sustainability

MDPI

Article

Energy Cost for Effective Ventilation and Air Quality for Healthy Buildings: Plant Proposals for a Historic Building School Reopening in the Covid-19 Era

Carla Balocco * and Lorenzo Leoncini

Department of Industrial Engineering, University of Florence, via Santa Marta 3, 50139 Firenze, Italy; lorenzo.leoncini@unifi.it

* Correspondence: carla.balocco@unifi.it

Received: 14 September 2020; Accepted: 19 October 2020; Published: 21 October 2020

check for updates

Abstract: The COVID-19 pandemic has changed the engineering/technical approach to building and plant design. In Italy, most of the school heritage belongs to historical buildings, which are not only under constraints for the protection and prevention of loss of cultural heritage but are often created with a different intended use. This fact implies that any plant engineering project is really complex. Starting from the current sanitary measures for reopening during the Covid-19 era and the crucial current research on this matter, the feasibility of plant retrofit/refurbishment solutions by means of effective ventilation and air quality are investigated. Various plant solutions based on demand-controlled mechanical ventilation, operating 24 h a day, seven days a week, without air recirculation mode, for a historical high school building were studied using transient simulations. A result comparison showed that it is possible to obtain healthy school environments by means of an optimal compromise between energy savings and the best ventilation conditions for indoor air quality (IAQ). Sustainability is understood as effective and efficient solutions for energy consumption reduction and environmental sustainability as a guarantee for people's safety and wellbeing.

Keywords: healthy environment; indoor air quality; wellbeing; historical building school; controlled ventilation; energy sustainability

1. Introduction

Today, energy efficiency is really a common target for buildings and plant systems, but the issue of preventing health risks deriving from environmental factors and pollutants, microorganisms, dispersion/diffusion, and particle tracing of droplets (i.e., the airborne patterns) carrying viruses has become so important that it calls for the involvement of different competent subjects and for the imposition an integrated interdisciplinary approach aimed at assessing indoor pollution, sustainability, and the quality of indoor environments, in particular, those of different working and social activities, such as schools [1–7].

As a matter of fact, there is a growing awareness among stakeholders, researchers, technicians, and public decision-makers of the importance of indoor air quality (IAQ) [4,5,8–11]. This is due not only to the results of epidemiological studies, which underline the sanitary importance of airborne chemical and biological contaminants but also to the fact that the sources of outdoor and indoor pollution are increasingly widespread. Indoor environment pollution is strictly connected to critical local meteorological conditions. Not only do they promote the spread of biological risk factors (e.g., pollen, vector insects, pest species), but they cause thermohygrometric alterations of the confined environments. This is especially the case for air temperature and relative humidity, producing moulds and the proliferation of pathogenic microorganisms, as well as the phenomena of chemical, physical, and biological photodegradation of materials [1,4,5,8,11]. As is well known, all the refurbishment and retrofitting interventions on existing building heritage are a complex task, in particular for historical state school buildings [12–20].

The European HESE study (Health Effects of School Environments [19]) of the World Health Organization (WHO) has demonstrated that indoor air quality (IAQ) in the investigated schools and classrooms was poor, causing respiratory health effects. At the same time, both the SEARCH project (School Environment and Respiratory Health of Children [20]) and the SINPHONIE project [21] have developed fundamental guidelines for governments and every kind of school for healthy and quality classroom environments.

Recent literature has highlighted the fact that existing school buildings are responsible for more energy consumption than newly constructed ones. The IAQ (i.e., ventilation and correct air changes per hour (ACH) and risk reduction of microbiological contamination) is so important that it can have a significant impact on student/teacher wellbeing, productivity, health safety, and performance [2,4,22–28] and also on a nation's healthcare system [11,29].

Extensive research has also shown how interventions for building–plant system adaptation and improvement of schools, especially within the context of cultural heritage, can lead to a significant reduction in energy consumption, with positive environmental and social effects. These studies have underlined the fact that this is achievable if design solutions are carried out by means of a compromise between energy savings and plant systems, *adaptivity/changeability*, acclimatisation, and easy maintenance [16–18,30]. However, in the face of current health problems, the existing air conditioning systems for school buildings, within the contexts of historical and architectural value, should be adapted and rethought/redesigned to guarantee IAQ and effective ventilation, hygiene, safety, and health, even before comfort [5,9,10,24,31–33].

Plant system installations in historic school buildings, which, over time, have undergone changes in use and functional reorganisation, is a very complex task. This is especially the case during this Covid-19 era: it can be very difficult for specific design issues (e.g., different equipment, energy recovery ventilators, heat recovery units, fan-coils, heaters, air inlet and outlet diffusers) and for technical issues (e.g., air/water ducts crossing inside walls and cavities without sufficient dimensions). Added to this are questions such as historical–architectural protection and preventive conservation constraints if buildings have cultural heritage [5,7,9,11–14].

In particular, historical school buildings in Italy have a partial utilisation of the structure in terms of usage time of different environments, good mass, and thermal inertia, but there is also the issue of low thermal insulation of the roof and floors, windows, and glazed systems [23,25,27–29]. This is the reason why heating systems are often not correctly dimensioned. The rooms are too cold in winter, and ventilation (air renewal, ACH) does not respect the minimum suggested limits [34], causing severe problems for environmental air quality and wellbeing.

National and international organisations have provided important guidance documents [35–43] as an addition to the fundamental guideline documents of the World Health Organization (WHO) [19,44,45]. Common basic indications concern the practical issue that in offices, schools, and public places, all the controlled mechanical ventilation systems must be kept on and in good working order. There must be continuous regulation systems on microclimatic parameters (temperature, relative humidity, CO_2), no air recirculation, regular filter cleaning, and, if necessary, provision for their total replacement with more efficient ones [35–49].

In particular, the extended operation times of controlled mechanical ventilation (i.e., starting ventilation at nominal velocity at least two hours before building/classroom usage time, and switching to lower velocity two hours after) and the CO_2 setpoint change for demand-controlled ventilation systems (DCV; i.e., to lower by up to 400 ppm to assure operation at nominal velocity, keeping the ventilation on 24 h for seven days, with lowered ventilation rates without the presence of people) are strongly recommended [45–50].

At the moment, the end of the health emergency is not foreseeable and two main factors, widely discussed, represent the key elements to controlling the COVID-19 pandemic, i.e., social distancing and effective ventilation in confined environments. Important research has highlighted how social distancing and the required minimum ventilation rate in different confined spaces, characterised by different exposition times of people, such as those being studied, i.e., public transportation systems (bus, subway, and airplane), schools/classrooms, restaurants, and offices, have very appreciable and positive impacts on decreasing infection risk [3]. The authors have provided a useful prediction model for an airborne virus, based on the quantification of basilar factor influence, such as occupancy density, ventilation, and exposure time, on infection probability.

Important research based on direct physical measurements and wide questionnaire surveys on many dwellings in Switzerland (both new energy-efficient buildings and existing upgraded ones) has investigated the compliance of the suggested conditions and proper values for VOCs and IAQ, with effective mechanical ventilation designs and energy renovation solutions. The authors have demonstrated that conducting energy renovation without mechanical ventilation, especially in old buildings, can produce higher indoor levels of air contamination [51].

The same authors developed their research by comparing IAQ conditions, occupants' health, and energy efficiency solutions of different buildings provided by mechanical ventilation systems and natural ventilation. Their findings have shown how dwellings with controlled mechanical ventilation systems can assure the prevention of outdoor fungal particle infiltration and a healthy environment [52].

Crucial findings have been provided and discussed by the authors of a recent work concerning a large-scale investigation on IAQ, energy, and occupant behaviour and satisfaction applied to energy-efficient dwellings in Switzerland. Experimental physical and statistical survey data results of green-certified Minergie dwellings, supplied by mechanical ventilation, and energy-renovated ones with natural ventilation, were compared. The authors highlighted that low energy consumption, IAQ, correct ventilation conditions, and the behaviour and self-reported wellbeing of occupants can be obtained by integrating effective measures for building physics improvement and mechanical ventilation plant installation [53].

Starting from these crucial recent studies [2,3,24,29,46–53], our research, by means of the assessment of an existing heating plant of a high school building in Florence, analysed and compared some possible refurbishment/retrofitting operations oriented towards energy savings and healthy environments. Different plant system solutions were assessed and compared using transient simulations, taking into account continuous operation over the year. It is suggested that they must be maintained 24 h a day, seven days a week, with possible night dimming [35–39]. The main objective is to guarantee a healthy classroom indoor environment and noninvasive, really achievable, easily maintainable plant retrofitting and renovation measures.

In our research, different mechanical ventilation solutions, with lower impact for IAQ management and control, effective indoor air ventilation, and the wellbeing and health of people in an existing historical school building, were investigated. An optimal compromise between building renovation (i.e., thermophysical performance improvement) and plant system retrofitting proposals (i.e., effective mechanical ventilation for safety/healthy indoor conditions) was obtained.

The research was developed, starting from the present situation under the Covid-19 era, by considering the resumption of regular school work, as well as various activities and lessons; all this in the presence of teachers and students and no longer at a distance, to which the proposed plant system solutions can be easily adapted.

A historical high school building in Florence (Italy) was the case study. The research presented here focuses on a ventilation effectiveness assessment by means of correct ACH, indoor air temperature, and relative humidity and velocity, with reference to the main literature and current national and international guidelines [35–45]. Possible plant system operations were studied using transient simulations, specifically oriented to its terminal units, dynamic control and adaptive proportional regulation. This was designed to ensure that the plant adapts to the building's thermophysics and indoor environment parameter changes. The plant engineering solutions studied were evaluated with reference to the main literature on this matter [3–7,10–18,51–53]. In particular, referring to [51–53], controlled mechanical ventilation with absolute air filtration (e.g., considering the use of HEPA filters) was the priority objective with respect to energy savings. This latter objective is very important in order to assure environmental impact reduction, and this was pursued by achieving the maximum heat recovery obtainable by the plant. All the proposed solutions were in compliance with the preventive protection constraints imposed by the Italian Heritage Protection Offices.

2. Materials and Methods

The present research aims at proposing and comparing some energy-efficient and effective operations for historical school building refurbishment and retrofitting by building–plant system renovation and air decontamination. Correct ventilation rates and ventilation effectiveness for IAQ, environmental quality and people wellbeing and health are the main objectives to identify and evaluate energy-sustainable design proposals of the plant system.

Dynamic simulations of the building–plant system, both in existing condition, the reference comparison case, and each design proposal were performed to quantify the environmental and thermohygrometric conditions, plant system efficiency, and ventilation effectiveness. The variation of external climatic stresses and internal thermal loads due to occupants and equipment were taken into account. The investigation of energy-sustainable plant solutions was carried out and discussed, with a view to limiting health risks due to the coronavirus COVID-19 pandemic. All the architectural, structural, plant engineering and energy consumption data of the existing building–plant system were derived from [15,17]. The functional and distributive reorganisation of the internal spaces (e.g., physical barrier installations such as clear plastic sneeze-guards and different desk allocations), in compliance with the current sanitary provisions to guarantee safe social distance and people occupancy density reduction, was not considered. At the moment, there are no data and information on this matter. On the other hand, a reduced crowding rate was taken into account, going from 100% to at least 50%.

Simulations were carried out using the commercial software TRNSYS [54], i.e., a complete and extensible simulation environment for transient simulation of any system, including multizone buildings. The software uses the transfer function method (TFM) for solving the governing equations of heat and mass transfers [54] based on Z-transform (ZT) set equations. The TFM, which makes use of the Z-transforms to solve the equation system describing heat and mass transfers in a building–plant system and, in particular, in a multi-layered wall, is the recommended method by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

Simulation results of the reference case were validated by comparison against real building energy consumption over three years (i.e., the annual billing invoice data of 2012–2014, provided by the Environmental Department of the Metropolitan City of Florence). The real energy consumption for building heating demand was obtained using annual consumption data, referring only to methane consumption for school heating during the winter period.

Since real energy consumption is strongly influenced by the external climatic conditions, it was normalised to the real heating degree days (HDDs) and then used for simulation model validation. The real HHDs, which are closely connected to annual energy consumption data (i.e., from annual gas billing consumption), were calculated using the corresponding real external climatic parameters. LaMMA (Laboratory for Meteorology and Environmental Modelling) provided us with all the data on an hourly basis, referring to the nearest meteorological station at nearby Sesto Fiorentino-Firenze (latitude 43.82°; longitude 11.20°).

Different plant system solutions were simulated at transient conditions, taking into account a new proportional and modulating control and regulation system, as well as new efficient and effective controlled ventilation plant solutions, in order to ensure IAQ and a healthy environment.

In particular, each new plant retrofitting proposal started from the improved performances of the building envelope, provided by both thermal loss reduction and the achievement of a mean radiant temperature value close to that of ambient air (decreasing radiant asymmetries due to cold window surfaces). The thermophysics improvement of the envelope at existing conditions, i.e., of the reference building as a comparison case, concerned the replacement of old single-glass, wooden window frames of low air resistance with double-glass wooden window frames. In addition, ground slabs, slabs separating heated and nonheated volumes, and cover roofs were thermally insulated [15,17]. No intervention on the perimeter walls was considered due to the historical value of the building and the architectural constraints imposed by the Italian Heritage Protection Offices. The renovation of thermal transmittance values of components/partitions refers to [55,56].

2.1. Transient Simulation

The building transient simulation was carried out through the Type 56 Trnbuild library, modelling a multizone system featured by thermal coupling of adjacent zones. The 19 climatised zones and 5 nonclimatised zones were featured in Trnbuild. The boundary climate conditions were derived from the test reference year (TRY) of the city of Florence by means of the postprocessing of TRY with psychrometric diagrams for humidity and sky temperature. The tilted solar radiation was calculated, starting from the horizontal one, applying the Reindl model [57] and using the Type 34 library, in order to take into account overhang and wing-wall shading effects.

In particular, the TRY (test reference year) is derived from detailed annual climate measured data of real years at a certain location and then based on the measurement interpolation extended to many years (up to 30). The TRY usually contains hourly data of climatic parameters such as outdoor temperature, solar radiation, relative outdoor air humidity, wind speed and direction, and quantity of rainfall. During recent years, more and more countries have updated their TRYs, providing a “future” TRY that takes into account predictions of future climate development and change.

The hourly set of meteorological data of the TRY, in compliance with [58], was automatically interpolated using the software in order to allow a subhourly calculation time-step. The solution of the heat transfer functions, every quarter of an hour, leads to highly affordable model consistency.

The Trnbuild library was also used to define the occupancy pattern and people behaviour, differentiating the students in the classroom from those in the gym. Both the sensible and latent indoor heat gains were evaluated in compliance with [58,59], while those from artificial lighting were connected to the light source typology. Current indications and guidelines on the subject [35–45] indicate that in the Covid-19 era, people density must be cut by at least 50% in comparison with pre-Covid-19 management. As a consequence, in the calculation model, the number of students for each classroom was reduced to 50% (i.e., in all the classrooms and the gym). The current opening time was taken into account: from 8:00 to 19:00 during weekdays; from 8:00 to 14:00 on Saturday; closed on Sunday. It is important to note that the occupancy pattern is a pivotal factor in calculating building energy needs because both the heating plant activation schedule and the mechanical ventilation system (HVAC) modulation depend on it.

The existing building–plant system, validated by means of the HDD method, was used as a basic model for all the investigated retrofit scenarios in order to keep the validation, as long as the “building envelope–climate surround” match is almost the same. Due to the constraints imposed on historical heritage buildings, the retrofit project mainly affected the plant system; it only affected the windows of the building system. Refurbishment solutions based on the transition from natural to controlled mechanical ventilation had particularly important consequences for energy needs and consumption.

In Trnsys Simulation Studio [54], each major component of both the heating plant and the ventilation system was modelled through a specific library, mainly developed by the TESS company. The Building Automation and Control System (BACS), which manages the whole HVAC system, is implemented through the TESS libraries. The implementation of high automated control is aimed at optimising plant energy efficiency and reducing the occupancy pattern variance. Despite the proportional modulation of the HVAC devices, the numerical reliability of the transient model was proven by the fast convergence during the simulation run. The Trnsys solver uses the so-called "successive method" for representing the thermal capacity of the whole system [54]. The differential equations were solved by the "modified-Euler method" algorithm. Applying these parameters, the simulation ran with the ratio of one hour simulated in 0.5 s real-time, using a standard 2.5 GHz dual-core processor, without any over-clock.

2.2. The Investigated Historic School Building and the Existing Heating Plant

The school building, Dante High School, was built in 1876 and has been used as a school since 1921. The building is not totally subjected to the constraints imposed by the Italian Heritage Protection Offices (called Superintendency), but the building and garden are protected (Figure 1). This means that interventions that may change the architectural features, such as an external cladding insulation system or solar thermal and/or photovoltaic system installation, are not feasible. On the other hand, the air-conditioning systems, such as the external units of air-source heat pump installation (e.g., in the garden or under the roof) could be implemented. The load-bearing structure is in stone masonry, the interstorey floors are in mixed iron and brick, and there is a pitched roof with warping in wooden beams and mantle in brick tiles. The windows have a wooden frame and are of single-glass.

Figure 1. Photos: (**a**) images of the Dante High School building; (**b**) a typical classroom; (**c**) a corridor on the first floor; (**d**) the gym; (**e**) entrance hall, collective space; (**f**) entrance staircase to the first floor.

This is the reason why the thermophysics performance of the building envelope is rather insufficient. The average thermal transmittance of the opaque components is 2.0 W/m^{2}K and, for the transparent components, 5 W/m^{2}K (i.e., those of the building reference case, before refurbishment/renovation [15,17]).

All the information about the thermophysical properties of the building components, the technical data of the existing heating plant system, the time profiles of the classrooms and gym use, the thermal loads due to people (students and teachers), and the lighting system and equipment were derived from the abovementioned literature [15,17]. The national calculation method provided by [60,61] was used to define different thermal zones, including circulation areas, administrative offices, classrooms, laboratories, attic, toilets, the gym, and changing rooms.

There is a heating system with a gas heat generator; indoor ventilation is natural due to infiltration and manual handling (Figure 2). The hydronic system supplies both the main building and the gym. The terminals are cast iron column radiators, operating at high temperatures, as well as an air heater for the gym. The conduction regime is intermittent, with preignition in the morning.

Figure 2. Photos: some internal views of the thermal power plant.

The on/off control system, together with the insufficient terminal sizing for different zones, involves important temperature fluctuations with respect to the setpoint value, and, sometimes, the latter is not reached. The results obtained from the analysis of the existing heating plant system in the abovementioned studies [15,17], developed before the current health emergency and highlighting that a significant energy saving of 45% can easily be obtained with the upgrade of the existing hydronic system, automatic regulation system installation, replacement of glazing and window frames (also considering a constant air change rate per hour (ACH) of 1 vol/h, together with the air permeability fixtures and window airing), were the reasonable starting point of our present research and new design proposals.

2.3. Refurbishment Design

The planned HVAC system was a hybrid hydronic–aeraulic heating plant, coupled with local air handling units for mechanical ventilation. The plant is powered by a centralised gas-fired condensing boiler. The hydronic pipelines act as both direct distribution, fuelling fan–coil devices, and primary distribution, fuelling the heating coil of the local air-handling units. The fan–coil design was sized to balance heat transfer through the building envelope, while the air devices make up the air, to balance the outgoing flow with incoming ambient air, guaranteeing indoor air renewal.

As a boundary condition of the filtered airflow rate (HEPA filters were considered) entering the classrooms and the gym, an air temperature setpoint value of 20 °C was assumed. Small local air-handling units (AHU) were used for heating the fresh air from the external temperature value to the setpoint value, with fixed point or climatic regulation.

It is important to highlight the fact that the switch from natural ventilation (i.e., external air infiltration and manual opening) to mechanical ventilation (i.e., controlled mechanical ventilation with heat recovery and absolute filtration system) is a keystone in the strategy against contamination and Covid-virus spread. This was a fundamental change from the existing reference case characterised by external air infiltration as the dominant ventilation mode. For this reason, simulations at existing conditions (the reference case) were carried out, assuming a daily and weekly average air change rate equal to 1 vol/h for all the thermal zones.

Dealing with a protected historical building means plant impact minimisation, avoiding any impact on architectural features and historical–cultural–social values. In the studied school, the hydronic pipelines connect the thermal power plant with each room, and the air devices were hidden behind plasterboard light countertops. The "hydronic" plant means that the indoor air temperature was set up at 20 °C during the daytime and in free-floating mode during the night and weekends. The complexity of any HVAC system design is due to the specific intervention context. The considerable room height, over 5 m, allowed this kind of design solution, but the entire building structure did not allow for centralised air management, i.e., a real central air handling unit, which is generally rather invasive.

According to the suggested health, safety, and prevention requirements [35–45], there are no recirculating air ducts, and the HVAC system operates in "all outside air" mode. Due to the aforementioned requirements, the devices were oversized, so as achieve a 4 vol/h indoor air change rate.

Each device was equipped with a heat recovery unit, composed of an air–air only sensible heat exchanger of the crossflow typology, for an effective energy-saving purpose. The average seasonal recovery efficiency of the crossflow heat exchangers was assumed to be 75%. This value was based on data for a similar commercial unit, taking into account the need for external air to be preheated during the winter night-time. This choice was made in order to avoid moisture freezing over the plate-fins.

The lack of a "recirculation" mode provided complex indoor air humidity control. This was due to the fact that during the heating season, the students were the main moisture source with respect to the external air, especially in the gym. The proposed plant system was able to control all the fluctuations and variations of the indoor air temperature.

However, the designed high air exchange rate was able to reduce the indoor humidity so that with the plant operating in a floating mode, the indoor air humidity value could only vary in the 43–57% range. As also widely reported in recent research [1,2,5,12–14], this fluctuation is still suitable and compatible with typical school activities.

The indoor temperature setpoint/setback and the plant activation schedule will be discussed in Section 3, considering the project proposal with a range from 20 °C to free-floating, coupled with an air change rate of 4 to 2 vol/h.

3. Results

Our research project was widely managed across 10 different Trnsys models: the existing building–plant system (i.e., the base comparison case), the case considering only envelope thermal improvement (i.e., building refurbishment), and eight settings of HVAC management, with different values of the control/regulation parameters and controlled mechanical ventilation conditions.

The existing building–plant system has 74 kWh/m^2 year of heating energy consumption, measured as primary energy, considering a 1.05 primary energy factor for natural gas. This situation, which is in compliance with current Italian energy regulation [55,56], is slightly lower compared to the situation in other European countries, as described in [62,63]. This is a common energy need scenario for building heating in the ante-Covid context.

In recent research on this subject, it was demonstrated that envelope thermal improvement leads to more valuable indoor thermal comfort rather than energy savings [23,25,26,28,62,63].

Under present conditions, the plant is unable to check the temperature setpoint. The replacement of all the windows with thermal-improved glazes and frames allows a reduction of the total heat loss so that the plant easily fits indoor thermal comfort requirements. In addition, mechanical ventilation is completely absent, and the air change rate due to natural ventilation is about 1 vol/h. The lack of automatic heating control was the main factor affecting the total building energy need: it happens despite the fact that local temperature control should be mandatory for centralised plants. On the other hand, all the eight developed HVAC options were strongly automated, both at central and local levels. In particular, for all the 8 HVAC solutions, the external air infiltration was considered absent, and the air change rate was modulated by the air handling units installed in each thermal zone. The modulation range was set between 4 (setpoint value) and 2 vol/h (setback value). The indoor air temperature was modulated from a setpoint value of 20 °C and a setback value in the range of 14–16 °C for comfort and energy-saving conditions.

In the refurbished plant configuration, a reference setting, connected to air change rate and indoor air temperature, was set at the corresponding setpoint values for the whole day and week. If this setting produces non-negligible effects from the energy and economic points of view, it allows the achievement of the IAQ and the healthy environment suggested by [35–45].

In order to define an optimal HVAC setting, taking into account the real-time profiles of use of the school, some different scenarios were simulated and assessed. For all these scenarios, the same setpoint values were used for the school opening time. For the school closing periods, the HVAC system was put in setback mode. Then, eight different scenarios were defined (Table 1). It is important to note that the high thermal mass of the masonry building envelope (i.e., thermal inertia) allowed plant solutions based on a free-floating mode without the indoor air temperature falling below 12 °C. It is also important to note that continuous ventilation is required for healthcare so that fan speed can be reduced but never turned off [35–45].

Table 1. Control parameters and energy cost of the eight investigated mechanical ventilation system (HVAC) configurations.

n.	Indoor Air Temperature Closing Time (°C)	Air Change per Hour (ACH) Closing Time (1/h)	Indoor Air Temperature Opening Time (°C)	Air Change per Hour (ACH) Opening Time (1/h)	Energy Cost (kWh/m^2 year)
01	20	4	20	4	131
02	20	2	20	4	116
03	16	4	20	4	106
04	16	2	20	4	95
05	14	4	20	4	97
06	14	2	20	4	87
07	free-floating	4	20	4	84
08	free-floating	2	20	4	79

3.1. HVAC Management Options

Current Italian energy regulations [64] state that for the climatic zone of Florence, the heating season spans 166 days, from 1 November until 15 April, and the indoor temperature setpoint value must be at 20 °C for school buildings. All the investigated retrofit solutions were assessed under the above conditions.

In the pre-Covid era, the heating plant was managed in a discontinuous mode, i.e., the indoor temperature was free-floating during the night and weekends. Consequently, the natural ventilation rate was near zero during the same time lapses. In this present Covid-19 era, under the hypothesis of the ventilation type switch, as discussed in Section 2, indoor air renovation must be continuous during the whole day and the whole week. Hence, a base setting, featured as 20 °C for the air temperature and 4 vol/h for the ventilation rate, for every day of the week was identified and used. Starting from this base setting, the air temperature and air change rate patterns were modified in order to reduce the building's energy needs during the school closing time, ranging, respectively, from 20 °C to free-floating and from 4 to 2 vol/h. In this way, different significant settings were designed and simulated, and the resulting energy needs were analysed and compared. In these indoor conditions, a healthy indoor environment was provided: wellbeing, safety and IAQ are guaranteed during all the periods of occupation and use of the school by teachers and students.

During the night and for the closed periods of the school, HVAC capacity is attenuated without health risks. The air temperature range is defined by considering the thermal inertia of the whole building in relation to the extent of the HVAC capacity attenuation time. The "dynamic internal areal heat capacity", evaluated as suggested in [56], was 165 kJ/m^{2}K. A high building inertia produces a small temperature fall during the night-time in setback and/or free-floating conditions.

3.2. Comparison of the Proposed Different Plant Settings for Building Energy Needs

In this section, the fundamental results obtained by transient simulation are discussed.

Table 1 shows the eight investigated settings of HVAC management and provides the corresponding seasonal heating energy cost. For the entire opening time, the indoor air temperature setpoint was

20 °C and the air change rate was 4 vol/h in all the classrooms, the laboratory, and offices, and also in the gym and its dressing rooms.

The building energy need, due to the proposed HVAC system, applying the BACS parameters and varying the control mode, is shown in Figure 3. The energy need is expressed as the primary energy amount (i.e., the weighted delivered energy amount) normalised on the building floor area and measured in kWh/m^2 year. The Dante School conditioned area is 3800 m^2. In the graph (Figure 3), the acronym "EP" means "energy performance", i.e., the expression of the building energy assessment for a tailored design configuration. The result comparison (Figures 3 and 4) provides the following crucial deductions:

- The continuous mode is the most expensive because it maintains the setpoint values during the whole day and for the whole week, regardless of the presence of people. On the other hand, the intermittent mode is the cheapest one. As expected, the night-time attenuation results correspond to intermediate values as a function of the setback value.
- The Trnsys results show that under free-floating conditions, the night-time air temperature never falls below 12 °C because the building masonry mass and thermal inertia are really high. In the morning, 2 h of system preignition to restore the setpoint by 8.00 was completely sufficient. Consequently, the 30% energy saving, achievable with the intermittent mode in comparison with the continuous mode, makes it the most suitable solution from the energy point of view.
- Due to the 75% average seasonal recovery efficiency, ventilation energy consumption is about a quarter of the total. Its absolute amount remains almost unchanged among the different control modes because when the indoor temperature is put at the setback value (i.e., at an air temperature value of 14 or 16 °C), at the same time, the air handling devices are put at the same value (i.e., the air inlet conditions are set at the design temperature setback for both the classrooms and the gym).
- The continuous mode conditions, compared with the existing state, provide an energy need increase of more than 75%, while at intermittent mode, the increase is limited to 15%.

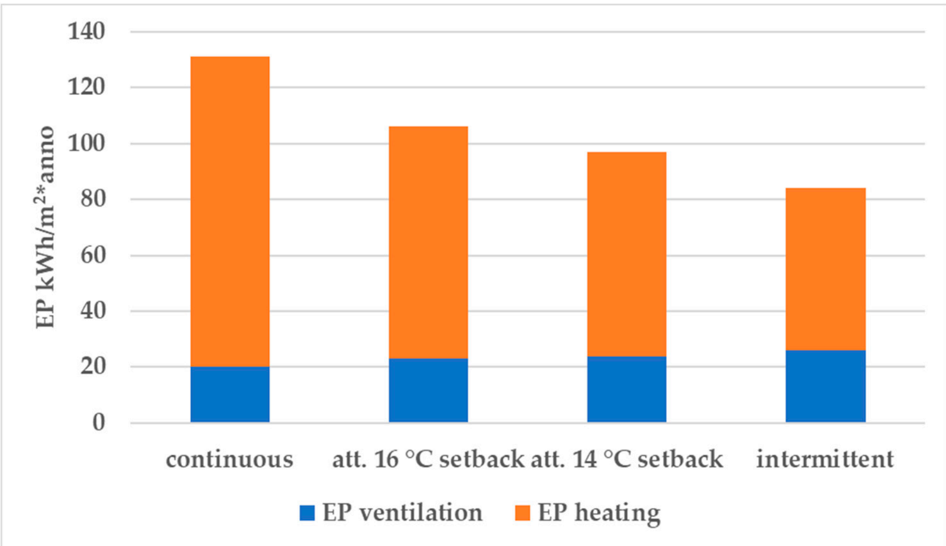

Figure 3. Building energy needs obtained by varying the indoor temperature control mode for a 4 vol/h continuous ventilation rate. (* anno, means for the entire heating period).

Starting from these results, the effects of air change attenuation and the correlated air temperature attenuation were investigated and assessed in order to explore further energy saving paths. Energy need accounted for a continuous 4 vol/h air change rate, in comparison with a 2–4 vol/h attenuated rate, for all 4 control modes, are shown in Figure 4.

An energy saving of 10% was easily obtained by means of air change rate attenuation while guaranteeing a healthy environment during the whole opening time of the school (this is shown in Figure 4). The reduced impact on the overall building EP is due to both the high efficiency of the heat recovery units and the poor thermal insulation of the whole building envelope.

On this matter, it is important to underline that regardless of the type of plant system and its regulation and control, the building envelope itself is highly energy-intensive. This is a very widespread and common aspect for historical buildings, which, despite having undergone plant system upgrades (e.g., mainly for safety and fire prevention issues, are not allowed interventions of improvement of thermophysical and energy performance of their envelope) due to the constraints imposed by the protection and conservation of cultural heritage. It has been widely demonstrated that masonry buildings, built without any layer of thermal insulation, are energy-expensive [14–18,65].

From the energy perspective, the optimal combination between intermittent air temperature control modes and attenuated air change rates led to an EP index of 79 kWh/m^2*year, which is very close to the one provided by the existing state, but it allows a 40% saving in comparison to the base setting (i.e., the continuous HVAC mode).

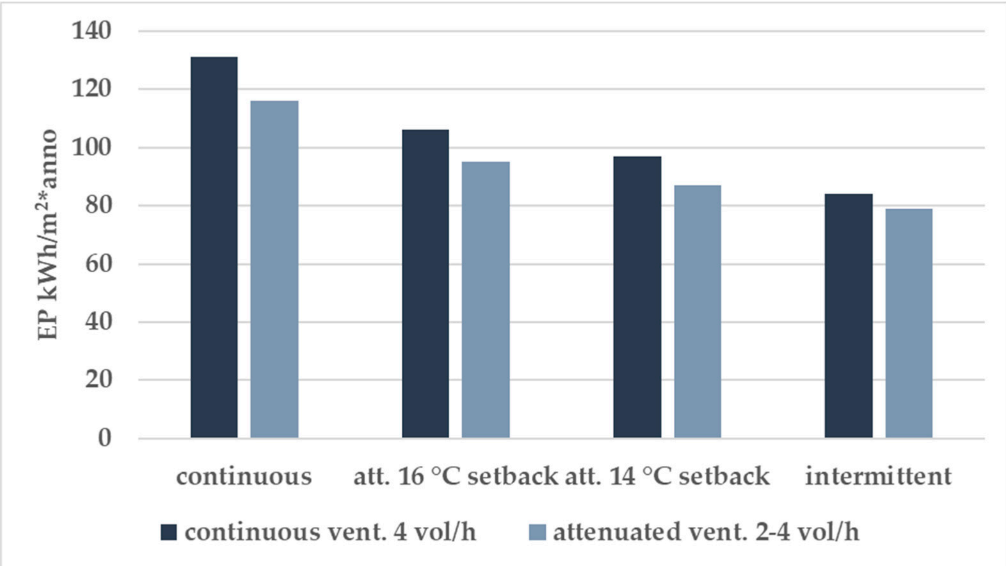

Figure 4. Building energy needs obtained by varying both the indoor air temperature control and the ventilation rate. (* anno, means for the entire heating period)

4. Discussion

All the investigated HVAC configurations produced a retrofit energy consumption that is higher than the one provided by the existing case. The obtained results, concerning the higher overall energy costs of refurbishment and specific plant retrofitting interventions, were predictable.

However, the concept of "sustainability" should also be understood in terms of guaranteeing people's health, safety, and wellbeing. As a consequence, building–plant system renovation (i.e., retrofitting/refurbishment efficient measures) and decontamination (i.e., IAQ by means of effective ventilation for airborne-contaminant removal) issues are fundamental, especially under reopening measures during the Covid-19 era. These aspects are even more important when connected to the suitability concept, i.e., also from the social–cultural and energy-use quality point of view for a historical school building, such as the one studied, of which there are many examples in Italy.

International organisations and recent standards encourage the design of HVAC systems with controlled mechanical ventilation, also demanding ventilation systems with CO_2 concentration control to prevent infection risks and the spread of the coronavirus disease [35–45]. For these reasons, a controlled ventilation system "*on demand*" was investigated, assuring plant operation at nominal velocity and guaranteeing ventilation for 24 h per day, for the whole week, with lowered ventilation rates (i.e., attenuation, not switched-off conditions) when people are absent.

The use of more window airing and, consequently, natural ventilation solutions, are certainly efficient and, therefore, advantageous from the energy consumption and cost points of view [4,5,9,10].

However, as has been shown in recent literature, the effectiveness of these solutions to ensure the correct ventilation of environments and IAQ conditions (i.e., hygiene, health, safety and comfort) to a great extent depends on occupant behaviour and a very long period of open windows [4,5,9,10,27,28,30,49,51–53].

5. Conclusions

Occupants' health, safety, and wellness can be achieved with HVAC plant system designs finalised to IAQ and ventilation effectiveness (demand ventilation control and airflow scheme effectiveness, correct air change rates), as widely demonstrated by [51–53]. All this is particularly complex when it must be designed for assuring health requirements, adapting existing and historical buildings to the pandemic context [51,53]. Since the air permeability of the building envelope and the natural ventilation due to manual window airing cannot ensure the minimum air ventilation rate (contaminant dilution and/or removal), the plant design must be based on demand, controlled mechanical ventilation and its correct management [8,18,51–53].

The important findings of our research highlight the need for a plant project aimed at efficiency and effectiveness, i.e., a compromise between energy savings and IAQ and people's health/safety. On the other hand, social distancing (also called physical distancing), functional reorganisation and the planned use of spaces can be significant support for correct and controlled mechanical ventilation. This is the case when any design proposal would be strongly conditioned by the preventive protection constraints imposed on cultural heritage buildings. In particular, solutions for optimised student distribution to contain contagion risk and virus spread could provide important help for the practical realisation of an effective airflow scheme with all external air, without recirculation.

With the perspective of reversibility and sustainability, external environments, though near to the existing school building (e.g., classrooms, laboratories, experimentation and study spaces), can be obtained using modular, removable systems. These can be easily assembled/disassembled (i.e., prefabricated modular designs that integrate the use of ecosustainable materials and components and renewable energy sources), and the HVAC system design would be less complex. This could also provide the connected energy cost balance by means of the combination of a reduced presence of people/users and the necessary physical distance, together with the attenuation of ventilation rate and air temperature for the periods of nonuse of the environments.

From our research findings, an important issue can be deduced: correct behaviour, together with proper management and maintenance of a mechanical ventilation air conditioning system, is the key element for guaranteeing IAQ and healthy environments. These crucial factors have a direct impact on energy-sustainable operations and environmental, social and healthy conditions of any school building.

Our findings show how retrofitted plant design strategies for historical school buildings are possible if based on the optimal compromise between energy savings and the best ventilation conditions for indoor air quality (IAQ). Sustainability is understood as effective and efficient solutions for energy consumption reduction and environmental sustainability as a guarantee for people's safety and wellbeing.

Our findings have implications that lead to a review and new discussion of retrofit and refurbishment energy costs, with the aim of temporary school solutions and architectural and structural designs that could be detachable, either as a unit or in parts, and used as classrooms and/or laboratories and study and training spaces for students. In addition, an important issue that could be a further development of this study would concern the assessment of scenarios of combined operations oriented to healthy requirements in relation to the connected energy consumption. This would require a multidisciplinary approach, with the involvement of many different experts from different disciplines.

This could be very important for suggesting effective and efficient solutions for adapting historical buildings to the pandemic context.

Author Contributions: The authors, C.B. and L.L., contributed equally to this work. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank the following people for providing data and information that was useful for the realisation of this study: Luca Fibbi and the technical staff of Consorzio LaMMA, Laboratory for Meteorology and Environmental Modelling (Sesto Fiorentino, Florence, Italy), and the Director and all his staff of the Environmental Department of the Metropolitan City of Florence (Italy).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Majd, E.; McCormack, M.; Davis, M.; Curriero, F.; Berman, J.; Connolly, F.; Leaf, P.; Rule, A.; Green, T.; Clemons-Erby, D.; et al. Indoor air quality in inner-city schools and its associations with building characteristics and environmental factors. *Environ. Res.* **2019**, *170*, 83–91. [CrossRef] [PubMed]
2. Wargocki, P.; Porras-Salazar, J.A.; Contreras-Espinoza, S.; Bahnfleth, W. The relationships between classroom air quality and children's performance in school. *Build. Environ.* **2020**, *173*, 106749. [CrossRef]
3. Sun, C.; Zhai, Z.J. The efficacy of social distance and ventilation effectiveness in preventing COVID-19 transmission. *Sustain. Cities Soc.* **2020**, *62*, 102390. [CrossRef] [PubMed]
4. Bartyzel, J.; Zięba, D.; Necki, J.; Zimnoch, M. Assessment of Ventilation Efficiency in School Classrooms Based on Indoor–Outdoor Particulate Matter and Carbon Dioxide Measurements. *Sustainability* **2020**, *12*, 5600. [CrossRef]
5. Stabile, L.; Buonanno, G.; Frattolillo, A.; Dell'Isola, M. The effect of the ventilation retrofit in a school on CO_2, airborne particles, and energy consumptions. *Build. Environ.* **2019**, *156*, 1–11. [CrossRef]
6. Gil-Baez, M.; Barrios-Padura, A.; Molina-Huelva, M.; Chacartegui, R. Natural ventilation systems in 21st-century for near zero energy school buildings. *Energy* **2017**, *137*, 1186–1200. [CrossRef]
7. Heracleous, C.; Michael, A. Experimental assessment of the impact of natural ventilation on indoor air quality and thermal comfort conditions of educational buildings in the Eastern Mediterranean region during the heating period. *J. Build. Eng.* **2019**, *26*, 100917. [CrossRef]
8. Choi, J.-S.; Lee, J.-H.; Kim, E.-J. Effects of ERV Filter Degradation on Indoor CO_2 Levels of a Classroom. *Sustainability* **2018**, *10*, 1215. [CrossRef]
9. Schibuola, L.; Scarpa, M.; Tambania, C. Natural ventilation level assessment in a school building by CO_2 concentration measures. *Energy Procedia* **2016**, *101*, 257–264. [CrossRef]
10. Stabile, L.; Dell'Isola, M.; Frattolillo, A.; Massimo, A.; Russi, A. Effect of natural ventilation and manual airing on indoor air quality in naturally ventilated Italian classrooms. *Build. Environ.* **2016**, *98*, 180–189. [CrossRef]
11. Peng, Z.; Deng, W.; Tenorio, R. Investigation of Indoor Air Quality and the Identification of Influential Factors at Primary Schools in the North of China. *Sustainability* **2017**, *9*, 1180. [CrossRef]
12. Marino, C.; Minichiello, F.; Ronga, P. Thermal-Hygrometric and Energy Performance Analysis of HVAC Systems for Educational Buildings in Southern Europe. *Int. J. Heat Technol.* **2016**, *34*, S573–S580. [CrossRef]
13. De Santoli, L.; Mancini, F.; Clemente, C.; Lucci, S. Energy and technological refurbishment of the school of Architecture Valle Giulia, Rome. *Energy Procedia* **2014**, *133*, 382–391. [CrossRef]
14. De Santoli, L.; Fraticelli, F.; Fornari, F.; Calice, C. Energy performance assessment and a retrofit strategies in public school buildings in Rome. *Energy Build.* **2014**, *68*, 196–202. [CrossRef]
15. Balocco, C.; Colaianni, A. Assessment of Energy Sustainable Operations on a Historical Building. The Dante Alighieri High School in Florence. *Sustainability* **2018**, *10*, 2054. [CrossRef]
16. Dalla Mora, T.; Righi, A.; Peron, F.; Romagnoni, P. Cost-optimal measures for renovation of existing school buildings towards nZEB. *Energy Procedia* **2017**, *140*, 288–302. [CrossRef]
17. Balocco, C.; Colaianni, A. Modelling of Reversible Plant System Operations in a Cultural Heritage School Building for Indoor Thermal Comfort. *Sustainability* **2018**, *10*, 3776. [CrossRef]
18. Lou, S.; Tsang, E.K.W.; Li, D.H.W.; Lee, E.W.M.; Lam, J.C. Towards zero energy school building designs in Hong Kong. *Energy Procedia* **2017**, *105*, 182–187. [CrossRef]

19. World Health Organization. *School Environment: Policies and Current Status*; WHO Regional Office for Europe: Copenhagen, Demark, 2015.
20. Italian Ministry for the Environment, Land and Sea (IMELS), School Environment and Respiratory Health of Children. Available online: http://search.rec.org (accessed on 23 July 2018).
21. SINPHONIE Project, the Schools Indoor Pollution and Health: Observatory Network in Europe. Available online: http://www.sinphonie.eu/ (accessed on 23 July 2018).
22. Domínguez-Amarillo, S.; Fernández-Agüera, J.; Minaksi González, M.; Cuerdo-Vilches, T. Overheating in Schools: Factors Determining Children's Perceptions of Overall Comfort Indoors. *Sustainability* **2020**, *12*, 5772. [CrossRef]
23. Campano, M.A.; Domínguez-Amarillo, S.; Fernández-Agüera, J.; Sendra, J.J. Thermal Perception in Mild Climate: Adaptive Thermal Models for Schools. *Sustainability* **2019**, *11*, 3948. [CrossRef]
24. Korsavi, S.S.; Montazami, A.; Mumovic, D. Ventilation rates in naturally ventilated primary schools in the UK.; Contextual, Occupant and Building-related (COB) factors. *Build. Environ.* **2020**, *181*, 107061. [CrossRef]
25. Corgnati, S.P.; Ansaldi, R.; Filippi, M. Thermal comfort in Italian classrooms under free running conditions during mid seasons: Assessment through objective and subjective approaches. *Build. Environ.* **2009**, *44*, 785–792.
26. D'Ambrosio, F.R.; Olesen, B.W.; Palella, B.I.; Povl, O. Fanger's impact ten years later. *Energy Build.* **2017**, *152*, 243–249.
27. Alfano, F.R.D.; Palella, B.I.; Riccio, G.; Toftum, J. Fifty years of Fanger's equation: Is there anything to discover yet? *Int. J. Ind. Ergon.* **2018**, *66*, 157–160.
28. D'Ambrosio Alfano, F.R.; Ianniello, E.; Palella, B.I. PMV-PPD and acceptability in naturally ventilated schools. *Build. Environ.* **2013**, *67*, 129–137.
29. Wanyu, R.; Chan, W.R.; Li, X.; Brett, C.S.; Pistochini, T.; Vernon, D.; Outcault, S.; Sanguinetti, A.; Modera, M. Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation. *Build. Environ.* **2020**, *167*, 106426. [CrossRef]
30. Becker, R.; Goldberger, I.; Paciuk, M. Improving energy performance of school buildings while ensuring indoor air quality ventilation. *Build. Environ.* **2007**, *42*, 3261–3276. [CrossRef]
31. Pacitto, A.; Amato, F.; Moreno, T.; Pandolfi, M.; Fonseca, A.; Mazaheri, M.; Stabile, L.; Buonanno, G.; Querol, X. Effect of ventilation strategies and air purifiers on the children's exposure to airborne particles and gaseous pollutants in school gyms. *Sci. Total Environ.* **2020**, *712*, 135673. [CrossRef]
32. Wachenfeldt, B.J.; Mysen, M.; Schild, P.G. Air flow rates and energy saving potential in schools with demand-controlled displacement ventilation. *Energy Build.* **2007**, *39*, 1073–1079. [CrossRef]
33. Vornanen-Winqvist, C.; Toomla, S.; Ahmed, K.; Kurnitski, J.; Mikkola, R.; Salonen, H. The effect of positive pressure on indoor air quality in a deeply renovated school building—A case study. *Energy Procedia* **2017**, *132*, 165–170. [CrossRef]
34. Energy Performance of Buildings–Ventilation for Buildings–Part 3: For Non-Residential Buildings–Performance Requirements for Ventilation and Room-Conditioning Systems (Modules M5-1, M5-4); EN 16798-3:2017. Available online: http://store.uni.com/catalogo/en-16798-3-2017?josso_back_to=http://store.uni.com/josso-security-check.php&josso_cmd=login_optional&josso_partnerapp_host=store.uni.com (accessed on 23 July 2018).
35. Italian Higher Institute of Health. Interim Indications for the Prevention and Management of Indoor Environments in Relation to the Transmission of the SARS-CoV-2 Virus Infection. Version of 23 March 2020; 10 p. ISS COVID-19 Reports No. 5/2020; ISS Environment and Indoor Air Quality 2020 Working Group ii: 2020. Available online: https://www.iss.it/coronavirus (accessed on 23 July 2018).
36. AICARR (Italian Association of Air Conditioning, Heating and Refrigeration). (2020-I). The Plants and the Spread of SARS-COV2-19 in the Workplace. AICARR, 2020. Available online: https://www.aicarr.org/Pages/Normative/FOCUS_COVID-19_IT.aspx (accessed on 23 July 2018).
37. AICARR (Italian Association of Air Conditioning, Heating and Refrigeration). (2020-II). AICARR Position on the Operation of Air Conditioning Systems During the SARS-COV2-19 Emergency. AICARR, 2020. Available online: https://www.aicarr.org/Pages/Normative/FOCUS_COVID-19_IT.aspx (accessed on 23 July 2018).

38. AICARR (Italian Association of Air Conditioning, Heating and Refrigeration). (2020). Protocol for the Reduction of the Risk from the Spread of SARS-COV2-19 in the Management and Maintenance Operations of Existing Air Conditioning and Ventilation Systems. AICARR, 2020. Available online: https://www.aicarr.org/Pages/Normative/FOCUS_COVID-19_IT.aspx (accessed on 23 July 2018).
39. U.S. Environmental Protection Agency (USEPA). *Report of the Environment: Indoor Air Quality*; USEPA, 2020. Available online: https://www.epa.gov/report-environment/indoor-air-quality (accessed on 19 April 2020).
40. *How to Operate and Use Building Services in order to Prevent the Spread of the Coronavirus Disease (COVID-19) Virus (SARS-CoV-2) in Workplaces*, REHVA COVID-19 Guidance Document, 3 April 2020 (This Document Updates 17 March Version, Updates will Follow as Necessary); 2020. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiHk-TW3MTsAhXJDaYKHQ35ADAQFjAAegQIBBAC&url=https%3A%2F%2Fwww.rehva.eu%2Ffileadmin%2Fuser_upload%2FREHVA_COVID-19_guidance_document_ver2_20200403_1.pdf&usg=AOvVaw17j5VEcLQ4Lh-KwWOnaj8_ (accessed on 19 April 2020).
41. Environmental Protection Agency (EPA), Guidance 2020: Indoor Air and Coronavirus (COVID-19). Available online: https://www.epa.gov/coronavirus/indoor-air-and-coronavirus-covid-19 (accessed on 19 April 2020).
42. ASHRAE April 2020, Issues and Statements on Relationship Between COVID-19 and HVAC in Buildings. Available online: https://www.ashrae.org/about/news/2020/ashrae-issues-statements-on-relationship-between-covid-19-and-hvac-in-buildings (accessed on 19 April 2020).
43. ASHRAE, July 2020, Updated Reopening Guide Schools and Universities. Available online: https://www.ashrae.org/about/news/2020/ashrae-introduces-updated-reopening-guide-for-schools-and-universities (accessed on 19 April 2020).
44. World Health Organization. *(2020-I). Getting your Workplace Ready for COVID-19*; WHO: Geneva, Switzerland, 3 March 2020.
45. World Health Organization. *(2020-II). Water, Sanitation, Hygiene and Waste Management for COVID-19*; WHO: Geneva, Switzerland, 2020.
46. Teleszewski, T.J.; Gładyszewska-Fiedoruk, K. Characteristics of humidity in classrooms with stack ventilation and development of calculation models of humidity based on the experiment. *J. Build. Eng.* **2020**, *31*, 101381. [CrossRef]
47. Vornanen-Winqvist, C.; Järvi, K.; Andersson, M.A.; Duchaine, K.; Létourneau, V.; Kedves, O.; Kredics, L.; Mikkola, R.; Kurnitski, J.; Salonen, H. Exposure to indoor air contaminants in school buildings with and without reported indoor air quality problems. *Environ. Int.* **2020**, *141*, 105781. [CrossRef] [PubMed]
48. Sundell, J.; Levin, H.; Nazaroff, W.W.; Cain, W.S.; Fisk, W.J.; Grimsrud, D.T.; Gyntelberg, F.; Li, Y.; Persily, A.K.; Pickering, A.C.; et al. Ventilation rates and health: Multidisciplinary review of the scientific literature. *Indoor Air* **2011**, *21*, 191–204. [CrossRef] [PubMed]
49. Fisk, W.J. The ventilation problem in schools: Literature review. *Indoor Air* **2017**, *27*, 1039–1051. [CrossRef] [PubMed]
50. Batterman, S.; Su, F.C.; Wald, A.; Watkins, F.; Godwin, C.; Thun, G. Ventilation rates in recently constructed U.S. school classrooms. *Indoor Air* **2017**, *27*, 880–890. [CrossRef]
51. Yang, S.; Perret, V.; Hager Jörin, C.; Niculita-Hirzel, H.; Goyette Pernot, J.; Licina, D. Volatile organic compounds in 169 energy-efficient dwellings in Switzerland. *Indoor Air* **2020**, *30*, 481–491. [CrossRef]
52. Niculita-Hirzel, H.; Yang, S.; Hager Jörin, C.; Perret, V.; Licina, D.; Goyette Pernot, J. Fungal Contaminants in Energy Efficient Dwellings: Impact of Ventilation Type and Level of Urbanization. *Int. J. Environ. Res. Public Health* **2020**, *17*, 4936. [CrossRef]
53. Yang, S.; Pernot, J.G.; Jörin, C.H.; Niculita-Hirzel, H.; Perret, V.; Licina, D. Energy, indoor air quality, occupant behavior, self-reported symptoms and satisfaction in energy-efficient dwellings in Switzerland. *Build. Environ.* **2020**, *171*, 106618. [CrossRef]
54. Trnsys 18, TESS Libraries and Manual. Available online: www.trnsys.com (accessed on 19 April 2020).
55. Italian Ministry of Economic Development. Ministerial Decree 26/06/2015. Application of the Methodologies for Calculating Energy Performance and Defining the Requirements and Minimum Requirements of Buildings. Minimum Environmental Criteria for Buildings Off.JItalianRepublic. 15 July 2015. Available online: Ww.sviluppoeconomico.gov.it/index.php/it/normativa/decreti-interministeriali/2032966-decreto-interministeriale-26-giugno-2015-applicazionedelle-metodologie-di-calcolo-delle-prestazioni-energetiche-e-definizione-delle-prescrizioni-e-dei-requisitiminimi-degli-edifici (accessed on 23 July 2018). (In Italian)

56. UNI EN ISO 13786:2018 Thermal Performance of Building Components—Dynamic Thermal Characteristics—Calculation Methods. Available online: http://store.uni.com/catalogo/uni-en-iso-13786-2018# (accessed on 19 April 2020).
57. Reindl, D.T.; Beckman, W.A.; Duffie, J.A. Diffuse fraction correlations. *Sol. Energy* **1990**, *45*, 1–7. [CrossRef]
58. UNI EN ISO 15927-4:2005 Thermal and Hygrometric Performance of Buildings—Calculation and Presentation of Climatic Data—Part 4: Hourly Data for the Assessment of the Annual Energy Needs for Heating and Cooling. Available online: http://store.uni.com/catalogo/uni-en-iso-15927-4-2005 (accessed on 19 April 2020).
59. UNI EN ISO 7730:2006 Ergonomics of Thermal Environments—Analytical Determination and Interpretation of Thermal well-being by Calculating the PMV and PPD Indices and Local Thermal Well-Being Criteria. Available online: http://store.uni.com/catalogo/index.php/uni-en-iso-7730-2006 (accessed on 19 April 2020).
60. UNI TS 11300-1:2014. Energy Performance of Buildings—Part 1: Determination of the Needs for Thermal Energy of the Building for Summer and Winter Air Conditioning. Available online: http://store.uni.com/catalogo/uni-ts-11300-1-2014 (accessed on 19 April 2020). (In Italian).
61. EN 15251:2008. Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. Available online: http://store.uni.com/catalogo/uni-en-15251-2008 (accessed on 19 April 2020).
62. Hitchin, R.; Thomsen, K.E.; Wittchen, K.B. Primary Energy Factors and Members States Energy Regulations. Primary factors and the EPBD. *Rep. Concert. Action Epbd* **2010**, 1–4. Available online: https://epbd-ca.eu/wp-content/uploads/2018/04/05-CCT1-Factsheet-PEF.pdf https://vbn.aau.dk/en/publications/primary-energy-factors-and-members-states-energy-regulations-prim (accessed on 19 April 2020).
63. Institute for Housing and Environment. IEE Project EPISCOPE. Available online: https://episcope.eu/building-typology (accessed on 19 April 2020).
64. Regulation Laying Down Rules for the Design, Installation, Operation and Maintenance of the Thermal Systems of Buildings for the Purpose of Containing Energy Consumption, in Implementation of Art. 4, Paragraph 4, of the Italian Law 9 January 1991, n. 10; Italian Standard. Available online: https://www.gazzettaufficiale.it/eli/id/1993/10/14/093G0451/sg (accessed on 19 April 2020).
65. Balocco, C.; Leoncini, L. The energy cost for air quality and proper ventilation to guarantee health. An analysis dedicated to a school. *Boll. Degli Ing. Rev.* **2020**, *7/8*, 1–23. (In Italian)