the hot water and chilled water produced by a centralized gas boiler (efficiency η, at rated conditions, equal to 0.76) and by an air-cooled chiller (EER, at rated conditions, equal to 3 Wth/Wel), respectively. These are the heat and cool generators already installed in the building. The DOAS is equipped with sensible heat recovery (efficiency, at rated conditions, 0.7). This HVAC system will be shortly called FC + DOAS.

Fig. 5. a) monitoring of air temperature, b) monitoring of relative humidity.
Really, the following considerations and aims motivated the thinking of some design alternatives:

a) avoiding centralized systems, at least for the new classrooms. Indeed, even if the recirculation of air is not provided (the designed one is a dedicated outdoor air system), anyway the air channels can be a route for airborne transportation, from a classroom to another one;
b) avoiding in-room terminals allows simplification of design (e.g., no need of collecting water condensed by fan-coils);
c) flexibility in the use of single HVAC systems. Given that this is a low-rise building, with sufficient technical spaces, dedicated rooftop HVAC systems, with DX (direct expansion) heating and cooling coils can be installed;
d) a dedicated rooftop for each classroom allows the perfect management of ventilation, microclimatic control, operation of recirculation, heat recovery, management of thermodynamic conditions of the supply air.

Finally, new different HVAC systems have been designed and modeled, whose difference is the installation of a heat recovery system, merely “sensible” (efficiency 0.75) and consisting of a flat plate metal matrix, in order to avoid any possible contamination between outside air and recirculation air. At the rated conditions, the COP and ERR of the DX heating and cooling coils are 2.75 Wh_{th}/Wh_{el} and 3.00 Wh_{th}/Wh_{el}, respectively. It should be noted that, for the seven new classrooms, seven dedicated rooftop AHUs are designed. Thus, no multizone systems are taken into account. The new tested HVAC systems, without (A) and with (B) the heat recovery, are depicted in Fig. 10. Before commenting the results, two notes: a) the impact of humidification has been neglected (no humidification set-point was assigned), b) the ventilation during the intermediate season (no cooling, no heating) is neglected. These choices are motivated by the fact that the impact of ventilation loads on the space conditioning would be evidenced, and conditions that will alter the comparison are not modeled.

Each HVAC system has been designed with different characteristics, in terms of total (mixed) air flow rate (TA) and outside ventilation air (OA), according to Table 2. Total air (TA) is the sum of outside air (OA) and recirculating air (RA). The ACH is referred to the total mixed supply air (TA, and thus OA + RA). Thus, it means that, alternatively to the configuration 0 (the DOAS + FC, Fig. 9), 5 further HVAC system typologies are modeled, based on the nominal occupancy of the classrooms:

1 All air System OA 7/14: an outside flow rate of 0.007 m^3/(s pers) is imposed, with a total mixed supply flow rate of 0.014 m^3/(s pers). Thus, OA is 50% of TA.
2 All air System OA 14/14: an outside flow rate of 0.014 m^3/(s pers) is imposed, with a total mixed supply flow rate of 0.014 m^3/(s pers). Thus, OA is 100% of TA.
3 All air System OA 7/21: an outside flow rate of 0.007 m^3/(s pers) is imposed, with a total mixed supply flow rate of 0.021 m^3/(s pers). Thus, OA is 33% of TA.

1 All air System OA 7/14: an outside flow rate of 0.007 m^3/(s pers) is imposed, with a total mixed supply flow rate of 0.014 m^3/(s pers). Thus, OA is 50% of TA.
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3 All air System OA 7/21: an outside flow rate of 0.007 m^3/(s pers) is imposed, with a total mixed supply flow rate of 0.021 m^3/(s pers). Thus, OA is 33% of TA.
4 All air System OA 14/21: an outside flow rate of 0.014 m³/(s pers) is imposed, with a total mixed supply flow rate of 0.021 m³/(s pers). Thus, OA is 67% of TA.

5 All air System OA 21/21: an outside flow rate of 0.021 m³/(s pers) is imposed, with a total mixed supply flow rate of 0.021 m³/(s pers). Thus, OA is 100% of TA.

All five HVAC alternative systems are available in both configurations of Fig. 10, and thus without and with (“Sens Rec”) Sensible Heat recovery.

As shown in Table 2, configurations 1, 2 and 3 handle, depending on the specific classroom, from 6.5 ACH (classroom 1F-3) to 7.9 ACH (classroom 1F-4 and 1F-6), while configurations 4 and 5 determine from 9.7 ACH (classroom 1F-3) to 11.9 ACH (classroom 1F-4 and 1F-6). These differences are due to the number of seats and/or different volumes of the rooms. In Fig. 11, the primary energy demands of the base system and of the design alternatives are shown. In figure A, the base system (FC + DOAS) is detailed and then compared, in the other parts of the figures (from B to F), to the energy demands of the design alternatives, with and without the heat recovery system, in the same picture.

The base system has primary energy demands (i.e., mean values for the whole building) equal to 1122 MWhp for the space heating and 147 MWhp for the space cooling, and it corresponds to an EPH and EPc (primary energy demands/m² for the space heating and cooling, respectively) equal to 94.7 kWhp/m²y and 12.4 kWhp/m²y. With reference to the new classrooms, and thus by excluding the remaining part of the building (not involved by consideration of design alternatives), the following results have been calculated (the subscripts H means “Heating”, C = “Cooling”, SC = “Annual Space Conditioning”) and the comparisons are always referred to the base case (FC + DOAS).

- **0 Base Case (Configuration 0) FC + DOAS:** $\text{EPH} = 120.2 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 27.7 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 148.0 \text{ kWhp/m}^2\text{y}$.
- **1 Configuration, All Air System OA 7/14:** $\text{EPH} = 108.1 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 8.4 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 116.5 \text{ kWhp/m}^2\text{y}$. The PES (primary energy saving) is of 31.4 kWhp/m²y, and thus around the 21%.
- **1BIS Configuration, All Air System OA 7/14 Sens Rec:** $\text{EPH} = 64.4 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 9.1 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 73.5 \text{ kWhp/m}^2\text{y}$. The PES is of 74.5 kWhp/m²y, and thus the 50%.
- **2 Configuration, All Air System OA 14/14:** $\text{EPH} = 139.2 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 8.5 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 147.6 \text{ kWhp/m}^2\text{y}$. There is a slight annual PES, almost negligible, 0.3 kWhp/m²y (0.2%).
- **2 BIS Configuration, All Air System OA 14/14 Sens Rec:** $\text{EPH} = 80.7 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 8.7 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 89.4 \text{ kWhp/m}^2\text{y}$. The PES is of 58.5 kWhp/m²y, and thus the 40%.
- **3 Configuration, All Air System OA 7/21:** $\text{EPH} = 123.8 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 12.4 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 136.2 \text{ kWhp/m}^2\text{y}$. The PES is of 11.7 kWhp/m²y, and thus the 8%.
- **3 BIS Configuration, All Air System OA 7/21 Sens Rec:** $\text{EPH} = 71.3 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 13.4 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 84.7 \text{ kWhp/m}^2\text{y}$. The PES is of 63.3 kWhp/m²y, and thus the 43%.
- **4 Configuration, All Air System OA 14/21:** $\text{EPH} = 174.8 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 12.4 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 187.1 \text{ kWhp/m}^2\text{y}$. There is an increase of energy demands, +39.2 kWhp/m²y (+26%).
- **4 BIS Configuration, All Air System OA 14/21 Sens Rec:** $\text{EPH} = 89.9 \text{ kWhp/m}^2\text{y}$, $\text{EPc} = 12.9 \text{ kWhp/m}^2\text{y}$, $\text{EPSC} = 102.8 \text{ kWhp/m}^2\text{y}$. The PES is of 45.1 kWhp/m²y, and thus the 30%.
5 Configuration, All Air System OA 21/21: $E_{PH} = 203.6 \text{kWh}_p/\text{m}^2\text{y}$, $E_{PC} = 12.5 \text{kWh}_p/\text{m}^2\text{y}$, $E_{PC} = 216.0 \text{kWh}_p/\text{m}^2\text{y}$. There is an increase of energy demands, +68.1 kWhp/m²y (+46%).

5 BIS Configuration, All Air System OA 21/21 Sens Rec: $E_{PH} = 107.4 \text{kWh}_p/\text{m}^2\text{y}$, $E_{PC} = 12.6 \text{kWh}_p/\text{m}^2\text{y}$, $E_{PC} = 119.9 \text{kWh}_p/\text{m}^2\text{y}$. The PES is of 28.0 kWhp/m²y, and thus the 19%.

All other results, in terms of energy demands, are provided in Table 3. It is quite clear that the use of heat recovery, in the cold climate of Campobasso, is necessary. Indeed, the high occupancy rate implies a high amount of ventilation air. By taking into account the opportunity of increasing - doubling or even tripling - this amount (i.e., 14 l/s and 21 l/s per person of ventilation air, during the first phases of recovery of the face-to-face didactics, can be suitable for removing and diluting eventual pathogens), the sensible heat recovery is very useful. It should be noted that all configurations equipped with heat recovery determine primary energy savings compared to the base case, and this PES ranges from 19% (All Air System OA 21/21 Sens Rec) to 50% (All Air System OA 7/14 Sens Rec).

Even if without the sensible heat recovery, the configurations All Air System OA 7/14 and All Air System OA 7/21 provide a more safe indoor air quality compared to the base case (or, at least, higher flexibility) because the OA flow rate is the same but there is no risk connected to a centralized system (i.e., air channels, mainly when the system is turned off, could be a route for transfer of virus-laden aerosols), without an increment of energy demands. Furthermore, having a dedicated system for each classroom (where the building geometry allows it) simplifies the management. Obviously, the investment costs of single separated systems could be higher. Conversely, the increase of the OA flow rates (14 l/s pers and 21 l/s pers), with wide ACHs and without heat recovery,
Fig. 9. the mixed air water systems, with in-room fan-coils (heating or cooling coil, according to the season) and centralized AHU, originally designed for the new classrooms.

Fig. 10. the new designed all-air systems, without (A) and with (B) the sensible heat recovery.
Table 2
Peculiarities of classrooms and designed alternatives for the HVAC systems here installed.

| Main peculiarities of the Classrooms | 1) All Air System OA 7/14 | 2) All Air System OA 14/14 |
|--------------------------------------|--------------------------|--------------------------|
| Floor                  | Seats | Volume | OA | TA | TA | ACH | OA | TA | TA | ACH |
| Room GF                |        |        | 0.007 m³/(s p) | 0.014 m³/(s p) | 0.007 m³/(s p) | 0.014 m³/(s p) |
| Room 1F-1              | 120    | 620.9  | 0.8 | 1.7 | 6048.0 | 7.3 | 0.6 | 0.8 | 3024.0 | 6.5 |
| Room 1F-2              | 40     | 220.4  | 0.8 | 1.7 | 6048.0 | 7.3 | 0.6 | 0.8 | 3024.0 | 6.5 |
| Room 1F-3              | 60     | 384.6  | 0.4 | 0.8 | 3024.0 | 6.5 | 0.6 | 0.8 | 3024.0 | 6.5 |
| Room 1F-4              | 80     | 403.7  | 0.6 | 1.1 | 4032.0 | 7.9 | 1.1 | 1.1 | 4032.0 | 7.9 |
| Room 1F-5              | 40     | 215.8  | 0.3 | 0.6 | 2016.0 | 7.7 | 0.6 | 0.6 | 2016.0 | 7.7 |
| Room 1F-6              | 39     | 204.1  | 0.3 | 0.5 | 1965.6 | 7.9 | 0.5 | 0.5 | 1965.6 | 7.9 |

Fig. 11. Monthly primary energy demands for the space conditioning of each analyzed HVAC configuration, compared to the base case (FC + DOAS), with and without heat recovery in the same picture.
induces a rising of energy demands for the annual space conditioning, and thus +26% (All Air System OA 14/21) and +46% (All Air System OA 21/21).

A summary of annual energy demands, in terms of primary energy, is provided in Fig. 12, where it can be seen the large variability that concerns the energy demands for the space heating while, with reference to the cooling season, no large variations occur. This is mainly due to the coldness of the site, Campobasso, in which the cooling period is very short, and to the use of the building that, as common in Italy, is scarcely occupied in July and August. Because of these reasons, energy demand for the summer air-conditioning is not so intensive.

In order to allow an immediate understanding of the impacts of the sensible heat recovery, the monthly values of energy demand for air-conditioning are provided in Fig. 13, with reference to the base case compared to all configurations without heat recovery (A), and with reference to the design alternatives equipped with the heat exchanger (B). Here, it is quite evident that, with reference to all months of the heating period, the presence of the sensible heat recovery is the discriminant: with this component, the energy impacts of the increase of the outside airflow can be limited significantly. Thus, as depicted in Fig. 12, it could be more convenient to provide 21 l/s of outdoor air per person (EPH = 107.4 kWh/m²y) than 7 l/s (EPH = 108.1 kWh/m²y), if the recovery of sensible energy from the exhaust air is applied in the first case and not in the second one. In addition, too many air changes (21 l/s per person instead of 14 l/s per person), even if allow a high capability and short time required by the HVAC for repressitinating the indoor design conditions at the early morning or after impulsive variations of heating loads, anyway these increase the energy requests for the air movement and thus the electric energy required by fans. Finally, the configuration 7/14 and 14/14 - with air changes ranging from 6.5 to 7.9 h⁻¹, depending on the specific classroom (see Table 2) - are enough to maintain the desired microclimate. On the other hand, even if energy demands for ventilating and ventilation are higher, the configuration 21/21 allows a higher indoor air quality and higher velocity of the systems in limiting the oscillation of indoor conditions. Moreover, under critical conditions, such as during an epidemic, this configuration allows wide management of OA.

### 4.3. Annual operating costs and environmental study

A last study derived from BES is the evaluation of annual costs for air-conditioning, by varying the HVAC systems configurations, and also the variation of environmental impacts and GHG emissions. In Fig. 14, a summary is proposed. In order to provide numbers easily understandable, whose order of magnitude is quite typical, the annual costs of air-conditioning and the tons of CO₂ eq emissions are referred to 100 m² of new classrooms.

The economic costs of the winter heating and ventilation range from 585 €/100 m² to >1650 €/100 m². About the cost of cooling, the outcomes are very similar for all HVAC configurations, and only the base case system, equipped with fan coils and a DOAS, shows higher energy demands (and thus higher costs), but this depends on the fan coil regulation. Anyway, the cooling energy demand is quite low and thus the percentage differences and the simulation error can be significant.

Of course, by confirming the results achieved for what concerns the energy analysis, by evaluating the year-around costs for the

### Table 3

| Configuration | HVAC System | EPH  | EPC  | EPSC | PES  | PES  |
|---------------|-------------|------|------|------|------|------|
| Base Case     | Fan Coil and DOAS OA 7/7 | 120.2 | 27.7 | 148.0 | ——   | ——   |
| Configuration 1 | All Air System OA 7/14 | 108.1 | 8.4  | 116.5 | 31.4 | 21%  |
| Configuration 2 | All Air System OA 7/14 Sens Rec | 64.4 | 9.1  | 73.5  | 74.5 | 50%  |
| Configuration 3 | All Air System OA 7/21 | 123.8 | 12.4 | 136.2 | 11.7 | 8%   |
| Configuration 4 | All Air System OA 7/21 Sens Rec | 71.3 | 13.4 | 84.7  | 63.3 | 43%  |
| Configuration 5 | All Air System OA 7/21 Sens Rec | 174.8 | 12.4 | 187.1 | 39.2 | 26%  |

* A negative PES means an increase of energy demand.
space conditioning, once again it emerges that energy savings are achieved when heat recovery systems are installed and, also in the case of a 100% OA, with high (i.e., 14/14 l/s person, ACH from 6.5 to 7.9 h^{-1}) or very high (21/21 l/s person, ACH from 9.7 to 11.9 h^{-1}) outside air changes, the economic expenditures are lower or similar compared to the base case (FC + DOAS). With reference to the annual microclimatic control, the costs range from 603 €/100 m^2 (minimum) to 1768 €/100 m^2 (maximum), connected to the adoption of the All Air System OA 7/14 Sens Rec and the All Air System OA 21/21, respectively.

In terms of GHG emissions, the outcomes are even more significant. Indeed, given the increasing share of renewables in the electricity conversion, the CO2-eq emission factor connected to the use of electricity is decreasing, as testified by the tables inferred in [50] (Annex I, Table A.I.6, LCA emission factor of electric energy). In the same study provided by the Covenant of Majors (Table A.I.1 [50]), it emerges that the LCA emission factor of natural gas has been quite constant in the last years. This supports the energy transition towards electricity. Finally, by varying the HVAC systems, the emissions for annual air conditioning of 100 m^2 of new classrooms can vary from 1.6 tons of CO2-eq to 4.7 tons of CO2-eq, and thus the environmental GHG emissions can be triplicated. Also in this case, with reference to the heating period, the use of sensible heat recovery, for all configurations, reduces the environmental impacts from 40 to 50%, compared to the same HVAC system without a sensible heat exchange between exhaust air and outside air.

5. CFD simulation: Air diffusion strategies, thermal and flow fields, air velocity and age of air

In this section, some common configurations for the supply and the extraction of air from the indoor environment have been designed, to evaluate the thermal fields in the various areas of the classrooms and, mainly, for understanding the thermal and flow fields and the age of the air in the breathing zones. Definitively, the air diffusion performances of four distribution configurations referred to the all air systems - and thus the new and suitable HVAC systems analyzed in the previous sections - are here examined.

The analyzed room is the 1F-2, a typical classroom of 81.6 m^2, which in the pre-COVID-19 period (according to the design idea) could accommodate 40 people: at today, by taking into account the necessary “social distancing” as a preventive anti-contagion measure [58], it is estimated an occupancy by 20 persons (Fig. 15, the number has been halved compared to the normal occupancy capacity), which, obviously, are sources of endogenous heat gains, due to the specific metabolic activity.

About the configuration of HVAC systems here modelled, this is the aforementioned All Air System OA 7/14 and thus system that provides, according to Table 2, ACH equal to 7.5 h^{-1} for the classroom 1F-2, with 50% OA and 50% RA. In a CFD study, the presence of the heat recovery systems does not have influence, and also the air recirculation does not affect the outcomes: indeed, besides the boundary conditions, the incident parameters are the total supply flow rate and its thermodynamic conditions. In the CFD model, by acquiring boundary conditions from the previous BES investigations, the following schemes for the air-conditioning ventilation (supply and extraction = 0.56 m^3/s) have been implemented and simulated:

- 6 ceiling square diffusers (directional 4 ways),
- 4 wall-mounted grilles, placed on the upper zone of the vertical walls,
- 10 wall-mounted nozzles, high turbulence, placed on the upper part of one of the two short sides of the room.
6 parallel strips of ceiling linear slot diffusers.

By excluding a lateral strip, useful dimensions for the arrangements of air diffusers were a length of 11.6 m and a width of 6.5. All configurations (Fig. 15) have been designed through the ADPI (Air Diffusion Performance Index) method [6,59]. Regarding the extraction systems, this consists of extraction grilles, placed on the floor, or in the lower part of the building walls (it depends by the configuration of the supply).

The choice of the diffusers arrangement, firstly, has been based on qualitative considerations and experience, in order to obtain uniform microclimatic conditions within the environment, by taking into account the volumetric flow rates, the distance between the terminals, the distance between diffusers and walls, as common in design practice.

Starting from typological distribution schemes, the ADPI method allowed the determination of the throw and thus the designing the specific air terminals: then, the CFD simulation is performed, by evaluating indoor uniformity, but also the flow vectors, preferring – for instance – a vertical movement of the indoor air, so that air exhaled by persons (with possible pathogens) does not invest other students but can be mainly directed towards the extraction grilles.

The description begins from the air diffusion configuration with square diffusers, six and placed on the false ceiling. As shown in Fig. 15a, the distance between each diffuser is 3.3–3.9 m while the distance from the nearest wall is 1.6–1.9 m. The air extraction is guaranteed by 4 extraction grilles (30x50 cm) placed in the lower part of the short walls. Each extraction grill is defined in the numerical CFD code by shape, size, and volumetric flow rate. The extraction airflow rate is 100% of that supplied into the environment, and thus, the resolution of Navier-Stokes equations (namely, the mass continuity) is not perturbed (i.e., no exfiltration air was assumed). The total volume flow released in room 1F-2 is 560 l/s, and thus 93 l/s are supplied by each diffuser, while 140 l/s are extracted by each extraction grill.

The design criterion of the air terminals started from the definition of the isothermal throw (T) (i.e., the distance covered by the flow between the center of the diffuser axis and the point where the airspeed decreased to the predetermined value of 0.25 m/s) and the characteristic length of the room (L) (i.e., the minimum distance between the diffuser and the closest obstacle, wall or interference with the throw of another diffuser). After a distribution hypothesis of the air terminals, the ambient thermal load was estimated, in the summer regime and design conditions. The throw of the diffuser, by considering a terminal speed of 0.25 m/s, was obtained by multiplying the ratio T_{0.25}/L (0.8 for ceiling square diffusers [6]) by the characteristic length of the room (L). In the case of square diffusers, this length is equal to 1.9 m, therefore the throw distance (T_d) is equal to 1.56 m. Having the volumetric flow rate, the air jet velocity, and the throw, it was possible to determine, from technical catalogs, the discharge velocity and the diffuser model. Given that the rooms of the second floor have common indoor heights, with the idea of considering also sloped platforms, low discharge velocities are established. In Table 4, all data for the air terminal design are reported, to deeply describe the configurations represented in Fig. 15: in the last two lines, the necessary data to model the air terminals for CFD models are detailed.

In the configuration B (Fig. 15b), the air is supplied by 4 wall-mounted grilles, located on the upper part of the longest wall, spaced by 2.9 m, while the extraction is performed by four extraction grilles (30x50 cm) located at the lower part of the opposite wall. Configuration C has ten wall-mounted nozzles, located at the upper part of the shortest wall. The three extraction grilles
Fig. 15. Air distribution system schemes: ceiling square diffusers (a), wall-mounting grilles (b), wall-mounted nozzles (c), ceiling linear slot diffusers (d).

**Table 4**

Data for air terminal design, input and output of the ADPI method.

|                      | Square diffusers | Wall mounted grilles | Wall mounted nozzles | Linear slot diffusers |
|----------------------|------------------|----------------------|----------------------|-----------------------|
| L - characteristic length [m] | 1.9              | 6.5                  | 11.6                 | 2.7                   |
| T0.25/L* [-]          | 0.8              | 1.5                  | 1.5                  | 0.3                   |
| Throw distance [m]    | 1.56             | 9.8                  | 17.4                 | 0.84                  |
| Supply flow rate [l/s] | 560              | 560                  | 560                  | 560                   |
| Air diffusers’ number [-] | 6               | 4                    | 10                   | 6                     |
| Supply flow rate/diffuser [l/s] | 93              | 140                  | 56                   | 93                   |
| Maximum ADPI* [-]     | 93               | 85                   | 85                   | 92                   |
| Cooling Load** [W/m²] | 65               | 65                   | 65                   | 65                   |
| Discharge air velocity [m/s] | 1.3             | 1.6                  | 2.86                 | 1.76                  |
| Dimensions [m]        | 0.35x0.35        | 0.43x0.22            | 0.16x0.16            | 6x0.05                |

* The values refer to the ADPI tables, and differ according to the air terminal type.
** The thermal load reported is a reference value of the ADPI tables, and it is close to that calculated for the room 1F-2.
defined for the CFD simulation as follow:

- ceiling square diffusers: four-way supply with a discharge angle of 60° (angle between the jet and the downward-pointing normal);
- wall-mounted grilles: two-way supply with a discharge angle of 0° (the flow is perfectly orthogonal to the wall where the grill is positioned);
- wall-mounted nozzles: one-way supply with a y-discharge angle of −5° (angle between the inward-facing normal to the surface and the local surface Y-axis);
- ceiling linear slot diffuser: one-way supply with a x-discharge angle of 20° (angle between the inward-facing normal to the surface and the local surface X-axis).

The CFD studies were performed by considering a typical winter day, the 4th of February, at 12:00 o'clock, and thus a common condition of lessons. The inlet air temperature (23 °C) was deduced from the dynamic simulation (BES). The CFD simulations were performed only during the winter period. The summer period was neglected in the CFD study, because, considering the Campobasso summer temperatures reported in Fig. 2, the building energy demand for cooling is quite low and thus the cooling service and energy demands are secondary.

Really, this study wants to be merely indicative, to propose a methodology for evaluating which is, in every specific design context, the best way for approaching the air distribution and diffusion scheme, in order to improve the indoor air quality in the breathing zone and for having feedback (in addition to the use of the ADP) on the air distribution system quality, also in terms of comfort and thermal gradients and asymmetry. In the following sub-sections, the results of each configuration are examined, with a focus on the uniformity of thermal–hygrometric parameters in the volume, the airspeed, the vertical thermal stratification, and finally the indoor thermal comfort and the age of the air in the occupied zones.

5.1. Air temperature

Vertical temperature gradients may occur in the indoor environment, since, for reasons related to the lower density, the warmer air tends to stratify upwards. For each configuration, the temperature gradient (T_{max} - T_{min}) was calculated for the central room volume, both in the horizontal and vertical sections, to verify the presence of local thermal discrepancies (see deepening in Section 2.4). In all cases, the air diffusion configurations guarantee good indoor temperature uniformity: indeed, the maximum temperature gradient is 1.3 °C and it concerns the solution A, in the plant view (Fig. 16).

Similarly, the vertical temperature stratification is almost uniform for all configurations, as clear in Figs. 17 and 18. A negligible vertical temperature gradient was found in sections B and D, namely for the wall-mounted grille (T_{max} - T_{min} = 0.7 °C) and ceiling linear slot diffuser (T_{max} - T_{min} = 1.1 °C) configurations. Anyway, the vertical and horizontal temperature conditions are quite uniform and these avoid localized discomfort and uncomfortable vertical differences.

5.2. Air velocity and flow fields

The obtained values of airspeed for all the examined air distribution configurations are suitable for the occupant thermal comfort, in all examined cases. Generally, in the summer regime, an air movement within 1 m/s is not excessively annoying, while, in wintertime, even the slightest perception of draught (air with speeds above 0.20 m/s) can be a cause of local discomfort. As clear in the Figs. 17 and 18, the airspeed in the occupied zone (from 0 to 1.1 m for seated people) is less than 0.2 m/s for the configurations A, B, and D, while, for the configuration C, the airspeed in the center of the breathing zone is about 0.5 m/s. This condition could cause a localized discomfort to the students sitting in the central part of the room. Excluding partly case C, all the solutions assure acceptable indoor airspeed.

Another interesting element to examine is the air movement in the occupied area. As particularly evident in Figs. 16 and 17, configurations A, B, and C involve a whirling air movement and the breathed air moves from one student to another. In the case D, on the other hand, the movement of the air is almost vertical (Fig. 18d), so that the exhaled air is then directly extracted in by the grilles positioned on the floor. This could be a valid solution to reduce the transportation of droplets from one person to another one.

5.3. Indoor thermal comfort, age of air and air quality

The different configurations were compared in terms of comfort according to the Fanger approach [60], and thus by calculating the PMV (Predicted Mean Vote) and PPD (Percentage of person dissatisfied) indexes. Some assumptions were done: the clothing resistance is equal to 1 clo, the metabolic energy equal to 1.20 met, typical for seated people, the relative humidity is equal to 50%. The airspeed, the mean radiant temperature, and the air temperature were automatically assumed from the CFD simulation and, as for the temperature, the air velocity and the age of the air were calculated for the entire classroom volume. Assuming a monitoring point near the first line of students, in case A, the PMV index is equal to −0.20, while the PPD index is 7% (table 5). The PMV value falls perfectly in the range of moderate indoor environments (−1 < PMV less than 1), while the percentage of dissatisfied is very low. In the configuration C, the PPD and PMV are quite the same (PMV = −0.23; PPD = 7%).

The most significant difference emerges by comparing the configuration C with D. In the latter case, the PMV is equal to −0.06, with a consequent PPD of 5.5%, confirming a perfect condition of indoor thermal comfort. All results demonstrate the effectiveness of the designed solutions for the HVAC system and air terminals, in terms of thermal comfort.

Really, it is important to underline that this investigation does not aim to evaluate the correctness of the simulated air terminals, in terms of thermal comfort merely, but also it wants to evaluate the movement of the indoor air, flow fields, the mean age of the air, which are closely linked to the number of diffusers, their position, the airspeed and the position of the extraction grilles. Indeed, looking at Fig. 19, the differences between the proposed configurations emerge.

In Fig. 19 (breathing zone), the range of age of air considered is between 0 and 484 s. Of course, the lower the age of the air, the fresher it is: the more it tends to blue color, the fresher it is. The age of air is “the length of time that some quantity of outside air has been in a building, zone, or space” [6] and it is directly correlated to the air quality. This indicator is useful for understanding
the effectiveness of the ventilation systems designed and for identifying the solution that better meets the needs of air purity and freshness. Thus, this parameter can be useful also for contagions’ prevention. As shown in Fig. 19, the configurations which have a lower average age of air are the A and D, both characterized by ceiling diffusers. In particular, the solution with ceiling square diffusers (A), has a maximum age of the air of about 176 s, while a minimum of about 88 s. In the configuration with linear slot diffusers (D), the minimum age of the air is similar to the previous one, but the maximum is around 300 s. This occurs only in the entrance area of the classroom and depends on the position of the extraction grills and the inclination of the inlet air jet (x-discharge angle of 20°), as shown in the section of Fig. 17d. The two other configurations can be considered less valuable from the point of view of air quality, and particularly this is true for the one with wall mounted grilles. In this case, the maximum age of the air is 484 s and concerns the back of the classroom penalizing the last line of students, while the minimum is around 300 s. As clear, the air distribution is not uniform, and the air quality can be considered worse compared to the other configurations. These results are in line with those of Ascione et al. [54] which showed a better air quality for a museum room with ceiling diffusers compared to the case with wall air terminals.

More in general, we can conclude that, for the room under consideration, all air terminal configurations give satisfactory results in terms of comfort and air quality. The configuration which guarantees better results regarding the uniformity of the air distribution and its purity, as well as optimal comfort conditions, is the one with linear slot diffusers (solution D). Indeed, this configuration guarantees a vertical displacement of the breathed air, and therefore reduces the possibility of diffusion of contaminants throughout the whole indoor environment. In addition, it could be noted that the airspeed in rooms with common heights is an issue requiring attention.

Here, we do not aim to propose universal solutions. Indeed, the analyses involved only a classroom and merely common air diffusers, in common configurations. On the other hand, each diffuser can be valid or unsuitable, depending on the whole air diffusion configuration and features of the room, building, facility and thermal loads. Conversely, the proposed approach is our main result. Finally, also a correct, deeply-investigated, checked air diffusion strategy could be a valid tool for allowing air movement from clean zones to dirty ones, and thus for supporting in preventing the spread of contagions.

6. Additional remarks and future studies

The lesson learned in 2020 will remain impressed in our minds. The catastrophic impacts of a pandemic for persons, economies,
Fig. 17. CFD longitudinal section. Temperature and air velocity for the following cases: ceiling square diffusers (a), wall-mounting grilles (b), wall-mounted nozzles (c), ceiling linear slot diffusers (d).

Fig. 18. CFD transversal section. Temperature and air velocity for the following cases: ceiling square diffusers (a), wall-mounting grilles (b), wall-mounted nozzles (c), ceiling linear slot diffusers (d).
social equalities are evident. Really, further food for thought can be found, starting from the positive effect of the lockdown on the earth's environmental conditions, ambient air, and water quality, with a decrease of pollution, even related to the reduction of energy intensity and use of fossil fuels. This has been evidenced in many studies, for instance [66,67] for China, concerning VOCs and many pollutants, and, in Europe, by [68,69], with investigations concerning the environmental benefits of lockdown respectively in locations of Spain and Italy. These and other studies, once again, underline that the impact of human activities on earth conservation is enormous: all citizens, by living their life, must play their part toward sustainability. Of course, many and many topics and issues must be addressed, starting from a global journey involving “all countries towards a more sustainable and equitable world” (literally from Oldekop et al. [70]). According to these authors, key challenges concern: a) the global value chains, b) the need for digitalization, c) the issue of debt and public finances and, d) climate change. The answer is the local and global cooperation, a multi-scalar approach, and it involves both the global North and South of the World, with important challenges concerning the human global rights (the contrast to poverty, the issue of migration, social protection, sustainability, affordable houses and cities, right jobs, food availability livelihoods, etc.).

Here, we need to remain in the field of energy efficiency of the built environment, and thus safe, secure, sustainable buildings and cities. Some key issues, already evidenced in the last decades by members of scientific organization, are now evident for everybody and thus the mandatory need of:

- sustainable buildings, suitable for life, including activities among which the personal care and wellness, the study and the work, at home and in remote ways. This implies that the current indices and parameters (for instance concerning the occupancy rate in social housing, or the standard equipment of standard houses) must be revised, by including also targets related to the wellbeing [71,72];
Regarding the aforementioned topics, the attention must be paid to both new urbanization and the built environment, and thus, as recently underlined by EU guidelines, the nearly zero-energy targets must concern both new constructions (Directive 2010/31/EU) and the retrofit of existing buildings (Directive EU 844/2018).

7. Conclusions
The proposed investigation coupled several methodologies of the architectural and technological engineering, for renovating classrooms of an Italian Educational building, with a view to the necessities of safety and healthiness. In the first semester of 2020, suddenly the World discovered a fragility with respect to pandemics. The modern economies and lifestyles are based on complete globalization and interchanges of people, things, information. In a few months, at the World scale, the COVID-19 caused hundreds of thousands of deaths, officially, but it is quite accepted that the statistics are greatly underestimated. Lockdowns interested most countries and, now (Autumn 2020), we are slowly acquiring new different normality, approaching again the “in-presence” activities. As we are researchers and professors, our desire is the recovery of frontal didactics, with and among students, in classrooms and labs. These face-to-face activities are expected for the next semesters, supported by a strengthening of e-learning and telematic activities. At the same time, university and educational buildings, given the high occupancy rates, must be safe and secure, and thus architectural and technological retrofits are necessary in order to contrast and avoid contagions of COVID-19 and other severe syndromes. Good practices in the matter of hygiene, social distancing, good habits and behaviors, frequent cleanings of hands and surfaces are mandatory, mainly to avoid direct affections. On the other hand, secondary transmission routes, related to nuclei droplets and small aerosols are possible and require dilution of pathogens, filtrations (also of the exhaust air), strong ventilation. Here, with reference to the already planned architectural renovation of a Department of the University of Molise (Italy), in which new classrooms will be built, a new investigation that couples two different numerical approaches (and thus a building energy performance (BES) simulation, O-D and in the domain of the time and with sub-hourly calculations extended to the whole year, and b) computational fluid dynamic (CFD) analysis, 3-D and referred to specific hours – is proposed.

The investigation begins with an accurate audit of the present building, with surveys on building components and energy systems, by monitoring the indoor conditions and acquiring the historical metered energy demands. Then, based on the available information, a suitable energy model has been defined by using a whole program for the building energy simulation, calibrated against the real energy demands from bills. After a model simplification to reduce the computational effort, the current building was modified, with reference to the digital model, for defining the new architectural distribution, with the design of the new seven classrooms.

With reference to the building energy analysis, starting from the originally designed HVAC system, a mixed air–water system with in-room fan-coils and an AHU handling merely outdoor air (i.e., a dedicated outdoor air system), then other configurations are investigated, and thus an all-air system with and without the sensible heat recovery from the exhaust air, with variable amount of outdoor air (from 33% to 100%, with a minimum of 7 l/s pers of OA) and air change rates varying from 6.5 to 7.9 h⁻¹ (configurations with total supply air of 14 l/s person) to 9.7–11.9 h⁻¹ (configurations with total supply air of 21 l/s person). The main outcomes reveal that:

- By considering the new classrooms, the annual primary energy demand for the space heating (EP₃) ranges from 64.4 kWhₚ/m² (OA 7 l/s pers, activation of sensible heat recovery and recirculation of air) to 203.6 kWhₚ/m² (21 l/s pers, 100% OA, bypass of the heat recovery).
- The heat recovery, in the cold climate of Campobasso (Italy, backcountry), is very effective in reducing the additional energy demands connected to the strong increase of outdoor air. Thus, AHUs must be equipped with flat plate heat exchangers, without the contamination of the outdoor air with the exhaust air (in this way, if there is the need of operating at 100% OA, sensible heat recovery can be effectively used).
- The use of sensible heat recovery allows significant energy saving. Indeed, also in case of high ACH (from 9.7 to 11.9 h⁻¹), the energy impact by varying the amount of OA, and thus 7, 14 or 21 l/s person, is limited, with EP₃ equal to 71.3 kWhₚ/m², 89.9 kWhₚ/m² and 107.4 kWhₚ/m², respectively. Of course, the same trends is achieved for the annual economic costs for the space conditioning and annual HVAC-related CO₂ₑq emissions, with differences also of 1165 €/100 m² and 3.1 tons CO₂ₑq/100 m², respectively, by considering the HVAC design alternatives requiring the lowest and highest energy demands, respectively.
- The increase of OA implies higher energy demands but also better indoor air quality, and thus a lower values of CO₂ concentration and lower ages of air. According to Wargocki et al. (2020) [81], this will have a positive impact on students’ performances, in terms of rapidity of reasoning and right answers to questionnaires, better learning and daily attendance.
- All design alternatives have similar energy demands for cooling, with EP₄ from 8 kWhₚ/m² from 12.9 kWhₚ/m² and the role of the heat recovery, in this climate and building use, is marginal during the cooling period.

Then, by considering the social distancing, the number of persons was halved in each classroom (i.e., from 120 to 60, from 40 to 20 and so on); this is what is happening in Autumn 2020 in Italy, with contemporary face-to-face didactics and e-learning. A CFD model of a specific classroom was created, and, by achieving all necessary boundary conditions from the previous BES simulations, a CFD study was performed, by investigating the air diffusion performances of four configurations (allowing 7.5 h⁻¹ air changes per hour): 6 ceiling square diffusers, 4 wall-mounted grilles, 10 wall-mounted nozzles (high turbulence), 6 parallel strips of ceiling linear slot diffusers. All configurations have been designed by means of the ASHRAE ADPI method, and also suitable air extraction systems were modeled. The following conclusions can be inferred:
- All air terminal configurations give satisfactory results in terms of thermal comfort, but the configuration which guarantees better results regarding uniformity of the air distribution and its purity, as well as optimal comfort conditions, is the one with linear slot diffusers.

- In terms of uniformity of air temperature, age of air and flow and thermal fields, with reference to the specific case studies, optimal microclimatic conditions were achieved by using linear slot diffusers, in six strips, parallel to the students’ row. This evaluation considers the following aspects: the indoor uniformity, the PMV according to the Fanger approach, the air movement directed by the person to the extraction grilles, so that the air breathed and exhaled by persons is then directed towards the grilles positioned on the floor and at the lower part.

Finally, according to the authors, the proposed study shows the importance of a correct HVAC system design, not limited to evaluations of different HVAC configurations in terms of energy, economy, and emissions, but also in terms of comfort and IAQ. It is essential to analyze the different air diffusion strategies so that suitable air quality, lack of stagnancy zones and overall thermal comfort can be guaranteed, with a view to the uniformity throughout the indoor environment. However, this design effort must also be accompanied by an important contribution in the maintenance of the system, such as control and replacement of filters (HEPA) and in the sanitation and correct ventilation of the rooms. The ventilation, indeed, is necessary for diluting and removing indoor pathogens and proper filters can reduce indoor contamination.

Really, what is noteworthy, more than the specific achieved results (i.e., these can vary, changing the use of the building or the climate, but also with varying the classroom geometry or loads), is the method. Flexibility and accuracy in predictions, also by means of the use of advanced numerical methods and coupled experimental (surveys, monitoring, audits) and numerical approaches (also of multiple nature, such the BES and CFD studies here presented), can support a conscious design. With this study, still ongoing, we want to make a first contribution to the recovery of normal life, and then try to rethink what we do every day: teaching and learning in the presence of students and teachers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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