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Comfort improvement in schools through energetic optimization of the building: Multicriteria analysis on a case study

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ABSTRACT

Comfort in public schools is influenced by many physical phenomena and by personal feelings. The sensation of discomfort is not only connected to the wellness and students' health, but it can affect their studying performance, learning and attention during the lecture hours.

In contexts in which social aspects, teaching and cultural growth are the main function of the building, the quality of spaces and comfort conditions should be taken into account and really projected in parallel with the architectural design of the building itself. The dialog between occupants' needs and architecture should be always opened and active in order to achieve a final result that satisfy the requests of actors that have taken part to the project.

One aspect that influence the quality of internal environment and comfort is the hygro-thermal condition of spaces provided by systems operation. To decrease the energy consumption, it is necessary to reduce the energy used by buildings with respect to the internal comfort conditions; as consequence, the energy saving is strictly connected to the assessment of parameters that affect internal comfort. To reach this target, designers must know the influence of thermal insulation and glazed surfaces on thermal condition of the spaces and occupants should understand how the energy consumption and management costs are severely influenced by the environment control parameters.

According to these basic concepts, this thesis analyses an existing school building located in the province of Milano and provides a list of possible intervention that aims to enhance internal comfort conditions and energy saving. The improvement of the building envelope considers the application of insulation layer for the opaque façade and the substitution of original windows with new ones, that aim to decrease the thermal transmittance of the envelope components. These types of interventions are a useful strategy to decrease the energy consumption in winter season, since the preliminary analysis underlined that the building under study is heating oriented. The evaluation of internal comfort condition has been verified according to the parameters of Predict Mean Vote and Predict Percentage of Discomfort showed by the standard UNI EN ISO 7730. Moreover, each intervention has been evaluated according to the adaptive comfort method of the standard EN 15251.

After the assessment of internal comfort and energy consumption, the evaluation of costs has been provided to understand the economical different between interventions. Also, the calculation of the payback period has been useful to evaluate the effectiveness of investments.

The improvement of the quality of internal environment in public buildings is often a difficult operation that is affected by the administration issues, slow bureaucracy and poor quality of tenders. In order to simplify the decisional process, each intervention among the three combinations analysed, have been compared with a multi-criteria analysis set on the output of the analyses (cost, primary energy consumed, comfort achievement, adaptive comfort and payback period). The ranking score, from 1 to 3 points, has been assumed equal to every variable of the multi-criterial analysis, even if they can assume different point ranges according to the priorities for action.

CHAPTER

1

Comfort and indoor environmental quality in school buildings

1.1. COMFORT IN SCHOOLS

School buildings are the physical space where children education occurs, but they are also places in which human relation and people receptions must be developed. According to this context, it is supposed that schools provide environment where students feel comfortable, safe in all manners and provide surroundings for them to be resourceful, sociable, productive and able to share knowledge. In fact, spaces and their objects could influence teaching philosophy, didactic and pedagogic issues with positive effects if their quality is good and wisely projected.

Estethic of architecture, quality of materials and good setting of interal space systems have been considered "superflous" elements, that would increase the initial cost of building construction or renovation. Therefore, in many public buildings, in particular schools, these issues are not taken into account in the project evaluation, since the it is always chosen the cheapest project, without considering its quailty.

The significance of internal comfort conditions in public buildings for the health and wellness has been emphasized in recent years since people spend about 90% of their time indoors. Comfort condition of spaces is reached when human body receives stimulus from the environment, which contribute to improve wellness sensation. This issue has been analysed form the technical point of view, including other dimensions that go beyond the quality of materials and spaces ergonomics. Comfort analyses, in fact, tries to investigate the effects on human mind, psychological wellness, ecologic and cultural issues among the *infinite* aspects of this subject. Therefore, comfort is a generic quality of internal environment, but it is also a complex issue since it involves many technical fields, different from each other. This *complexity* can be appreciated in the research of its quality. A good environment quality and thus, good comfort conditions are reached when the quality level of all its aspects (hygro-thermal, visual, illuminance, psychological …) is very high. The low quality of just one technical aspect among this *complexity* could compromise the entire quality of comfort; thus, occupants perceive discomfort sensations and complain about it. Comfort and discomfort are strictly connected. In fact, discomfort and low quality of internal conditions were the first real engine of innovation and improvement changes; thus, the research of better comfort generates new inventions to avoid discomfort.

The relationship between internal environmental conditions and student achievement is well known. Nevertheless, the ways to improve indoor comfort is not so trivial. Despite all benefits brought by building technology development, there are some psychological and physical issues of school environment such as noise pollution and high level of carbon dioxide emissions that could compromise the quality of comfort in schools. In fact, good indoor climate would decrease the number of illness and improve the productivity of students and more in general for occupants. *Sick Building Syndrome* (SBS) is the new kind of *illness* that hit occupants of buildings, where people suffer from symptoms of illness or feel unwell without finding specific causes.

Considering the energy consumed by building operation on the long period from the economic point of view, the cost of poor building quality is much higher than the cost of the energy used if the same building was made with higher performant materials. In fact, energy consumption in buildings keeps increasing due to the operation of equipment such as ventilation and conditioning systems, heating and cooling. However, some researches show that high energy consumption do not always provide good internal comfort conditions [Butala, Novak, 1998]. Thus, current European and American standards are written in order to satisfy the need of indoor environmental criteria related to the energy consumption calculation, performance and operation of buildings because energy certification has no sense if the qualities of internal spaces are not specified.

Actually, in most of the public school building the quality of internal environment is very low and therefore there is no comfort conditions in the great part of the occupied hours. High levels of noise, inadequate air temperatures, oversized or undersized lighting systems and insufficient equipment are some of the negative effects that affect students' performance, while hygro-thermal conditions, visibility, acoustic and indoor air pollutions are main determiners of internal environment quality and comfort. Ventilation plays an important role in the improvement of internal conditions. Naturally ventilated or poorly ventilated buildings can get very hot in summer period due to the rise of air temperature that could cause illnesses and diseases. On the other side, buildings with mechanical ventilation and active conditioning systems may complain, for instance, the quality of recycled air if it is not filtered properly. In fact, the air cleaning process in mechanical systems should guarantee the elimination of pollutant species and odours, that may be present in moist air of recirculation, but sometimes its functioning is compromised by low maintenance and technical failures. In other situations, internal temperature is too high in winter that occupants have to open window to chill the environment or else, internal temperature decrease too much in summer and light occupants' clothing, based on the external climate conditions, is not sufficient to feel comfortable. Another important aspect related to the ventilation topic is the air infiltration through windows and doors. The infiltration air flux mainly depends on the absence of sealants and gaskets on the edge of windows' frame and it is strictly connected to the external climate conditions, in particular, wind pressure. The presence of draught can cause local discomfort for people set near windows or doors, in particular during winter season, since they are hit by cold and direct air flux.

More in general, comfort of internal environment can be classified as hygro-thermal comfort, acoustic comfort, visual and Illuminance comfort and psychological comfort.

1.2. THERMAL COMFORT

According to the literature, there are two types of thermal comfort related to indoor conditions: *static steady state (or non-adaptive)*, and *adaptive*.

The *static steady state* model, developed by Povl Ole Fanger (July 16th, 1934 – September 20th, 2006) in the late 1960s, is mainly described as a balance between the environment and the human body. This balance is influenced by six variables and the combinations of them generate states of thermal comfort conditions. The variables involved into the calculation are: air temperature, mean radiant temperature, air movement, relative humidity, clothing insulation and metabolic rate, which is related to the type of activity. The empirical evaluation of thermal comfort is provided by the Predict Mean Vote PMV, that indicate, with average approximations, if a group of people exposed to the same environment conditions feel hot, cold or neutral.

Static Steady state, was the first model created by scientists (since it is described by a simple physics relation) and it was suddenly used by standard to give a guideline to building designers. Standard EN ISO 7730 and its previous versions are based on this kind of model.

On the other hand, a new comfort model was developed by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) and explained as *Adaptive comfort approach* in standard ASHRAE 55. Also, in the European code UNI EN 15251, the first part proposes the use of non-adaptive model for building cooled with mechanical systems, while in the second part, it recommends the application of *Adaptive approach* for buildings that use natural ventilation to eliminate thermal loads. In other words, the standard suggests optimizing the building envelope and its orientation considering limitations imposed by the *Adaptive approach* and, where the optimization design is not sufficient, it is possible to add mechanical cooling systems.

The *Adaptive* model is based on the idea that human thermal comfort is strictly related to the thermal condition of outdoor environment: temperature of indoor space depends on temperature of external spaces. Thus, the range of comfort condition is larger in naturally ventilated buildings respect to HVAC conditioned buildings.

The two methods proposed by the literature and used by standards are both correct, but they need to be clarified. The *Non-Adaptive approach* is based on expected comfort conditions of people just entering the room under study, e.g. visitors; while adaptive approach is set on expected comfort conditions of occupants that have being there for longer time, e.g. worker in his office. The model also considers that people adapt very quickly to the bio effluents in a space and less adaptation to odours related to building materials, ventilation pipeline, fans or other chemical pollutant.

Which is the best approach that can be used to guarantee good quality of indoor spaces? The answer is not so trivial. In fact, for theoretically point of view, the best method depends on the type of space and the type of occupants. For example, in a conference room or a theatre, cinema and lecture room, since most of the people enter at the same time it is better to use adaptive approach, even because people adapt in short time to the odour level. Instead, the design of comfort condition of an office room and shops where the people flow is continuous along the working hours, the use of *Non-Adaptive approach* may achieve better results in terms of environmental quality, workers satisfaction and energy saving.

Temperature of human body

Body temperature in homeothermic animals (like mammals and birds), is closely controlled to keep it nearly independent of external environment temperature. This means that human body is able to keep its internal temperature quite constant by changing other variables. Temperature of the body, is associated to human health since ancient time; the awareness of this issue brought scientists of 17th, 18th century to create an instrument able to calculate the temperature variation of the body. Therefore, the first task of thermometer was related to the evaluation of human illnesses and after many years to calculate the temperature of environment. After many experiment and technological variation of this instrument, it was discovered that the deeper internal part of the body was less subjected to the thermal environment fluctuation: thus, human body temperature was not uniform. Its value[1] near the heart and the abdomen, called *human core*, was nearly 37°C. Recently, it was discovered that this value may increase if the body is subjected to a long-term physical effort. The ability of human body and animal to keep internal temperature around a specific value is guaranteed by the thermoregulation process.

Thermoregulation system

Thermal comfort is a combination of subjective sensation and several objective characteristics of the environment. Thermal sensation of human body is regulated by brain and nervous system, that work like a controller: stimulus form the environment are registered, transmitted to the brain, elaborated and sudden, it sends some output signals to specific organs.

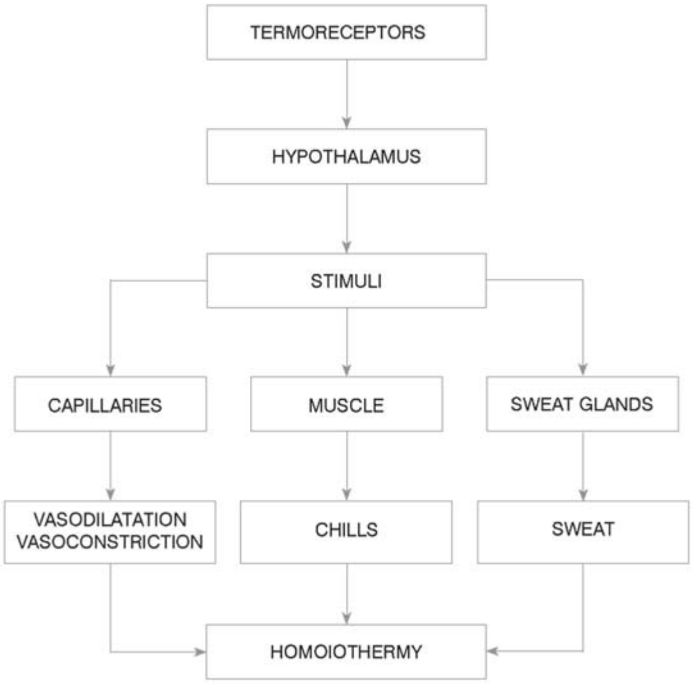
The perception of “cold” or “hot” is permitted by the presence of thermoreceptors placed under the skin that are in charge of transmit thermal inputs (signals) to the brain passing through the nervous system which connects the brain to the rest of the body. These specific thermoreceptors and their nerve endings are called *thermoregulation system*. Once they have received the signal, they act to mitigate the temperature of the body with the temperature of the environment.

Thermoregulation systems or mechanism of human body that permits to have a constant temperature are:

- Natural: physiological granuloma activity[2] or complementary activities like sweating and chills
- Artificial: clothing or modification of environmental thermal parameters.

[1] The measurement was taken with a subject at rest or light activity.

[2] Physiological granuloma activity: involuntary modification of blood flux near the skin (vasodilatation, vasoconstriction). In such way, it is possible to modify the thermal exchange between the body and the environment by the variation of blood flux density and consequently, maintain the temperature of the body equal to 37°C ± 0.5 °C.



Thermal balance of human body

Temperature of human body inside the core[3] must be kept at 37°C with a daily variation of ± 0.5°. This is possible if the metabolic balance or the variation of internal energy ΔU is null; any variation of internal energy can generate an increment (if $\Delta U > 0$) or decrement (if $\Delta U < 0$) of the body temperature; in these cases, thermal regulation system acts on specific organs in order to avoid any variation of internal energy.

Thermoregulation system is responsible of the balance between mechanical energy generated by internal biochemical processes of the body, metabolic rate[4], the thermal flux and work exchanged with the environment. If the balance is satisfied there is no variation of internal energy of human body; thus, the internal mean temperature of the core remains constant.

Even though it is easy to understand, it is difficult at the same time to define the thermal balance by equations. The global balance under steady state conditions considers the human body as an open system that exchange heat with the environment by conduction, convection and radiation. [5]

$$\Delta U = mc\frac{dT}{dt} = \dot{M} - \dot{W} - \dot{Q}_{cond+conv+rad} - \sum \dot{m}\Delta h$$

$mc\frac{dT}{dt}$ is the transient accumulation of energy within the core and the skin masses

$\dot{M}$ is the metabolic rate

$\dot{W}$ is the work being done

$\dot{Q}_{cond+conv+rad}$ is the heat loss to the surrounding by conduction, convection and radiation

[3] Core of human body: it's the central part of the body in which there are placed vital organs.
[4] Metabolic rate: this term indicates the sum of processes inside the human body that transforms the chemical potential energy of food into other forms of energy. Metabolic processes are basically exothermic
[5] Formula taken from the article *Human thermal comfort*, by Isidoro Martinez

$\sum \dot{m}\Delta h$ is the enthalpy loss associated to the mass flow (water exhalation and respiration)

Moreover, the calculation of human body thermal balance be expressed as

$$S = M - W - C - R - K - E_{skin} - C_{resp} - E_{resp}$$

S is the thermal storage

M is the metabolic rate

W is the work done by the subject

C is the heat loss due to convection

R is the thermal loss due to radiation

K is the heat exchanged by conduction

E_{skin} is the evaporation contribution from the skin

C_{resp} is the convective loss due to respiration

E_{resp} is the evaporative loss in respiration

The ideal comfort condition is reached when the balance is verified e.g. $S = 0$ and the temperature of the body is kept constant (steady state condition). Moreover, with this balance it is possible to calculate the clothing insulation requirement in cold conditions and the expected sweating in hot environment.

When $S > 0$ the temperature of the body tends to increase e.g. during summer days.

When $S < 0$ the temperature of the body tends to decrease.

Metabolic rate

According to standard ISO EN 9886 the metabolic rate of human body is related to the heart rate, that correspond to the oxygen consumption or physical work performed during dynamic muscular activity.

$$M = M_0 + \frac{HR - HR_0}{RM}$$

M_0 is the metabolic rate at rest

HR_0 heart rate at rest under neutral thermal conditions

RM increase in heart rate per unit of metabolic rate

HR heart rate calculated as:

$$HR = HR_0 + \Delta HR_M + \Delta HR_S + \Delta HR_T + \Delta HR_N + \Delta HR_\varepsilon$$

HR_0 heart rate at rest, meats per minute

ΔHR_M increase in heart rate due to dynamic muscular load

ΔHR_S increase in heart rate due to static muscular work

ΔHR_T increase in heart rate due to heat stress

ΔHR_N increase in heart rate due to mental load

ΔHR_ε increase in heart rate due to other factors

Metabolic rate is generally measured in Met (1 Met=58.15 W/m^2) and is strictly dependent on the activity level or muscular work: a person under thermal comfort conditions has metabolic rate equal to 1 Met, while sleeping is 0.8 Met, 1.2 Met is generally used for light activity and during sport activity its metabolic rate can reaches values even higher than 10 Met. The total heat loss of human body in comfort condition is nearly 70 W/m^2 (ASHRAE 55-appendix A).

Energy metabolism in children and young people is strictly connected to the activity level of their body that is related with the phases of growth and the development of skeletal and muscular structures. If at early age (0-3 years) the energy metabolism priority is associated to the brain and neural processes, with growth of the muscular system and formation of its functional facilities there is an increase of metabolic energy consumption on kinesis, that takes a great part in the daily energy balance (Son'kin- Tambovtseva, 2012).

For many decades the researchers tried to explain the cause of the variation in metabolic rate of people during their life and in particular what happens in early age that require a higher energy consumption than in the adult age. Some explanations can be related to smaller relative surface of the body of children, growth of relative muscular mass value in adolescent age, lower relative mass of internal organs with a high rate of oxidizing metabolism and many other, but it is the combination of these factors that cause a rise of metabolic rate in young people. In adult age, these mechanisms tend to decrease causing also a reduction of the metabolic rate.

Since the project focus on the secondary school where students' age is between 11 and 15 years, the metabolic rate considered in the further analyses is set on 90 W/m^2 for the sensible heat and 60 W/m^2 for the latent heat, even if they are average values that includes the difference between male and female metabolic rate.

Clothing value calculation

Adaptation is one of the natural characteristics of every living specie of the Earth even if the limits of human adaptability on the environment conditions are quite relevant respect to the other living species belonging to the animal word. Nevertheless, the Evolution of Specie worked in our favour giving to us a superior intelligence, that we used to create by ourselves the instruments to adapt and survive to the specific climate conditions. For instance, many animals are cladded with fur that decrease its density when the external temperature is high and increase its density in winter to keep the body warm. As we know, since the Evolution delated fur from human body, we used to clad our skin with clothing and change them according to the climate conditions. In fact, the normal way to adapt our body to the environment conditions is related to the type of clothes worn. Since clothing reduces the body's heat loss, they can be approximately classified according to their insulation power. The main unit of measurement is the Clo, that stand for m^2°C/W and 1Clo=0.155 m^2°C/W.

The resistance to dry heat loss and evaporative heat loss of clothing is regulated by the standard EN ISO 9920 assuming steady state conditions and examine the influence of body movement and air penetration on the thermal insulation and water vapour resistance.

Some values of thermal insulation of common clothes is shown in the table C.1, Annex C of the standard EN ISO 7730; in addiction, it is reported the calculation method to determine the dynamic insulation characteristic of clothing.

1.3. ILLUMINANCE COMFORT

The light condition of school spaces contributes to improve (or decrease) the level of internal comfort. In particular, it is important to set the correct level of illuminance in classrooms and lecture places, where students spent most of their time. The incorrect setting of illuminance system in workplaces may cause many distribution effects on human sight that could compromise the performance of their occupants. There are many parameters that could affect the quality of light perception such as the position desk and blackboard, the distance respect to the light source and the type of lamp for the artificial light; combined together, these parameters may generate significant discomfort conditions as well as risks for human health. Instead, good lighting provides an appropriate level of illumination for visual performance without any undesired effects as well as improving students' attention. Therefore, in order to enhance visual comfort conditions, it is necessary to apply the source light considering the type of space and the behaviour of occupants.

Light should guarantee an adequate visual comfort to let a correct sight on working desks and form the desk to the blackboard. It is important to consider also the position on the blackboard and windows since in some hours of the day, natural light hit the black surface making the blackboard' writings no more visible from some desk positions. In this case, the classroom should be provided with specific artificial light system, that avoid this disturbing effect.

On the other hand, Lighting can create emotional perception if it is strictly *projected* with architecture. Many architects used the combination of natural and artificial light to generate emotion and sensations in user. The strategy to manipulate the matter and its geometric shape to achieve some architectural emotional targets such as low weight sensation, heaviness, high impact or dynamic animation of spaces have been made with the use of light.

In the end, in particular natural Sun light has a biological function for all the living species of the Earth. Its presence is required to carried out biochemical process that allow the functioning of the physical body.

Natural and artificial light

Good lighting conditions determine the visual comfort and visual performance. Visual comfort is the condition" "where the workers have a feeling of well-being" [EN 12464-2011] and the visual performance is the condition "where the workers are able to perform their visual task, even under difficult circumstances and during long periods" [EN 12464-2011].

These conditions can be achieved by the combination of natural and artificial light, knowing that the result may be affected by geographical zone of the building and the type of clime. In fact, natural light is a "variable" source that is not always available: Sun light can be used during the day but the day hours (and consequently Sun light availability) depends on latitude. It is well known that the number of day hours in countries places near the Poles are subjected to seasonal variation which generates less than five or six day hours in winter and about nineteen in summer season[6]. In addition, the natural light gain may be reduced by climate conditions.

Looking at the past, the importance of Sun light was a common knowledge so that ancient populations turned the Sun into a god with human appearances; its cult was very important for many civilizations from

[6] The number of day hours described in the paragraph are relate to the Norwegian city Bergen and the hours of natural light are calculated in January and July where the peak have been registered.

Africa, South and Central America and Middle East. In fact, solar light was one of the primary source for agriculture, sowing and farming; in addition, it determines the daily routine of human activities because it was the unique free lighting source respect to oil lamps and candles, whose fuels were expensive.

There is also an indirect effect of Sun light on people; many studies and researches investigated psychological effects of natural light on human body and demonstrate that it has a positive influence on human psyche so that it could determine the performance of workers in some specific cases (even if the cause of this relation are not so clear). One of the possible explanation on why we are keener on natural light and not on artificial one has ancient origins. Since the human sight has evolved during millions of years under the influence of the Sun, the use of natural light may enhance visual comfort for occupants and contribute to improve their well-being. This is well known by many architects that sometimes focus the design of the whole project on the interaction between matter and natural light to add spatial quality on internal environment. This additional space quality derives from the presence of windows, openings towards the outside and glazed surfaces. If windows are correctly dimensioned, the sight of the external environment may contribute to enhance the quality of internal spaces, providing also positive sensation for occupants.

From the optimization point of view, since the solar light depends on the solar path, the orientation of the building is also relevant. According to the climate and geographical zone, the position of the building, respect to the solar track may affect the amount of natural light gained during the year. Designer should maximize the natural light gain in order provide a good quality of internal environment, but also achieve energy saving. This ambition is well defined by technical data reports of CIE: International Commission on Illumination[7] on which standards regarding light and lighting are based. The Commission aims to increase the energy efficiency and decrease the energy expended by artificial lights, while improving the illumination quality of internal spaces. In fact, artificial lighting system is required when natural light is not able to satisfy the needs of visual comfort and visual performance. All type of building need the prescience of artificial light system to guarantee visual conditions and the continuity of activities at any time of the day; but opposite to natural light, the use of artificial light increases the energy expended by the building and increase the operation costs. Thus, it is important to design the lighting environment in order to exploit natural light as much as possible and set good artificial light system keeping the quality of the environment and visual comfort among the targets of the project.

Light quality and light parameters

However, the concept of quality is not related to unique light characteristic, but it may include many aspects on light parameters and their effects on the surrounding object and people. Therefore, visual comfort is reached when there is a well-balanced combination between light characteristics.

The traditional setting of light quality is based on the illumination level inside the room and on the correct brightness distribution to avoid problems related to glare and light reflection; also, it may include some light characteristics such as colour and rendering and it must be not too diffuse or not too directional because it may annoy occupants. It is clear that the balance between these characteristics is very difficult to assess; in particular for buildings used by many people which have different personal visual comfort expectation.

[7] *Light quality and energy efficiency* was the title of the international conference organized by CIE in 2014 to establish energy calculation criteria for lighting systems.

Since it is impossible to achieve a 100% of satisfaction, nowadays, the concept of light quality is changed. The possibility to control light parameter by users is one of the key-process of the new approach to guarantee visual comfort in buildings like schools and offices. Moreover, energy efficiency, daylight integration and the use of light as interior design elements contribute to enhance the quality of the space.

The distribution of light (natural or artificial) inside a classroom o working place affect visibility of occupants and mainly determines the visual comfort condition. The strength of a light source, according to literature, can be described in terms of *Luminance* and *Illuminance*.

Luminance [cd/m^2] is the amount of light re-emitted from a specific surface area that varies with solid angle. This measurement is strictly dependent on incident angle ray-surface. Too high luminance could generate problems of glare and light reflection on item surfaces, while too low luminance could affect the visual definition.

Illuminance measures the amount of light that hit a specific surface. For specific visual tasks the designer must evaluate the *illuminance* level [lux or lumen/m^2] on the area in which activity may takes place, considering all the geometric characteristics of the area and its type of materials and finishing. Moreover, the illuminance level in the surrounding areas have to be evaluated in order to determine the presence of barriers to light rays or reflection and glare effects. Here, illuminance may be one level lower than in the visual task area. These parameters are described by the Standard EN 12464 *Light and lighting, Lighting of workplace -Part 1: indoor work places.*

Illuminance on the task area	Illuminance on immediate surrounding areas
E_{task} lux	lux
> 750	500
500	300
300	200
200	150
150	E_{task}
100	E_{task}
< 50	E_{task}

Table 1 Relationship of illuminance on immediate surrounding to the illuminance on the task area

The standard shows also and another important parameter, *Illuminance Uniformity* U_0 that indicates the ratio of the minimum illuminance and the average illuminance on a surface:

$$U_0 = \frac{E_{min}}{\bar{E}}$$

Standard UNI EN ISO 12464 suggest using Illuminance Uniformity values of ≥ 0.4 in the immediate surrounding area, but it may change according to the type of occupants' activity.

Visual comfort and visual performance can be influenced also by *colour temperature* and *light rendering*. The *light colour* describes the colour appearance of the light rays on surfaces and it is measures as a temperature [K]. Moreover, the variation of this parameter changes the room's atmosphere and consequently, may be used to create suggestive and emotional effect. The choice of light temperature is not so trivial since the incorrect colour could generate bad sensation of occupants; it depends on the type building and the activity for which the room has designed, but also on the culture of occupants and their behaviour.

Standard divides light temperature (or colours) into three categories: warm intermediate and cool.

Colour appearance	Correlated colour temperature T_{CP}
Warm	< 3300 K
intermediate	3300-5300 K
Cool	> 5300 K

Table 2 Lamp colour appearance groups

Colour rendering index is a method to measure and specify Colour Rendering properties of light sources compared to natural light or a reference light source. CRI values are included into a range 0-100, where the maximum value (100) means that all colours illuminated by a specific light match perfectly the sample colours.

Problems of glare

High intensity light source may create disturbing effects like glare and reflectance on surfaces. In many classrooms, offices and conference rooms or sport arenas, the position of light system on the ceiling combined with an incorrect lamp choice can and generate overhead glare that cause visual fatigue, eye strain and disturbs of human sight.

According to standard EN 12464, glare can be classified in two categories: discomfort glare and disability glare. Discomfort glare generates annoying feeling without decrease sight performance, but it is a subjective phenomenon that hasn't been directly linked to a physiological cause. On the other hand, disability glare affects visibility performance and the optical resolution, causing temporary blindness.

As a subjective property, the evaluation of overhead glare is achieved by tests that require the presence of people; during the experiments they are asked to regulate light intensity or declare if certain light conditions are comfortable or not [*Ling, Yan, Liu, Wang, Peng, Knoop, Heynderickx, 2011*]. Among the approaches proposed by literature there are some efficient methods such as tuning the target luminaire luminance relative to the reference criterion of comfort, rating and categorization of comfort that are frequently used in the evaluation of discomfort glare.

Moreover, the analytical evaluation of glare can be done using the international index *Unified Glare Rating* UGR (developed by CIE in 1995) which shows the correlation of glare from all visible lamps and he background illumination of the room. According to standard EN 12464, the URG value is calculated as:

$$UGR = 8\log_{10}\left(\frac{0.25}{L_B}\sum\frac{L^2\omega}{p^2}\right)$$

Where

L_B is the background luminance [cd/m^2]

L is the luminance of the luminous parts of each luminaire in the direction of the observer's eye [cd/m^2]

ω is the solid angle of the luminous part of each luminaire at the observer's eye

p is the Guth position index[8] for each luminaire (displacement from the line of sight)

The UGR index is valid for light sources characterized by a projected area between 0.005 and 1.5 m^2. If the source has a bigger or smaller projected area, the UGR index would be underestimated or overestimated. Another limitation of the equation lies in the *Guth Position Index p* which must be approximately 60° above the point of fixation, but in general, this is one of the most reliable and analytical method for indoor glare.

The equation works out results in the range from 5 to 40; the following table, from Standard 12464, proposes a correlation between UGR value and discomfort glare effect generation.

UGR	Discomfort Glare Criterion
≤10	Imperceptible
13	Just perceptible
16	Perceptible
19	Just acceptable
22	Unacceptable
25	Just uncomfortable
≥28	Uncomfortable

Table 3 Discomfort glare assessment

Type of area, task or activity	E_m	UGR	U_0	R_a	specific requirements
Classroom, tutorial room	300	19	0.60	80	Light should be controllable
Auditorium, lecture hall	500	19	0.60	80	Light should be controllable to accommodate various A/V needs
Practical rooms and laboratories	500	19	0.60	80	
Entrance halls	200	22	0.40	80	

Table 4 Lighting requirement for interior area, task and activities: educational building

[8] is based on two angles: α that is the angle from vertical of the plane containing the source and the line of sight in degrees and β which is the angle between the line of sight and the line from the observer to the source. The Guth position index is expressed as:

$$P = exp\left[\left(35.2 - 0.31889\alpha - 1.22e^{-\frac{2\alpha}{9}}\right)10^{-3}\beta + (21 + 0.26667\alpha - 0.0029663\alpha^2)10^{-5}\beta^2\right]$$

1.4. INDOOR AIR QUALITY (IAQ)

The Air Quality of Internal environment (IAQ) is affected by the presence of pollutant species and toxic agents, chemical, physical or biological which can be dissolved in the air or can settle on wall surfaces, ceiling and floor. If the concentration of one pollutant specie reaches the threshold value, it may generate unhealthy condition of the closed environment and may decrease indoor comfort conditions for occupants.

In order to save energy, the envelope is becoming more and more *impermeable* to thermal fluxes. This means that the new design concept would limit the exchange of air to the outside and infiltrations. In this way it is possible to control and reduce part of the heat lost by ventilation during winter and part of heat gains in summer. If there is no air flux exchange (and therefore heat gain/loss) through the building envelope, the indoor air quality would be compromised. Thus, regulations impose a minimum ventilation rate in order to guarantee a healthy internal air quality, considering in the energy calculation of the building the thermal energy associated to ventilation.

Problems related to low Indoor Air Quality

In many buildings where the ventilation process is not working or not designed properly there could be low indoor air quality conditions. Basically, the low IAQ creates damage to human health and damage to the building itself since the presence of pollutant and high level of relative humidity can deteriorate building materials.

Many studies on human health demonstrate that bad air conditions generate several types of illness related to respiratory track and olfactive apparatus. In fact, these parts are more subjected on toxic agent attack due to the thin membrane, that cover the respiratory tract and due to its large surface. Among the non-fatal pathologies there are seasonal allergies and intolerances which affect most part of people who live in big towns and many children; but if people have been exposed to polluted environment for long, these illnesses can degenerate into serious disease. Ictus, obstructive pulmonary and lung cancer are the fatal-illnesses, that cause death. In fact, these pathologies are recognized as human disease of 21-century and affect in particular the people in the Third-Word where the condition of both external and internal are very low, since air filters are not used for any device that works with solid fuel.

Moisture accumulation is the main consequence of the absence (or low rate) of ventilation air change and it is the first cause to building deterioration. In fact, the presence of moisture increases the internal relative humidity and accumulation of biological species that cannot be expelled to the outside environment. The combination of these aspects may create damages to construction elements such as water condensation on internal surfaces, chemical deterioration and dissolution of weak materials like gypsum, discoloration of finishing, volume change, swallow, shrinkage that could create degradation of appearance, cracking or structural failure and the growth of biological forms such as mould, plants and dust mites (Straube John, 2012).

Type of pollutant agents

Internal air is full of different kind of pollutant substances. There isn’t a unique source of them since their chemical structure is composed by many chemical species. In fact, there are thousands of pollutant compounds dissolved in air and most of them fatal for humans; luckily, their concentration in normal environment (residential, office, commercial buildings, schools) is not so high to cause damages to people, but there are situations in which it may increase or there are places where the operation of a particular devices generate toxic substances, that can be inhaled by workers.

Among pollutant chemical spices present in the air, VOCs (volatile organic compounds) are one of the most common in residential and light work environment like schools and offices. They are emitted by furniture finishing or furniture structure, cleaning and spry products or by inefficient exhaust pipelines. All these compounds are classified in VOC category, since they contain carbon and to identify as *normal-environment* pollutant.

The following tables show properties, the Average Limit Value (VME) and the World Health Organization (WHO) of the most common pollutant substances.

Name	Carbon dioxide
Chemical formula	CO_2
Property	Uncoloured gas
Molar mass	44 g/mol
Source	- Heating systems in buildings: 1 g of burned carbon produces 1.9 l of CO_2 - Human breath: 15-20 l/h for light bench work (office)
Effect	PH variation if it is introduced inside the human body
Limit values	WHO: 0.15% (1500 ppm) VME: 0.5% (5000ppm)

Name	Carbon oxide
Chemical formula	CO
Property	Uncoloured gas
Molar mass	28 g/mol
Source	- Environment and water eating systems
Effect	Oxygen reduction in the space; it can cause headache, dizziness, nausea
Limit values	VME: 35 g/m^3 WHO: 10 mg/m^3 (8h), 30 mg/m^3 (1h), fatal 1400 mg/m^3

Name	Nitric oxide
Chemical formula	NO
Property	Uncoloured gas
Molar mass	30 g/mol
Source	- Cooking systems - External air
Effect	Irritation of respiration track
Limit values	WHO: 40 µg/m^3 VME: 30 mg/m^3

Name	Toluene
Chemical formula	C_7O_8
Property	Uncoloured liquid
Molar mass	92.1 g/mol
Source	- Painting, ink, finishing, cosmetic products
Effect	Temporary damages to the nervous system and brain; it causes nausea and hemicrania. It is also dangerous to liver and kidneys

Limit values	VME: 190 mg/m^3

Name	Benzene
Chemical formula	C_6H_6
Property	Uncoloured liquid
Molar mass	78.1 g/mol
Source	- Engine, wood combustion - Solvent for painting, plastic material, synthetic rubber and drugs
Effect	Organ tumours, leukaemia
Limit values	VME: 3.2 mg/m3

Name	Formaldehyde
Chemical formula	HCOH
Property	Uncoloured gas
Molar mass	30g/mol
Source	- Synthetic resin, furniture finishing - Insulation foam
Effect	Eye and respiratory track irritation, headache, skin disease, asthma
Limit values	WHO: 100 µg/m^3 VME: 0.37 mg/m3

Name	Asbestos
Chemical formula	-
Property	Silicate mineral
Molar mass	30g/mol
Source	- Building and civil construction elements
Effect	Lung cancer, mesothelioma and asbestosis (pneumoconiosis)
Limit values	WHO: 1 to 4 x 10^{-5} for 100 fibres

Name	Radon
Chemical formula	Rn
Property	Uncoloured gas
Molar mass	210 g/mol
Source	- Spread in the earth
Effect	Respiration track tumours
Limit values	WHO: 40 µg/m^3 VME: 30 mg/m^3

Relation with ventilation

It is possible to enhance the lever of internal air quality by setting the ventilation system correctly. In this way pollutant species present in the air like CO_2 and odours are eliminate or at least reduced.

The calculation of the amount of air needed by the room depend by many factors such as the occupancy rate, the kind of work done, the efficiency of the ventilation system and so on.

The ventilation flow rate can be calculated as

$$\dot{V} = ACH \ \cdot V = \frac{\dot{m}_{int}}{\rho_{i,max} - \rho_e} \left[\frac{m^3}{h}\right]$$

Where

V is the volume of the room

ACH are the number of air-change generally imposed by standard

$\rho_{i,max}$ is the maximum concentration of a pollutant specie of the internal environment

ρ_e is the concentration pollutant specie of external air

Form the equation above, it is possible to calculate the air flow rate required to eliminate a specific pollutant agent (air density=1.2 kg/m^3).

CO_2:

$$\dot{V} = \frac{\dot{m}_{int}}{\rho_{i,max} - \rho_e} = \frac{38000 \ mg/h}{(1500 - 350) \cdot 1.83 \ mg/m^3} = 18 \frac{m^3}{h}$$

Odours:

$$\dot{V} = \frac{\dot{m}_{int}}{\rho_{i,max} - \rho_e} = \frac{1 \ olf}{(0.3 - 0.1) pol} = 5 \frac{l}{s} = 18 \frac{m^3}{h}$$

Water vapour:

$$\dot{V} = \frac{\dot{m}_{int}}{\rho_{i,max} - \rho_e} = \frac{72 \ g/h}{(7 - 4) g/kg} = 24 \frac{kg}{h} = 20 \frac{m^3}{h}$$

1.5. PSYCHOLOGICAL ASPECTS

Comfort design in school buildings is a requirement that corresponds to the natural need of wellness and the necessity to feel comfortable sensations from internal environment.

The reaction of human body in specific internal conditions does not provide only physiological reaction, but is a mirror of all body variables that are stimulated by this specific environment condition. Therefore, it is possible to identify some areas of human body such as neurological, visceral, cognitive and behavioural, which are more sensible to comfort variation.

People can receive stimuli thanks to the sensorial experience that they earned by the environment and elaborate by the five senses: sight, hearing, smell, touch and teste. All of them are involved into the environment evaluation even if their reaction can be very different or even neutral in some cases.

The sight is the sense more stimulated when a person enters in a new space, since its cerebral area is the most extended among the five senses. In fact, visual perception can influence the brain functioning and the thoughts generations. Therefore, it is necessary to improve the aesthetic quality of internal environment and provide a good illumination in work places (desks and blackboard) that is translated into the balance of natural and artificial light to encourage students' attention. Moreover, all physical space characteristics such as geometric shapes, volume and colours can affect human sensation and generates situation of high stress or negative impressions.

Noises from external environment or adjacent rooms or else from building system operation can disturb the classroom atmosphere and distract students' attention. Nowadays, the awareness of effects on students' performance generated by the presence of acoustic noises has no more been underestimate in school building projects. In fact, building renovation tends also to improve the acoustic insulation of spaces used for lectures.

The best indicator of indoor air quality is the smell. Smell is the weakest sense since it can be alternated by mild illnesses, but it is very important in the evaluation of air quality. The presence of pollutant species can generate some temporary discomfort situations. In particular, school buildings may suffer of poor ventilation air change that contribute to accumulate a big quantity of organic pollutant in the moist air (very annoying for people that enter in the space for a while). Fortunately, the adaptation of human smell to organic pollutions is relatively fast and the annoying odours are no more precepted after few minutes. One of the most relevant organic pollutant specie is the carbon dioxide CO_2 generated by human respiration process. Relatively high concentration level of CO_2 could generate breathing trouble, but also it can cause drowsiness and consequently a reduction of students' attention. On the other hands, smell's sensorial cells are more susceptible to chemical species that are present in air, therefore it is more difficult to adapt on this kind of odours.

Hygro-thermal characteristics of internal environment are felt by human body and they give an important part of comfort evaluation. Sensation of too cold or hot environment can be picked up thanks to the presence of sensorial cells placed on the skin. In particular, this sensation in school buildings derives from the contact of the skin body with furniture like chairs and desks. In fact, their temperature is strictly connected with air temperature of the environment. Thus, it is important to regulate hygro-thermal characteristics of internal spaces in order to improve occupants' comfort.

The taste, intended as aesthetic sense of architectural beauty, takes into account the sphere of emotions and the involuntary though system. Many studies made on this filed try to evaluate the influence of the good quality of architecture on students' performance [Beate Weyland, 2016]. Results show that classroom made with particular attention in the finishing and geometrically balanced contribute to improve students' achievements of about 6%.

The awareness of all these aspects have to be taken into account in the development of school building projects. In the last year, the sensitization of designers on the comfort achievement is getting results. In fact, even if the construction of public buildings must respect specific financial aspects, designers work in order to create strategies to achieve a good level of comfort condition, while containing costs.

CHAPTER

2

Methodology and project goal

2.1. METHODOLOGY

This work aims to define some interventions for building renovation, by the application of passive and active strategies, to improve internal comfort condition and reduce the energy consumption of the secondary school Piero Mascagni in Melzo (MI), used as a case study. The analyses investigate the relation between internal comfort achievement in school classrooms and the energy used by the systems to improve it in order to establish if the improvement of comfort, according to the building envelope renovation, implies an increase of energy consumption or not. The intervention of building renovation has been analysed form the economical point of view to calculate the initial cost of construction and the payback period. In the end, the interventions analysed have been compared together taking into account the level of internal comfort, the amount of primary energy consumed by the systems according to the characteristics of the envelope and the cost of construction. This comparison can be a useful instrument that contractors, public commission or clients can use as a technical support to establish which is the best intervention of renovation among the possible choices, according to their main target. They can choose the less expensive intervention or the one that guarantees the highest level of internal comfort or else, the intervention that consume less energy. Thanks to this instrument, contractors or clients are free to choose the intervention that they want according to a specific parameter (e.g. the lowest energy consumption) knowing the effects provided by this choice on the other parameters (e.g. comfort level or construction costs).

Passive strategies taken into account for the building envelope renovation are related to the improvement of thermal performance; therefore, the original structure of the building and its masonry are kept equal to the baseline construction and insulation layers have been added on the external/internal surfaces of the envelope components. The outputs, in term of primary energy, underline that the application of these interventions provide significant decrease of the energy consumption. Despite the good results obtained by the implementation of passive strategies, further optimizations are still possible. In fact, it is considered to apply some active strategies that aims to improve the thermal efficiency of conditioning and distribution systems. The original heating system for winter season, that is composed by traditional boilers and old ducts, has been substituted with a new one more efficient and eco-friendly among the possible technologies available on the market; moreover, the simulations on this issue consider the use of chillers to cool down the spaces in summe,r even if the original building doesn't have it. The results of these analyses underlined again a significant reduction of the primary energy consumption.

After the application of passive and active strategies for the building renovation, the period of systems operation has been assessed in order to achieve a good level of internal comfort condition. The schedule optimization for the heating and cooling systems and the use of natural ventilation in some period to cool down internal air demonstrate that comfort level has increased, and the energy consumption of the building has been reduced.

Comfort analyses have been provided according to the static approach showed by the standard UNI EN ISO 7730 considering the operation of heating system in winter, cooling system in summer months and natural ventilation during the middle and the cooling season. Moreover, the same building has been analysed according to the adaptive approach described by the standard EN 15251. In this case, chillers have been substituted by natural ventilation in summer months, May, June and September. The main parameter taken into account during the analyses are the hygrothermal characteristics of the thermal zone under study. Acoustic, illumination and fluid dynamics aspect were not taken into account during the simulation in order to have slender calculation, even if they are important aspect that should be considered to get a more reliable result. Also, measurements on internal air quality has not been provided because such variables must be directly measured on site since they deal with real people, specific type of furniture and real quality of external air that can pollute internal air and affect its quality.

All the simulations have been done with IESve software and based on a three-dimensional model building in AutoCAD. The output of each simulation has been handled in Excel in order to collect the most important data into charts and tables.

2.2. Evaluation of internal environment: reference standards

Indoor thermal comfort is among the most important factors that affects occupants' well-being, health and the quality of their work in buildings. Since people spend most of their time in buildings like schools and offices and do their main activities there, it is important to guarantee good comfort conditions. For these reasons, standards impose specific parameters for indoor environment according to seasonal climate variation (related to the geographic position of the building), type of occupants and activity, clothing insulation and special requirements.

Workplace such as office and service sector buildings, schools, university campus and all other types of building not interested by a specific indoor environment can be projected according to standards for internal comfort, UNI EN ISO 7730 and EN 15251 valid in Europe and ASHRAE 55 for Unit States. These three regulations speak about thermal comfort with different approaches since they were not written in the same period; therefore, their methods to achieve comfort conditions is based on different specific goals.

Thermal stress for workplaces subjected to high temperature due to the presence of specific machineries (like metal factories or similar) can be assessed with method shown in standards EN ISO 7243 and EN ISO 7933. Moreover, standard ISO TS 14415 gives further information about indoor comfort conditions for people with special requirement and disabilities.

UNI EN ISO 7730

European Standard UNI EN ISO 7730 shows an analytical method to calculate the *static steady state* thermal comfort or discomfort of occupants exposed to the specific thermal conditions. It is applicable to many environment conditions where occupants' activity can be assumed as light work, like offices, school and residential. Methods explained in the standard consider that it is not possible to guarantee comfort condition for everyone; thus, it gives a rage of acceptable values that minimize the value unsatisfied people.

The evaluation of internal environment is done by using some indicators according to the micro-climate local conditions such as the Predict Mean Vote, PMV and the Predicted Percentage of Discomfort, PPD which are also called Fanger's indicator since he was the father of static comfort and their creator.

Predicted Mean Vote, PMV

This index is used to identify the thermal sensation of a large group of people exposed to the same environmental conditions. It is set on a 7-points scale (from +3 to -3 considering also 0) in which the evaluation is based on the thermal balance between human body and the heat losses to the environment. Negative values are referred to the perception of cold temperature and lower is the number, colder is the environment. On the other hand, positive numbers stand for hot conditions. Comfort is reached when the PMV is close to zero.

According to the standard UNI EN ISO 7730, PMV can be calculated for different metabolic rates as+:

$$PMV = [0.303 \cdot \exp(-0.036 \cdot M) + 0.028] \cdot \left\{ \begin{array}{c} (M-W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-W) - p_a] - 0.42 \cdot [(M-W) - 58.15] \\ -1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) \\ -3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - f_{cl} \cdot h_{cl} \cdot (t_{cl} - t_a) \end{array} \right\}$$

Where:

M is the metabolic rate [W/m^2]

W is the effective mechanical power[W/m^2]

i_{cl} is the clothing insulation [m^{2}K/W]

f_{cl} is the clothing surface area factor+

t_a is the air temperature [°C]

t_{mr} is the mean radiant temperature [°C]

p_a is the water vapour pressure [Pa]

h_c is the convective heat transfer coefficient [W/m^{2}K]

t_{cl} is the clothing surface temperature [°C]

PMV scale evaluation	
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table 5 Seven-point thermal sensation scale

The acceptable limit imposed by the standard depends on three categories of expected comfort, where the evaluation sample is done on an ideal human with average thermal sensibility. The evaluation doesn't take into account specific situation that can affect human thermal balance.

PPD

PPD is an index used to predict the mean value of thermal evaluation of a large group of people living in the same indoor environment conditions and it is based on PMV. This value determines a quantitative prediction of the percentage of satisfied and not satisfied people who feel too warm and too hot. It is developed to be applied on stationary conditions

[8] and for relatively moderate environment like closed spaces for human activities.

PPD is calculated as

$$PPD = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.217 \cdot PMV^2)$$

The method can be applied when boundary conditions of the considered environment match the following parameters:

PPD boundary condition characteristics		
M	0.8 ÷ 4	met
I_{cl}	0.0 ÷ 2	clo
θ_i	10 ÷ 30	°C

[8] It is also possible to apply this method when there are variation of internal parameters such as variation of temperature and relative humidity, as long as the variation range is small compared to the value itself.

θ_{mr}	10 ÷ 40	°C
v_r	0.0 ÷ 1	m/s
P_v	0.0 ÷ 2700	Pa

Table 6 PPD boundary conditions

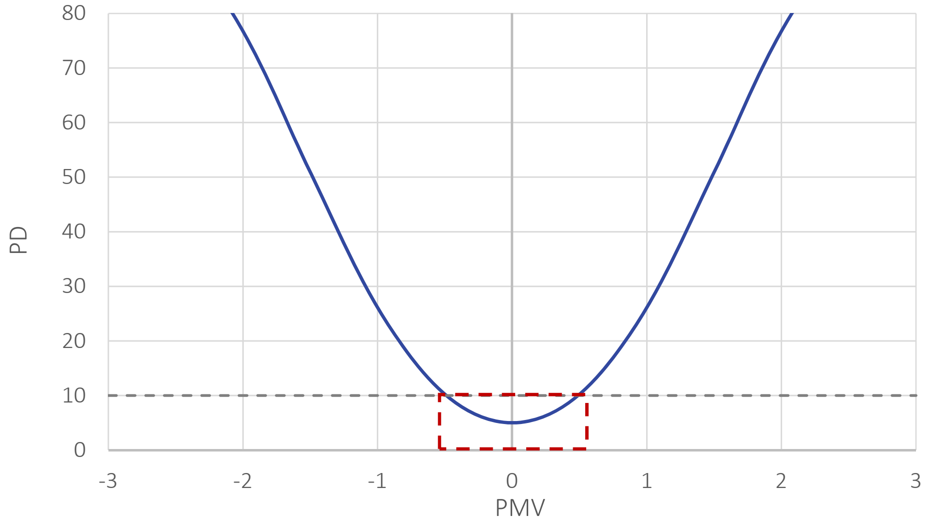


Chart 1 PPD as a function of PMV and comfort area (red desh-line)

Local thermal discomfort

After the analyses on general thermal comfort, the standard focuses on the evaluation of local discomfort which can be a disturbing factor for occupants. These situations are generated by a non-uniform distribution of thermal parameters inside a closed indoor space, considering both vertical and horizontal variations and the type of activity done by occupants. Local thermal discomfort is generated when there is a significant variation of one of thermal parameters such as ambient temperature T_a, mean radiant temperature T_{mr} relative humidity of the ambient φ_a and air velocity v_a.

The local thermal discomfort conditions can be associated to

- *Draught*: that is generated by the presence of a cold/hot air flow generally near windows, other kind of apertures or devices that create air movement. The model can be applied to people at light activity level, for the whole body close to neutral and for prediction of draught at the neck.

$$DR = (34 - t_{a,I})(v_{a,I} - 0.05)^{0.62(0.37 \cdot v_{a,I} \cdot 0.4 + 3.14)}$$

- *Vertical air temperature difference:* due to the difference in precepted temperature between ankles and the head.

$$PD_v = \frac{100}{1^{5.76 - 0.856 \cdot \Delta t_{a,v}}}$$

- *Warm or cool floor:* in this case the precepted temperature is generated by too high/low surface temperature of the floor and the ceiling.

$$PD = 100 - 94^{-1.378 + 0.118 \cdot t_f - 0.0025 \cdot t_f^2}$$

– *Radiant asymmetry:* it is caused by the radiant variation in most cases related to the transmitted solar rays or by radiant devices such as radiant floor or ceiling.

$$PD_{warm\ ceiling} = \frac{100}{1 + e^{2.84-0.174 \cdot \Delta t_{pr}}} - 5.5$$

$\Delta t_{pr} < 23°C$

$$PD_{cool\ wall} = \frac{100}{1 + e^{6.61-0.345 \cdot \Delta t_{pr}}}$$

$\Delta t_{pr} < 15°C$

$$PD_{cool\ ceiling} = \frac{100}{1 + e^{9.93-0.50 \cdot \Delta t_{pr}}}$$

$\Delta t_{pr} < 15°C$

$$PD_{warm\ wall} = \frac{100}{1 + e^{3.72-0.052 \cdot \Delta t_{pr}}}$$

$\Delta t_{pr} < 35°C$

Where

$t_{a,I}$ is the local air temperature °C

$v_{a,I}$ is the local mean air velocity m/s

$\Delta t_{a,v}$ is the vertical air temperature difference between the head and feet °C

t_f is the floor temperature °C

Δt_{pr} is the radiant temperature asymmetr

EN 15251

European standard EN 15251 is extremely wide. It tells about thermal comfort in different way respect to the older UNI EN ISO 7730, since it considers also the adaptation of human body to the environment conditions.

EN 15251 is useful asses thermal comfort of new buildings with and without mechanical cooling systems and to evaluate the occupants' satisfaction in existing buildings according to the type of activity, type of climate and national differences. It was developed by the European Union in order to decrease the energy consumption in building field according to directive 2002/91/CE, which explains that more than 30% of the total energy is used by building systems. Therefore, the aim of the standard is to provide criteria to assess internal comfort condition and well-being by extending the comfort range and changing occupants' behaviour. In this way, the system operation time can be reduced and consequently their energy demand.

In the first part, EN 15251 brings together existing information about indoor comfort conditions, considering, in particular, the optimization of thermal comfort, air quality, acoustic characteristics and visual comfort; in this way, designers can take into account many aspects in their calculation working out more reliable results. In the second part, it considers the difference between mechanical ventilated (Fanger model) and naturally ventilated buildings (adaptive model) and the expectations of their occupants.

The design input criteria for dimensioning of buildings, heating, cooling, mechanical and natural ventilation systems start considering the thermal environment condition of spaces. The evaluation is done with the calculation of PMV, PPD and local thermal discomfort indices explained by UNI EN ISO 7730 for building with mechanical heating/cooling systems and without mechanical cooling systems instead of using air temperature as a main design parameter. Also, it considers the influence of indoor air quality and the ventilation rates, independent of season. The design of ventilation systems and required ventilation rates should be done according to national regulations, which are different from residential and non-residential buildings, considering also the presence of infiltrations and air cleaning process. In the end, the system design criteria must consider the effect of humidity, lighting environment especially for non-residential buildings and noise control of HVAC that UNI EN ISO 7730 does not take into account. The following tables show the parameters purposed by the standard to achieve the minimum lighting and acoustic comfort.

Type of building	Space	Maintained illuminance Em at working areas, lux	UGR	Ra	Remarks
Office building	Single office	500	19	80	at 0.8 m
	Open plan office	500	19	80	at 0.8 m
	Conference room	500	19	80	at 0.8 m
Educational building	Classroom	300	19	80	at 0.8 m
	Classroom for adult education	500	19	80	at 0.8 m
	Lecture hall	500	19	80	at 0.8 m

Table 7 Design illumination levels

Building	Type of space	Sound pressure level [dB(a)]	
		Typical range	Default design value
Office	Small office	30 to 40	35
	Conference room	30 to 40	35
	Landscape office	35 to 45	40

	Office cubicles	35 to 45	40
School	Classroom	30 to 40	35
	Corridor	35 to 50	40
	Gymnasium	35 to 45	40
	Teacher room	30 to 40	35

Table 8 Design A-weighted sound pressure level

To perform energy calculation according to the standard EN ISO 13790 the internal environment conditions must be specified, in particular thermal conditions. Moreover, the energy assessment has been done considering the internal air quality and the minimum ventilation rates imposed by national regulations because they provide thermal losses. Since occupants' thermal comfort expectation in natural ventilated buildings is different from the conditioned buildings, the standard proposes two criteria for systems dimensioning. Buildings with mechanical ventilation should be ventilated during unoccupied hours with a minimum ventilation rate and increase when the building is occupied. If the ventilation system has a variable flow, the ventilation rate should vary from the minimum to maximum value according to the amount of pollution, moisture and thermal load. On the other hand, building naturally ventilated should guarantee the minimum air change during the occupied hours by using manual tools such as windows and openings.

Moreover, for non-residential building such as offices and schools, the standard requires the calculation of energy demand associated to lighting systems since they are not dependent by season and a minim illumination should be guaranteed in every space of the building.

The long-term evaluation of internal environment can be with some indicators. This evaluation can be a good instrument to consider the evolution of the indoor quality along the year, since occupants' comfort conditions and satisfaction decrease with time. This effect can be connected to a decrease of building/systems performance, low maintenance or can be a physiological effect of human mind that tends to achieve the best comfort conditions everywhere. Therefore, standard EN 15251 purposes various indicators in charge of evaluate internal environment such as degree hours, weighted PMV-PPD and others.

ASHRAE 55

Standard ASHRAE 55, currently used in USA, describes comfort conditions of indoor environment according to the type of occupants and their activity and give information to evaluate the internal condition for existing buildings where light activity is done. It specifies the "combinations of indoor thermal environment factors and personal factors" [ASHRAE 55] to achieve thermal comfort conditions that satisfies most of the occupants inside the thermal zone. In addition, the limits described can be applied not only for buildings, but also for other environments such as public and private transportation, where people activity is light. Like the European codes, the standard does not take into account specific cases like extremely thermal environments or comfort condition for special spaces like surgery rooms and hospitals, which are regulated by other standards, since their requirements are more restrictive.

As already explained in the European standards, comfort condition is determined by the combination of physiological and psychological aspects and they are not the same for everyone. The metabolic rate (1.0-1.30 met), clothing insulation (0.5-1.0 clo), air temperature, mean radiant temperature, air speed and humidity are the main factors that can significantly influence occupants' comfort sensations, even if it can be affected by expected conditions. One of the limits of this standard is related to the application of these factors only in a steady state condition.

The evaluation of comfort conditions is regulated by the Predict Mean Vote and by the Percentage of Discomfort people, whose calculation is the same explained into UNI EN ISO 7730, giving also some information about the relation between these two factors. In addition, it considers the use of thermophysiological simulations to assess comfort conditions during the design process. In this case, the combination of design thermal parameters such as operative temperature, air speed, PMV and clothing insulation must fall into the comfort range imposed by the graphical method of the standard.

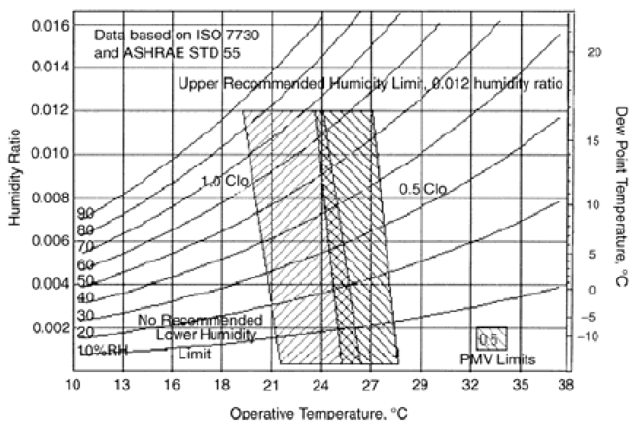


Figure 1 NON-ADAPTIVE APPROACH: Operative temperature from ASHRAE 55 mechanically ventilated building

$$T_{min,Icl} = \frac{[(I_{cl} - 0.5\ clo)T_{min,1.0clo} + (1.0\ clo - I_{cl})T_{min,0.5\ clo}]}{0.5\ clo}$$

$$T_{max,Icl} = \frac{[(I_{cl} - 0.5\ clo)T_{max,1.0clo} + (1.0\ clo - I_{cl})T_{max,0.5\ clo}]}{0.5\ clo}$$

Where

$T_{max,Icl}$ upper operative temperature limit for clothing insulation I_{cl}

$T_{min,Icl}$ lower operative temperature limit for clothing insulation I_{cl}

I_{cl} thermal insulation of the clothing in question (clo)

ASHRAE 55 considers also the influence of local thermal variation that can compromise occupants' comfort sensation. Local thermal discomfort cases explained there are the same of UNI EN ISO 7730 without any category differentiation.

In buildings cooled with natural ventilation, the standard purposes some indications about building design and methods to cool internal environments without any HVAC system, underlining the importance of occupants' behaviour and their clothing habits.

The WELL Building standard

The WELL Building Standard is a certification protocol that connect building design with human health and well-being of occupants. It is based on a dynamic rating score system which was developed in October 2014 thanks to the integration of building technology with medical and scientific research, but also combined with existing literature and standards.

The WELL Building Standard is administrated by the International WELL Building Institute (IWBI) that has a strong collaboration with the developers of LEED Green Building Rating System. Therefore, WELL protocol was designed to implement the leakage of LEED in the evaluation of comfort, human health and wellness.

The strategy imposed by WELL certification is based on pilot programs that are available for many building sectors such as residential, offices, retails, educational facilities, restaurants and researchers are studying the specific requirements to develop other programs for sport facilities, healthcare and communities. They can be applied on new entire buildings or existing, on just some internal spaces or else on core and shells.

There are three levels of achievements, Silver, Gold and Platinum. The level evaluation is based on score system that attributes credits to a list of specific building characteristics. To maintain WELL certification, buildings must be recertified every three years, since the degradation of material and spaces can influence comfort conditions for occupants and affect their health and well-being.

Organization of WELL building standard

The WELL Building Standard is divided into seven categories of wellness called concepts such as Air, Water, Nourishment, Light, Fitness, Comfort and Mind. These categories are composed by 105 features that are "intended to address specific aspects of occupant health, comfort and knowledge" [The WELL building Standard v1 with Q4 2017 addenda]. Then, each feature is divided into parts focused on specific building needs and contains one or more requirements dedicated to specific parameters. When requirements are satisfied, the feature earns credits.

Features can be classified as preconditions or optimizations. Precondition features must be achieved to get the WELL certification; if they are not satisfied the certification has no sense. While optimization features are not required to be achieved for the minimum standard. Credits of optimization features plays important role in the achievement of Gold and Platinum certification.

After a preliminary assessment, every WELL feature is verified on-site by a WELL assessor that spend one or three days inside the building to perform test and measurements on air and water quality, sound propagation and light level.

Comfort according to the WELL philosophy

One of the seven parts of the WELL protocol has been written to guarantee internal comfort conditions for occupants. The section of the certification gives some general information on the comfort assessment, but it recommends applying specific standards, that show parameters and strategies to achieve comfort.

According to the introduction on comfort assessment reported in the certification, the building design must reduce "the most common sources of physiological disruption, distraction and irritation and on enhancing acoustic, ergonomic, olfactory and thermal comfort to prevent stress and injury and facilitate comfort, productivity and well-being" [The WELL building Standard v1 with Q4 2017 addenda].

The acoustic aspect are the first reported by the protocol. It suggests to pay attention during the design process to avoid the formation of holes and tunnels that may collect external noises and bring them into the building. Also, internal noises should be avoided, in particular the one generated by systems and by the turbulent air flow into duct of distribution systems; or else, avoid rumbling sound.

The presence of uncontrolled sound may cause disturbing effect and decrease social interaction between occupants and their learning or productivity. Also, it generates mental stress on the nervous system of the human body. Therefore, in order to avoid disturbing effects generated by noises, designers must provide noise barriers and acoustic insulation layer in the building construction design.

Ergonomic and visual studies must be provided during the design process to prevent stress and injury due to incorrect posture that causes muscular diseases of occupants. Moreover, the protocol suggests paying attention to the accessibility of spaces for disable people.

Thermal comfort assessment can be done according to the project guideline showed by the American standard ASHRAE 55. Six primary personal and environmental variables contribute to an occupant's thermal comfort: air speed, dry bulb temperature, radiant temperature, humidity, metabolic rate and clothing or other insulation, all of which interact to create a subjective, individualized response. Knowing that thermal comfort may affect humour and productivity, the protocol recommends paying attention in the type of comfort that the building would provide, and it differentiate static thermal comfort by the adaptive one. Moreover, since thermal comfort is a personal sensation that can't be equal for everyone, it is better to provide areas inside the building with different thermal gradients; in this way, individual thermal comfort devices can ensure that occupants can choose areas with temperatures that best fit their thermal preferences.

In the last twenty years, the use of radiant system is spread out. According to the protocol, radiant system can be used to improve thermal comfort and to guarantee a good level of building flexibility if they had been considered in the design process. In fact, the use of radiant systems respect to traditional radiators, permit to have a quite uniform distribution of temperature and a lower dust transportation. Also, the mean radiant temperature in a space can be kept lower compared to convective heating, providing the benefit of a slightly higher relative humidity in winter time.

In the end, the protocol advises to keep into account the quality of internal air. The application of filters and barriers in the air distribution system may improve internal air quality and decrease pollutant species or disturbing odours.

Score calculation

Each of seven concepts is evaluated on a numerical scale independently and the final WELL score is calculated on the total number of preconditions and optimizations achieved across the process.

The calculation of concept scores and the overall WELL score is based on the following equations:

$$FAIL \qquad if\ \left(\frac{PA}{TP}\right) < 1 \qquad \Rightarrow \qquad WS = \left(\frac{PA}{TP}\right) \cdot 5$$

$$PASS \qquad if\ \left(\frac{PA}{TP}\right) = 1 \qquad \Rightarrow \qquad WS = 5 + \left(\frac{OA}{TO}\right) \cdot 5$$

Where

PA means Preconditions Achieved

TP means Total Preconditions

WS means Wellness Score

OA means Optimizations Achieved

TO means Total Optimizations

The WELL level is associated to the final concept score which is based on the sum of preconditions and optimization achievements. Total score from 0 to 4 is not significant because it would mean that some preconditions were not met. From 5 to 6 points identify Silver category; 7 to 8 score for Gold level and 9-10 for Platinum one.

The following example is related to a building office that was certified as Gold level.

Concepts	Preconditions		Optimizations		Concept score
	Applicable TP	Achieved PA	Applicable TO	Achieved OA	
Air	12	12	17	3	5
Water	5	5	3	0	5
Nourishment	8	8	7	7	10
Light	4	4	7	2	6
Fitness	2	2	6	3	7
Comfort	5	5	7	2	6
Mind	5	5	12	12	10
Total WEEL score WS	41	41	59	29	7

Table 9 WELL score example

LEED protocol

Due to the climate change of the last century, many countries of the European Union, signed the plan Energy 2020 on the 10th November 2010. This guideline is a list of targets to reach at the end of the year 2020 and sustainability is the main topic. To respect the plan Energy 2020, many countries set their own economy on the improvement of the energy efficiency of buildings (towards NZEB) and on the reduction of transportations. But these are just two strategies among the possible solutions that can be applicable on construction fields.

By now, the concept of environmental evaluation is spreading out and it is collecting many achievements because it considers the holistic aspect of buildings. It evaluates the sustainability of many variables of the project from the building site to the CO_2 emission during material transportation or material production, wastes in terms of water and materials and their life cycles, the quality of indoor air and so on.

The sustainability protocol evaluates the impact of the building on the environment considering the contribution of all these parameters. This is the case of LEED protocol, Leadership in Energy and Environmental Design, created by U.S. Green Building Council in 1998.

There are different versions of LEED protocols according to the type of building under study. This variation in the structure of the certification is based on specific requirement of buildings, their function and the type of occupancy rate. In this way, the evaluation of the building performance can be more accurate and reliable respect to a generic certification that doesn't consider the influence of many aspects.

LEED for schools can be applied to nursery, primary and secondary schools. It keeps the same structure of the baseline protocol, but it introduces more prerequisites and credits on the specific intended use.

Limits of energy-environmental certifications

Energy-environmental certification like LEED are set on specific needs of the birthplace context in which they are created. Difference in climate zones, economic aspects, urbanization, standards and regulation context may produce less reliable results. "Thus, it is very important to consider and make a comparison between the energy-environmental point that must be acquired by the building and the standard regional (or national) regulation"[El Asmar, Titon, Srour 2016].

Nowadays, to clarify the result and make it more reliable according to the geographic position of the building under study, there is a new generation of protocols which is more flexible, adaptable to the local conditions and able to consider many local aspects (SBTool).

Structure of the protocol and score system

The LEED protocol has a well-organized structure which is divided into categories. Each category is associated to a specific aspect of the building design, construction, life cycle of material and environmental impact. Categories are divided into prerequisites and credits which are associated to a point rate according to building performance. They define the ambient needs that must be satisfied by the building design. Prerequisites represents the minimum performance that the building must have; since they are the minimum standard imposed by law, they don't take part to the final score. On the other hand, credits express the performance of the building in each category. A variable score is attributed to them with a minimum point equal to 1. The sum of points earned by credits determines the level of certification. The maximum score is equal to 100, but the fulfilment of the category innovation in design and Regional

Priorities can add 10 points more to the final score. The minimum score to obtain the certification is 40 points.

Indoor environmental quality

The LEED certification starts with the determination of prerequisites and the minimum program requirements (MPR) which are linked to the building legislation of the country and the respect of the GBC regulation on energy.

Then, the part useful to determine the final score is divided into categories that are linked to the site sustainability, water efficiency, energy and atmosphere, material and resources, indoor environmental quality, innovation in design and regional priority.

The category of the evaluation of indoor environmental quality presents the guideline to achieve a good level of internal comfort for occupants. In particular, there are more relevant aspects that guarantee this goal like thermal condition, illumination systems and air quality. Moreover, for existing buildings, the certification score takes into account the cleaning operation and maintenance that contributes to improve the internal air quality.

According to the LEED v4 Italian guideline for schools, each prerequisite or credit is based on the American standard regulation, in particular ASHRAE, but it underlines to apply local regulation if they are more restrictive.

As said before, the protocol starts with the verification of the prerequisites for the type of building and continue with the credits achievements, defining for them the minimum and maximum points.

Among the prerequisites for school there are the settings of minimum mechanical and natural ventilation. The calculation of the flow rate and specific system requirements can be done according to the European standards EN 15251 or EN ISO 13779. On the other side, the design of natural ventilation can be set on the reference standard ASHRAE 62.1 or local regulations which demonstrate that natural air flow rate calculated is sufficient to guarantee an acceptable level of internal air quality. Moreover, smoke is not allowed in any part of the school since it is an educational building and the minimum acoustic levels must be satisfied. In particular, noises from mechanical systems must be lower than 40 dB and classroom must have acoustic insulation panel on the ceiling to avoid noise propagation if the classroom volume is lower than 566 m^3.

In the credits part, it is evaluated the quality of internal air (1-2 points) at first. Points can be earned by the correct use of mechanical ventilation system, if it is present decontamination of pollutant species system at the main entrance or air filtration system and CO_2 controllers. Naturally ventilated buildings must demonstrate that the air flow rate entering in the thermal zones is sufficient to dissipate loads caused by internal gains and to guarantee air quality everywhere. Mixed systems are also taken into account and their requirements considers both the one of mechanical and natural ventilation.

After, the certification focuses on the Internal Air Quality associated to the productions of VOCs and chemical species produced by materials (1-3 points) that can affect the human health. It gives a list of material with their emission limits and provide methods to calculate these limits on site.

Considering the construction phase, the certification reserves some credits to the construction indoor air quality management plan (1 point) and to the indoor air quality assessment (1-2 points) that must be evaluated in the construction/renovation phase, following a specific procedure explained in these sections.

The credits concerning thermal comfort (1 point) suggest applying standard UNI EN ISO 7730 and EN 15251 for Europe or its equivalent ASHRAE 55 for buildings in USA. In addition, it reminds the use of space control systems to imitate local thermal discomfort and energy waste.

The illumination part is divided in interior lighting with artificial lamps (1-2 points), daylight (1-3 points) and the respect of quality views (1-2 points). The presence of artificial light is required in school spaces in order to guarantee a sufficient illumination for the activities. The lighting system must have three levels of intensity (on, off and intermediate) and use lamps with maximin luminance of 2500 cd/m2 and CRI equal or higher than 80. Moreover, designers should use only LED to provide direct illumination.

The building should use natural light instead artificial light according to the weather conditions. To control the intensity of solar light, the building must have some solar screed (internal and/or external) to avoid glare and visual disturbing effects. Virtual simulations have been done to demonstrate that the illumination level is between 300-3000 lux on the work plane. The presence of windows should guarantee the entrance of natural light, but at the same time they give a view of the exterior. The certification gives point according to the quality of the external landscape to promote the natural environmental protection, to integrate the external environment into the project and design it to improve its quality.

In the end, the acoustic credit (1 point) can be earned if the mechanical systems are correctly insulated to guarantee an insulation equal or lower than 35 dB. Tests on mechanical systems are done after the construction phase when the building has already finished.

2.3. DESIGN PARAMETERS AND COMPARISON BETWEEN STANDARDS

Comparing the American standard with the European codes it is possible to notice that they deal with same issues, but the Europeans are more restrictive and more accurate, since they consider three categories of comfort condition. On the other side, the American ASHRAE 55 does not specify comfort categories, but values reported correspond to the average (and in most cases equal to category B or II) of the EN. Also, it is more specific in the evaluation of the indoor air quality and the ventilation rate requirements.

Global thermal discomfort percentage

The following table shows the maximum allowable design percentage for the Predict Percentage of Dissatisfied and the Predict Mean Vote written in the standards. As written before, the European code divide them into categories (A, B, C for UNI EN ISO 7730 and I, II, III for UNI EN 15251), while the American one report an average value which correspond to the category B (II) of the UNI.

Category	PPD %		PMV %	
	UNI EN ISO 7730 - EN 15251	ASHRAE 55	UNI EN ISO 7730 - EN 15251	ASHRAE 55
I (A)	< 6	< 10	-0.2 < PMV < 0.2	-0.5 < PMV < +0.5
II (B)	< 10		-0.5 < PMV < 0.5	
III (C)	< 15		-0.7 < PMV < 0.7	

Table 10 PD and PMV categories of comfort. Comparison between European and American standards

Local thermal discomfort percentage

The same considerations can be done for the Local thermal discomfort, underlining that EN 15251 doesn't take into account this issue directly, but it purposes to consult standard UNI EN ISO 7730.

Category	DR%		PD%					
			Vertical air temperature difference		Caused by warm or cool floor		Radiant asymmetry	
	UNI EN ISO 7730	ASHRAE 55	UNI EN ISO 7730	ASHRAE 55	UNI EN ISO 7730	ASHRAE 55	UNI EN ISO 7730	ASHRAE 55
A	< 10	< 20	< 3	< 5	< 10	< 10	< 5	< 5
B	< 20		< 5		< 10		< 5	
C	< 30		< 10		< 15		< 10	

Table 11 Local thermal discomfort percentage form UN EN ISO 7730 and ASHRAE 55

Operative temperature of air

The operative temperature proposed by standards are quite clear; nevertheless, there are big differences in the evaluation of operative temperature related to the mechanically conditioned and naturality conditioned spaces.

For instance, UNI EN ISO 7730 doesn't specify the type of conditioned space because it is based on non-adaptive (or static steady state) comfort and the kind of conditioning system is not relevant. In fact, it reports a unique value for the set point temperature To and its variation ΔTo according to the category of expected thermal comfort and the type of activity.

EN 15251 suggests using operative temperature values equal to the one of UNI EN ISO 7730 for building with mechanical conditioning systems, considering the same categories. The determination of internal operative temperature for naturally ventilated buildings can be done using a graphical method (Acceptable operative temperature range chart) reported inside, which is based on ASHRAE 55. In both cases, the charts express a relation between the external temperature and the internal operative temperature, considering the adaptation of human body to the environment conditions.

The difference between European and American charts on the determination of operative temperature consists in the definition of the limits of the acceptable ranges. EN 15251 defines three categories of comfort ranges which are indirectly connected to specific values of PMV and PD; while ASHRAE 55 define two ranges of operative temperature limits to achieve 80% and 90% of acceptability.

The following table shows some value belonging to standards UNI EN ISO 7730 and EN 15251 corresponding to 1 clo for heating season and 0.5 clo for cooling season for the office and classroom category and the chart of operative temperature from EN 15251 and AHSRAE 55 in adaptive approach.

Type of building space	Category	Operative temperature °C			
		Range for heating season 1.0 clo		Range for cooling season 0.5 clo	
		UNI EN ISO 7730	EN 15251	UNI EN ISO 7730	EN 15251
Single office, Landscape office, Conference room, class	I (A)	22 ± 1.0	21 - 23	24.5 ± 1.0	23.5- 25.5
	II (B)	22 ± 2.0	20 - 24	24.5 ± 1.5	23 - 26
	III (C)	22 ± 3.0	19 - 25	24.5 ± 2.5	22 - 27

Table 12 NON-ADAPTIVE APPROACH: Operative temperature from UNI EN ISO 7730 and 15251 with mechanical cooling

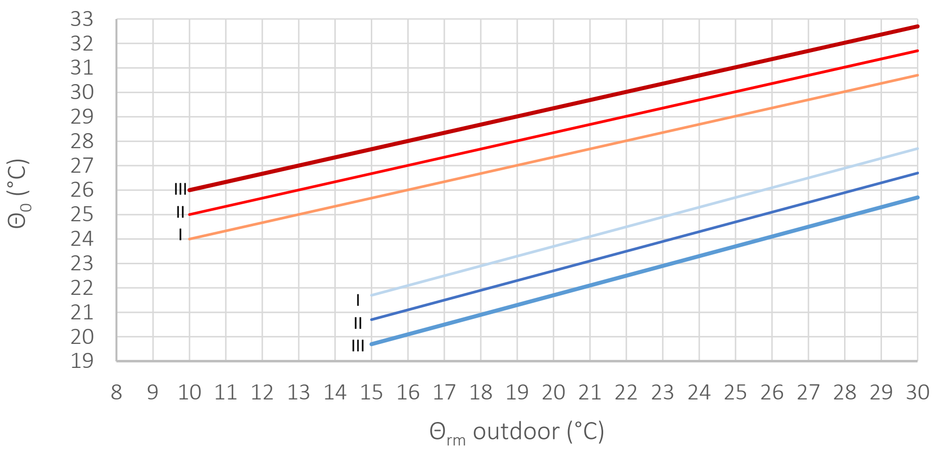


Chart 2 ADAPTIVE APPROACH: Operative temperature Θ_0 from UNI EN 15251 naturally ventilated building

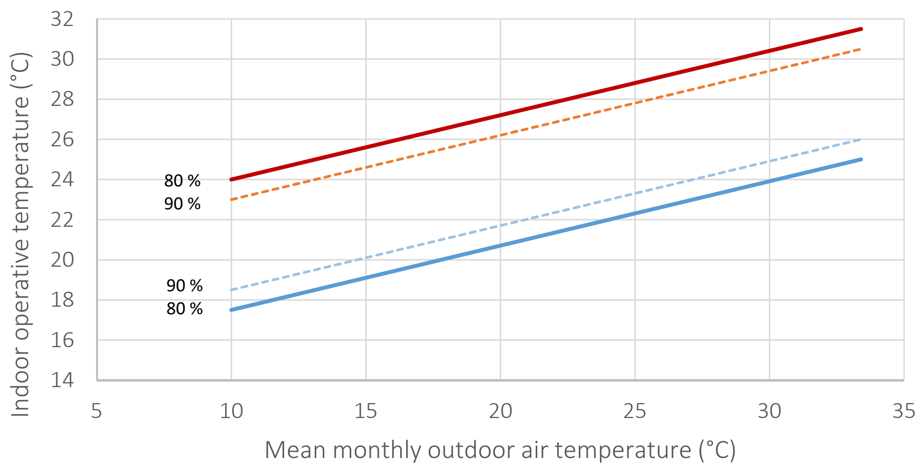


Chart 3 ADAPTIVE APPROACH: Operative temperature form ASHRAE 55 naturally ventilated building

Local Operative temperature and local temperature variation

In addition to the operative temperature of the environment, standards UNI EN ISO 7730 and ASHRAE 55 report the values of the maximum allowable temperature variation in order to avoid local discomfort. Again, the European code gives value according to the type of category, while the American regulation reports only one value which correspond to the intermediate category (B) of UN EN ISO 7730.

Category	Vertical air temperature difference °C		Floor surface temperature range °C		Radiant temperature asymmetry °C							
					Warm ceiling		Cool wall		Cool ceiling		Warm wall	
	UNI EN ISO 7730	ASHRAE 55	UNI EN ISO 7730	ASHRAE 55	UNI EN ISO 7730	ASHRAE 55	UNI EN ISO 7730	ASHRAE 55	UNI EN ISO 7730	ASHRAE 55	UNI EN ISO 7730	ASHRAE 55
A	< 2		19 to 29		< 5		< 10		< 14		< 23	
B	< 3	< 3	19 to 29	19 to 29	< 5	< 5	< 10	< 10	< 14	< 14	< 23	< 23
C	< 4		17 to 31		< 7		< 13		< 18		< 35	

Table 13 Local operative temperature and temperature variation form UNI EN ISO 7730 and ASHRAE 55

ASHRAE 55 shows also the maximum variation of the indoor operative temperature in case of drifts and ramps during a specified period.

Time period	0.25 h	0.5 h	1 h	2 h	4 h
Maximum Operative Temperature change allowed	1.1 °C	1.7 °C	2.2 °C	2.8 °C	3.3 °C

Table 14 Limits on operative temperature drifts and ramps from ASHRAE 55

Air velocity

The relative air velocity in standard UNI EN ISO 7730 is calculated keeping the relative humidity constant and equal to 50% and turbulence intensity of 40%. Three charts, related to the three categories, are proposed by the standard to show correlation between local air temperature, local mean air velocity and turbulence intensity. The limits in air speed according to the standard must be no higher than 0.90 m/s in summer and 0.15 m/s in winter.

Type of building, space	Category	Activity W/m²	Maximum mean air velocity m/s	
			Summer	Winter
Single office, Landscape office, Conference room Classroom	A	70	0.12	0.1
	B		0.19	0.16
	C		0.24	0.21

Table 15 Maximum air speed from UNI EN ISO 7730

Standard EN 15251 describe the correlation between the air velocity and the operative temperature variation with a unique chart in which the two variables are linked together by an exponential correlation. Moreover, the standard suggests the reader to check UNI EN ISO 7730 in order to have more detailed information. It shows an upper limit of the air speed near 0.9 m/s.

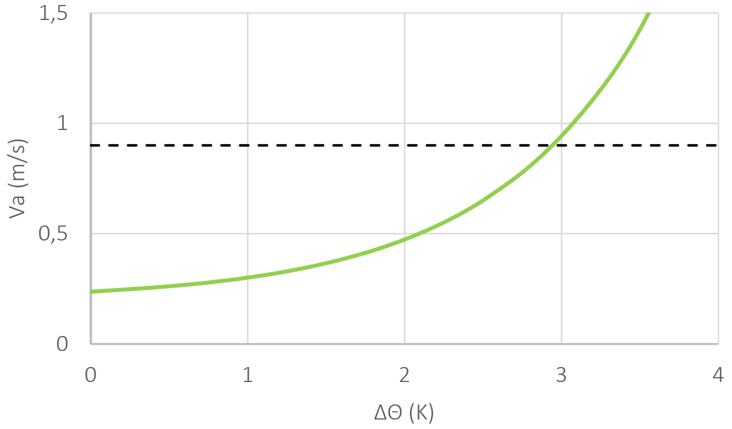


Chart 4 Air speed chart from UNI EN 15251

Again, American regulation ASHREE 55 describe the air velocity calculation with a graphical method, close to the UNI EN ISO 7730, in which there is a correlation between the operative temperature variation and air speed. The standard imposes un upper limit of air velocity equal to 0.82 m/s calculated for sedentary activity (office), more restrictive than the European codes EN 15251 and UNI EN ISO 7730.

In general, ASHRAE 55 and UNI EN ISO 7730 are more detailed respect to EN 15251 because more variables can be read form the chart; also, ASHRAE 55 presents a second chart showing the relation between air speed and Predicted Mean Vote where there are also some indications about local control of air speed and measurements.

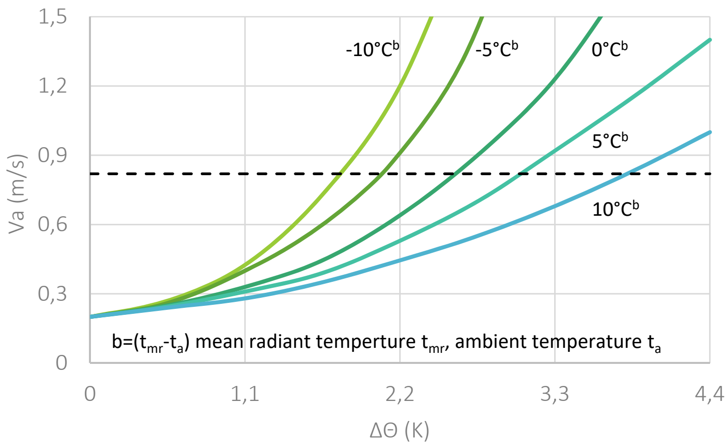


Chart 5 Air speed chart from ASHRAE 55 (European units), UNI EN ISO 7730

Humidity

In standard UNI EN ISO 7730 there is no information about the design value of humidity.

EN 15251 recommends design values of humidity related to humidification and dehumidification according to category I, II, III, while ASHRAE 55 reports only the upper limit of humidity ratio: X should be no higher than 0.012 g^v/kg^{da} that correspond to a dew-point temperature of 16.8°C.

UNI EN 15251 Type of building or space	Category	Design relative humidity for dehumidification %	Design relative humidity for humidification
Spaces where humidity criteria are set by human occupancy. Special spaces (museum, churches) may require other limits	I	50	30
	II	60	25
	III	70	20

Table 16 Relative humidity from UNI EN 15251

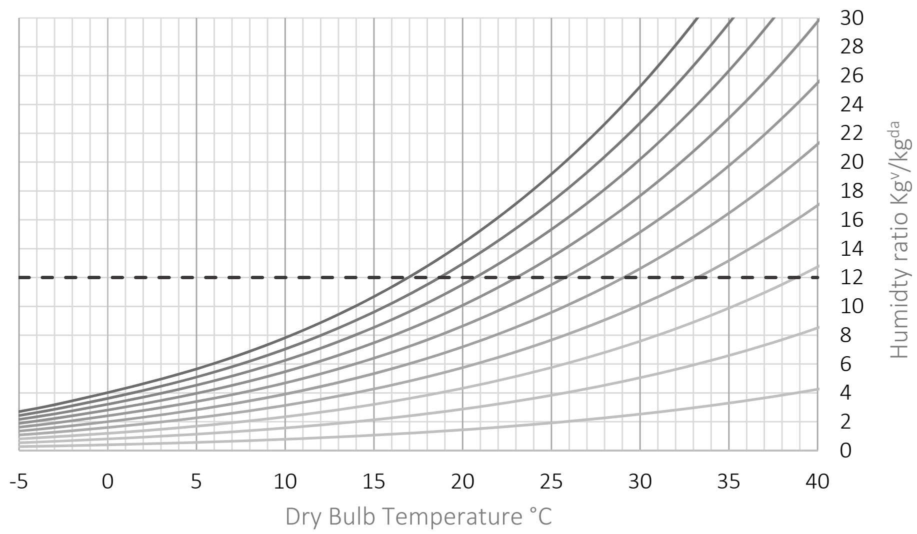


Chart 6 Relative humidity upper limit from ASHRAE 55

Ventilation rate and Indoor Air Quality

Ventilation rate should be based on the pollutant load that affect the ventilated space.

The control of internal air quality is an important issue that can affect the human health and many physical and psychological aspects. Ventilation rate and indices of air quality are not taken into account in standards UNI EN ISO 7730 and ASHRAE 55. Nevertheless, standard EN 15251 reports an informative chapter related to the evaluation of the air quality of the internal environment that has some common parts with American code ASHRAE 62.1-*Ventilation for acceptable indoor air quality*. Obviously, this standard is more detailed with respect to EN 15251, since it deals with only ventilation and IAQ topics.

Focusing on ventilation, EN 15251 proposes an analytical method for calculating the minimum ventilation rate, in order to dilute bio-effluents, form the human breath. The design outdoor airflow q_{tot} required is calculated as:

$$q_{tot} = n \cdot q_p + A \cdot q_B$$

Where

n number of occupants

q_P ventilation rate for occupancy per person l/s,pers

A occupied floor area m2

q_B ventilation rate for emissions from building l/s,m^2

The standard ASHRAE 62.1 proposes the same equation changing the variables name: $V_{bz} = R_p P_z + A_z R_a$ where R_p is q_P, P_z is n, A_z is A and R_a is q_B.

The following table show different parameters used by the two standards. The difference between them is relevant from the design point of view. ASHRAE shows lower values respect to the European code that makes difference between categories of expected comfort conditions. The reason of this difference must be searched at the base of design criteria of the standards: the America code is based on *adaptive occupants* (people that work there), while the European code on *non-adaptive occupants* (visitors). Thus, EN 15251 is more restrictive with respect to ASHRAE 62.1.

Type of building	Floor area m^2/person	Category	Minimum ventilation rate for occupants only			Additional ventilation for building l/s,m^2				Total l/s,m^2			
			l//s,m^2	l/s,pers									
			EN 15251	EN 15251 q_p	ASHRAE 55 R_p	EN 15251 q_B very low polluted building	EN 15251 q_B low polluted building	EN 15251 q_B non-low polluted building	ASHRAE 55 Ra	EN 15251 q_{tot} very low polluted building	EN 15251 q_{tot} low polluted building	EN 15251 q_{tot} non-low polluted building	ASHRAE 55 V_{bz}
Single office	10	I	10	1.0	2.5	0.5	1.0	2.0	0.3	1.5	2.0	3.0	0.55
		II	7	0.7		0.3	0.7	1.4		1.0	1.4	2.1	
		III	4	0.4		0.2	0.4	0.8		0.6	0.8	1.2	
Landscape office	15	I	10	1.0	2.5	0.5	1.0	2.0	0.3	1.2	1.7	2.7	0.48
		II	7	0.7		0.3	0.7	1.4		0.8	1.2	1.9	
		III	4	0.4		0.2	0.4	0.8		0.5	0.7	1.1	
Conference room	2	I	10	1.0	2.5	0.5	1.0	2.0	0.3	5.5	6.0	7.0	1.55
		II	7	0.7		0.3	0.7	1.4		3.8	4.2	4.9	
		III	4	0.4		0.2	0.4	0.8		2.2	2.4	2.8	
Classroom	2	I	10	1.0	3.8	0.5	1.0	2.0	0.3	5.5	6.0	7.0	2.20
		II	7	0.7		0.3	0.7	1.4		3.8	4.2	4.9	
		III	4	0.4		0.2	0.4	0.8		2.2	2.4	2.8	

Table 17 Ventilation rate from UNI EN ISO 7730, 15251 and ASHRAE 55

Concerning the Indoor Air quality, standard EN 15251 reports design values for air flow rate per person, flow emission for pollution (human bio effluents) and the corresponding values of CO_2 for the three categories, while ASHRAE 62.1 calculate the CO_2 concentration related to the occupancy rate and the type of activity by an equation (ASHRAE 62.1 Appendix C: minimum physiological requirements for respiration air based on CO2 concentration).

Category	Expected Percentage Dissatisfied	Airflow per person l/s/pers	Air flow building emission pollutions q_B l/s,m2			Corresponding CO_2 above outdoors in PPM for energy calculation
			Very low polluting building	Low polluting building	Non-low polluting building	
I	15	10	0.5	1.0	2.0	350
II	20	7	0.35	0.7	1.4	500
III	30	4	0.2	0.4	0.8	800

Table 18 Ventilation rate for non-residential building and CO2 concentration form UNI EN 15251

Standards remind to used clean air for ventilation system. This issue is deeply explained in standard ASHRAE 62.1 that takes into account air-cleaning systems and their maintenance. The quality of internal air is affected by the quality of external air used in Air Handling Units, recirculation air flux, clearing devices placed in the distribution systems and by the ventilation effectiveness.

Since a big amount of ventilation air flow comes from outside, it is important to check the external air quality during the operation of the ventilation system by some tests to calculate the concentration of specific pollutant species, e.g. VOCs. One serious problem is related to buildings placed in city centre where the quality of external air is very low, in particular during rush hours in which air is more contaminated by exhaust car gas. In these cases, it is better to reduce the amount of eternal air when traffic is high by disposing some restrictive valve in the inlet ventilation channel [Olesen, 2012].

Some systems adopt recirculation of internal air as a strategy to reduce the energy expended: part of the air that enters in the conditioned room is coming from outside, while the remain part is recirculated. In this case it is necessary again to check the quality of both internal and external air flows; in particular, the quality of recirculation air is mostly compromised by the presence of occupants' pollutant like CO_2, bacteria, bio effluents and other organic components coming from devices placed in the distribution system or directly inside the room. Once identified which kind of pollutant is more present, it is possible to choose the cleaning device (filter) that is usually placed in the distribution system. Also, it is necessary to guarantee the maintenance of the Air Handling Unit, distribution pipes and shafts and fans or terminals.

The ventilation rates described by the standard are set on occupancy of the room, but its efficiency may be compromised by the type of distribution system or terminals that could reduce the amount of air entering in the room due to geometry problem of the section, connections pipe-pipe, obstructions, pollutant concentrations and so on. Consequently, the *fresh air* is no more sufficient to satisfy the ventilation need of the room and the air quality is reduced.

The ventilation effectiveness is taken into account by ASHRAE 62.1 and described as:

$$\varepsilon_v = \frac{V_{Bz}}{V} = \frac{C_e - C_s}{C_i - C_s}$$

Where

V is the inlet ventilation rate

V_{Bz} is the breathing zone ventilation

C_e Is the pollutant concentration of external air

C_s id the pollutant concentration of supply air

C_i is the pollutant concentration at breathing level

The design of ventilation system must take into account the effectiveness of ventilation and its variation along the whole year: this means that it is necessary to set ranges of air flows for heating and cooling seasons also considering the personal control it is required.

2.4. PARAMETER ANALYSES ON A SIMPLE MODEL

This section presents an analysis on one simple model to test some parameters imposed by standards. In this way it is possible to understand the generic trend of these parameter, useful to develop further analyses on the case study. All the simulations have been done with IESve and data collected into charts and tables to understand the yearly variation of some comfort parameters showed by standards.

The sample *Shoebox* used during simulations is a simple room which has the dimension, geometry and windows shape of the case study school.

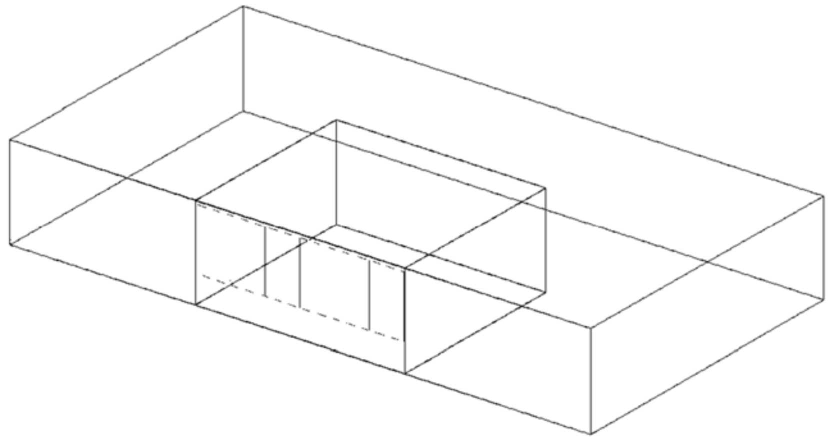


Figure 2 Sample model for test simulations

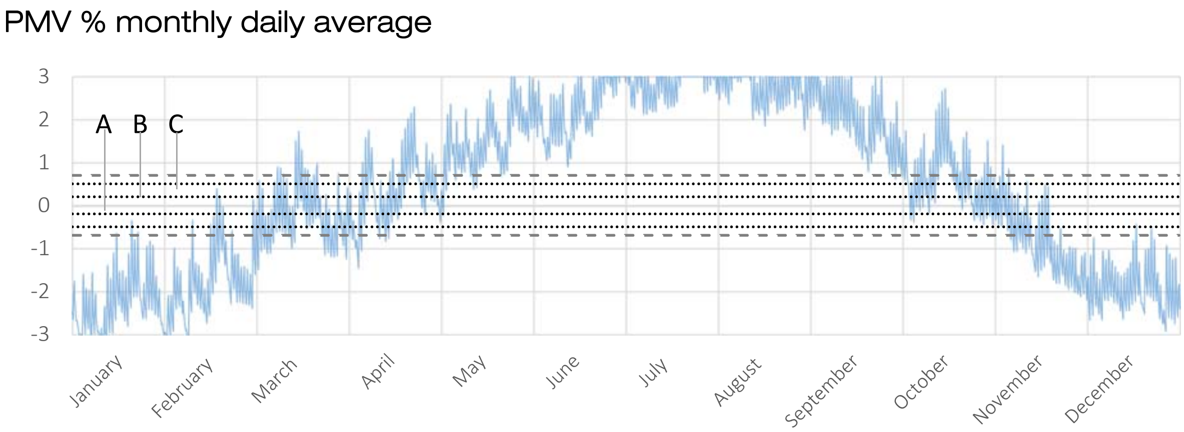


Chart 7 Monthly daily average of PMV

PPD % monthly daily average

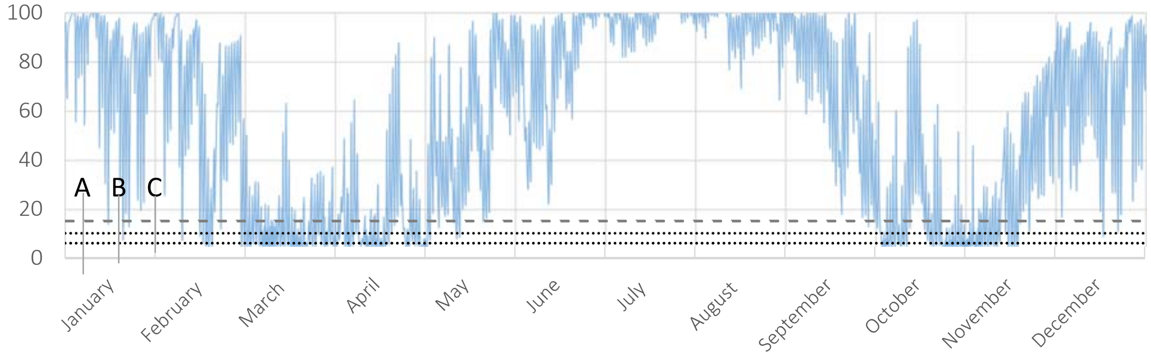


Chart 8 Monthly daily average of PPD

T_{op} Operative temperature:

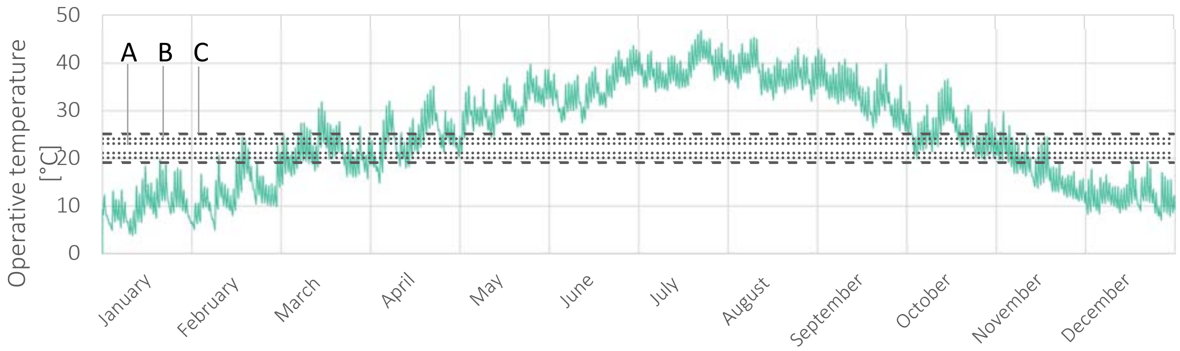


Chart 9 Non-adaptive: heating, monthly daily average

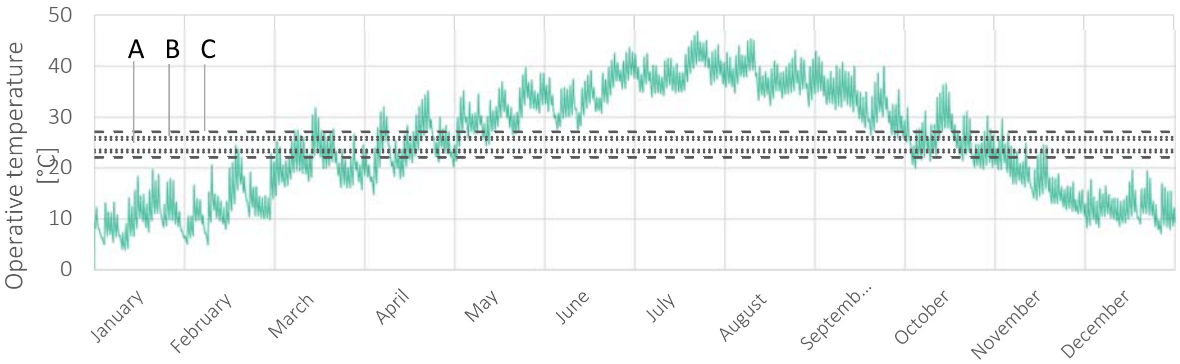


Chart 10 Non-adaptive: cooling, monthly daily average

Local temperature:

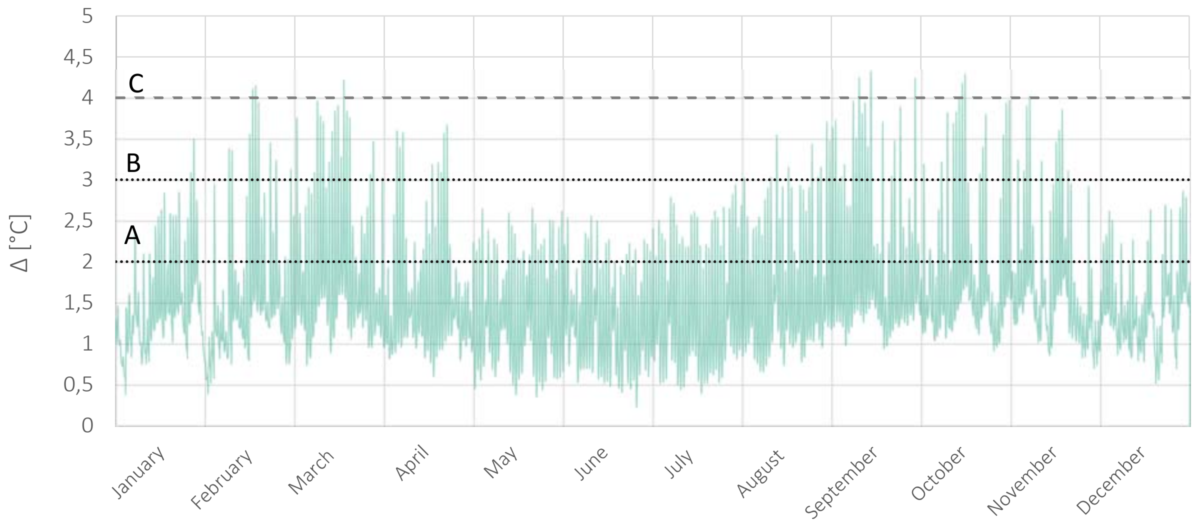


Chart 11 Vertical air temperature difference (ceiling-floor): hourly values

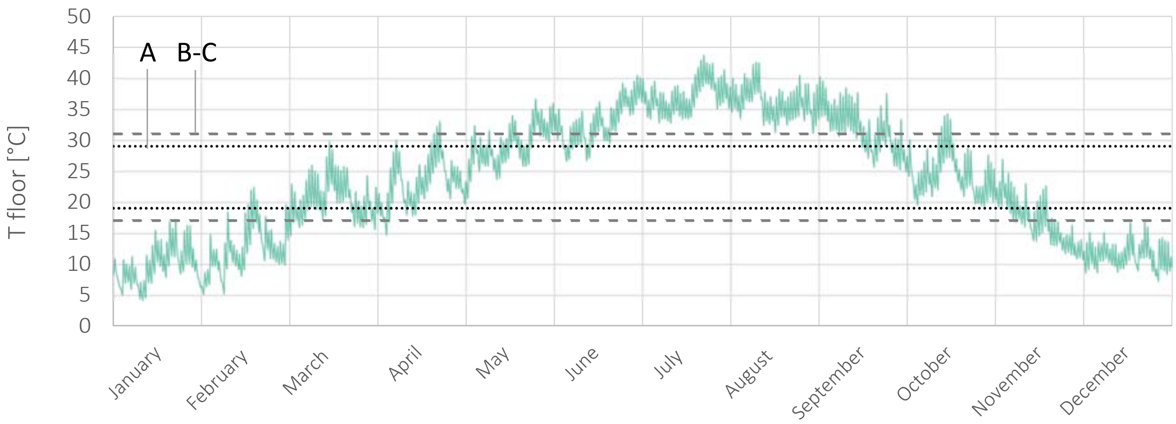


Chart 12 Floor surface temperature: hourly values

The two main parameter that are used to describe and evaluate thermal comfort inside the building are PMV and PD.

The first chart describes the trend of the Predict Mean Vote. Its trend along the year follows the trend of the operative temperature of the thermal zone. In fact, in winter, this value is very low and in summer it increases until the highest value. This means that comfort is not guaranteed in these two seasons. Instead, in March, April and some days between October and November, the value of PMV is in the comfort range described by UNI EN ISO 7730. PD is calculated from PMV and its variation along the year is in accordance with it. PD reaches the highest value in winter and summer while it decreases during the middle season.

2.5. ENVIRONMENT QUALITY CONTROL AND BUILDING SYSTEMS

Most of Italian schools was built in the *Italian Economic Boom* from 1950' to 1960' where the unique aim of the government was to rebuild cities damaged by the Second World War. Due to this ambition, building projects were designed in order to minimize the construction time and to save money. Thus, the quality of materials, architecture, internal comfort and systems efficiency were not taken into account until 1976 when the first standard on limitation of energy consumption 373/1976 was written. This means that school buildings waste a lot of energy to warm up internal spaces, since the quality of the envelope is very low in most cases. In addition, heating systems are old and their efficiency not adequate to satisfy actual requirements on energy saving.

In geographical zone like south-central Europe, the presence of conditioning systems is almost required in every building, because in winter temperature is too low to have comfort inside spaces and in summer, sometimes, solar gain overheat rooms, creating discomfort. Therefore, it is necessary to choose and set the correct boiler and/or chiller to guarantee internal comfort, considering also the energetic aspect.

2.5.1. HEAT PUMPS AS A UNIQUE SYSTEM FOR HEATING AND COOLING

According to the first phenomenological statement of the second law of thermodynamic, "no process is possible whose sole result is the transfer of heat from a body of lower temperature to a body of higher temperature". Therefore, it is necessary to use a certain amount of mechanical work to extract heat from a colder body and give it to a hotter one. Heat pump mechanism is based on this principle. In fact, devices whose functioning is based on this principle can be used to heat of chill the internal environment of buildings and it is a valid alternative to the traditional boiler o electric chillers. Moreover, the application of this system to produce domestic hot water in residential buildings, retails, hotels and other buildings has produced satisfactory results.

Reversible heat pumps can be used to heat and cool the internal environment by the inversions of the circuit. Some device for conditioning big buildings are able to heat some zones and chill others at the same time.

The physics related to the heat pump functioning is known since 1850', but it application on real machines didn't produce any useful results for many years. In 1973, the oil crisis and the improvement of technology, underlined that it can be useful to use heat stored in a cold source instead of producing it directly with thermal cycle machines. Therefore, heat pump devices can be more efficient than boilers.

Nevertheless, heat pumps have been placed on the market only in 2000 when besides the crisis of energy and fuels industry arise environmental problems, mainly connected to the burn of fuels and the toxicity of their emissions for human health and the Earth. Issues on energy crisis, environmental protection and healthcare have driven many countries to promote the use of alternative plants less polluting than the traditional plant that use fossil fuels. In this context, heat pumps can be a sustainable choice to set the conditioning system of buildings if correctly sized.

Mechanism

The heat pump functioning is based on two kinds of mechanism, one that exploit intermediate fluid compression, called vapour compression cycle and the other based on the absorption cycle. Most common heat pumps belong to the first category. This vapour compression heat pump is composed by a closed loop in which an intermediate fluid is circulating and is subjected to a sequence of transformations such as compression and expansion. In each thermal cycle (composed by two expansions and two compressions) the fluid extracts a certain amount of heat from the external reservoir and give it to the internal environment.

The thermal cycle of the heat pumps is completed when the vector fluid pass one times through the four components of the loop. The intermediate fluid is in charge of absorbing heat form one reservoir when it passes form vapour to liquid state and release it to the other reservoir during the opposite transformation. Therefore, the intermediate fluid must have specific characteristics that allow the transformations with little temperature variation. Nowadays, heat pumps use hydrochlorofluorocarbon (HCFC) as an intermediate fluid, even if it is a great greenhouse gas that contributes to the climate change. On this topic, scientists are working to define a new type of environmental friendly strategy.

The mechanism of heat pump starts when the intermediate fluid in contact with the external environment undergoes an isobaric expansion in the evaporator. The increase of the volume generates a decrease of the fluid temperature, but since the system is not isolated, the fluid absorbs heat form the external environment, according to the second law of thermodynamics (heat moves from a hot body to a cold one). At this stage, the fluid is in gaseous phase.

Then the fluid in form of vapour undergoes an adiabatic compression in the compressor where the increment of pressure and the reduction of the volume provide an increase of the fluid temperature.

After, the fluid is compressed at constant pressure by the condenser. During the transformation, the fluid passes form vapour to liquid state and release heat to the internal environment since the system is not isolated, decreasing its temperature.

Then, in the last step of the thermal cycle, the fluid is adiabatically expanded in the expansion valve. Since it is not able to give heat to the external environment it decreases its temperature and when it enters in the evaporator, in contact with the external environment, absorbs heat passing form the liquid to vapour state and the thermal cycle starts again.

The absorption machine uses a mix of fluid with different vapour resistance and the compression phase of the compressor in substituted with a series of transformations.

Instead of vapour compression, the refrigerant (ammonia or lithium bromide) of an absorption system is absorbed by a secondary substance, called absorbent (water). The mixing of refrigerant + absorbent forms a liquid solution. This solution passes through a pump that increases its pressure. The mechanical work used by the pump is very low since the specific volume of the liquid solution is lower than the refrigerant at the vapour state, providing energy saving respect to the vapour compression system.

The choice of the heat pump depends on the type of building, its size, thermal loads present in the environment and the terminal of the conditioning systems. Vapour compression heat pumps are used where the terminals of the system work with low temperature since the functioning of vapour compression cycle is based on relatively low difference of temperature of the two reservoirs. Therefore, the maximum temperature provided by the system is equal to 48-50°C, that is associated to the use of floor radiant heater and fancoils or chilled beams for the cooling.

If the heating system is composed by radiators or the environment is warmed by air systems that work with high temperature (near 65°C) the vapour pressure heat pump is not sufficient. In these cases, it is better to use heap pumps with Enhanced Vapour Injection or heat pumps with double thermal cycle [Caleffi, 2007].

Heat pumps efficiency

The efficiency of the heat pumps can be measured with according to the energy source and the activation mode. In general, the efficiency of any device is calculated as the ratio of the useful energy and the energy consumed by the device.

The electric vapour compression heat pumps in heating mode express their efficiency by the Coefficient of Performance COP, while the same coefficient is called Energy Efficiency Ratio EER in the cooling mode.

$$COP = \frac{|Q_H|}{|W|} \qquad EER = \frac{|Q_C|}{|W|}$$

Heat pumps based on the absorption cycle express uses natural gas and their performance with the Gas Utilization Efficiency GUE that is the ratio of the useful power and the thermal power provided by the combustion natural gas.

$$GUE_H = \frac{|Q_H|}{|Q_{ng}|} \qquad GUE_C = \frac{|Q_C|}{|Q_{ng}|}$$

Air source heat pump

Air source heat pumps use the external air as a heat source. Air temperatures vary seasonally, and moisture content fluctuates, therefore air source heat pump seasonal efficiency is always influenced by the climate conditions. The colder the air temperature, the harder the heat pump must work to lift the temperature up to what is required for heating. Therefore, the COP of air source heat pumps is more variable than other devices that uses e.g. ground or water as a primary source of heat. "Also, as heat energy is taken out of the air, droplets of water can freeze on the heat pump heat exchanger which then means the heat pump must *defrost* so the cycle can begin again. For this reason, air source heat pumps are slightly less efficient than their ground and water source counterparts, however this slight loss of efficiency is reflected in costs – they are typically less expensive to install. The most common type of air source heat pump used in dwellings is an air to water heat pump – the water referring to the method of heat distribution, i.e. through a floor heating system which uses water" [SEAI,2013]. Other types of air source heat pumps include exhaust air heat pumps, which are usually fitted to ventilation systems to provide domestic hot water or domestic hot water and heating, air to air heat pumps, which use the ventilation system instead of water systems such as under floor heating or radiators.

Water source heat pumps

Water source heat pumps use the heat energy available in water as a heat source. "Water source heat pumps can be *open* or *closed* loop. Open Loop - sometimes referred to as a *water to water* heat pump. Water to water heat pumps are open loop, which means that the water is passed directly through the heat pump, the heat is removed, and then the water is dumped back into a *discharge* well or other water source. Closed Loop – in the case of a lake, river or stream collector, often a series of pipes are laid to extract heat from the water, but instead of taking the water directly into the heat pump as you would in an open loop water to water system, a mixture of anti-freeze and water in a closed pipe loop is used to extract the heat (similar to a ground source collector)" [SEAI, 2013]. In this way, it is possible to extract the heat from the stream, river or lake, but do not use the water itself. Ground water is an ideal heat source for heat pumps since its temperature fluctuation is not very high and always in the range of 12-15°C; however, it should be noted that water must be present in sufficient quantity so that drinking water resources are not affected. Also, when extracting from a well, the water must be re-injected downstream (of the groundwater flow). The water also passes directly through the heat exchanger of the heat pump in an open-loop system, therefore the water quality is an important consideration (hardness, corrosivity etc.).

Surface water, such as a river, lake or the sea, can be used in either a closed or open loop system, however a closed loop system is likely to required much less maintenance. Protection against debris and physical damage and obtaining the necessary permissions from the Environmental Protection Agency are also important considerations for surface water collectors. The use of ground water is regulated by regional standards in order to decrease the waste of water source, respect protected feuds and avoid water pollution.

2.5.2. TERMINALS

This section considers some type of terminals used in the conditioning systems starting from the more traditional one, radiators, to the passive strategies generally used in NZEB strategies. Each type of terminal has been analysed considering their pro and cons, their influence on global and local discomfort and energy system requirements.

The type of terminals chosen are the ones used in the case study simulations.

Radiators

Radiators are the first type of modern terminal used to heat the environment, that have been introduced in the second half of the 1900 century, even if the technology invention belong to previous century. At the beginning, most radiators were made from cast iron; a few are made from aluminium. Nowadays, they are completely integrated into the building furniture design. In fact, their shape and their material can change according to specific requests.

Radiators are simple heat exchangers which distribute the heat by natural air circulation and they use a circuit of hot water to heat the metal case, that transmits the heat to the environment. Due to this mechanism, radiators work with high temperature of water, usually near 65-75°C with an operative difference in temperature of 50°C between hot water and the environment. Therefore, they need specific boiler that is able to provide sufficient energy to reach those temperature.

The correct sizing of radiators guarantees the achievement of comfort conditions inside the room. However, they can be considered as spot heat sources that cause a inhomogeneous distribution of environmental temperature. At first, radiators heat the air in contact with them, which is why rooms heated by radiators are prone to cold spots, meaning that the air is cold in the middle of the room and very hot next to the radiators. This effect may cause local discomfort and cold sensation for people too far from them and hot sensation for the one next to them. On the other hand, if the average temperature of the environment is too low for some people, they can *regulate* the air temperature next to them by getting close to the radiation or vice versa if the ambient temperature is too high.

Radiators are the traditional and cheapest terminal mainly used in buildings to heat the environment. Despite their qualities, radiators can be activated only in winter season with hot water to warm the internal environment; in summer season their functioning cannot be exploited to chill. Therefore, the conditioning system must have different terminals to achieve comfort in summer.

Hydronic radiant heating floor

Water-based radiant floor provides heat in a room from the floor up to the ceiling. They are composed by panels made with plastic and insulation material on which the hot water pipeline circuit is placed. Their operation temperature is near 30°C, much lower respect to traditional radiators that work in 65-75°C range. Thanks to this low value of water temperature and thus, low power request, this system can be coupled with a small generators or other less powerful devices such as heat pumps and condensing boilers (mainly used in residential buildings). The use of more environmental friendly boilers contribute to decrease the energy consumption and the emission of toxic substances and finally, the cost of energy.

The concept for radiant heating floor is not new. Ancient Romans used hot water pipes to warm floors, and it's been the preferred heating system in Europe since the 1970s. In fact, the use of radian floor heating guarantees a uniform distribution of the ambient temperature and reduce local discomfort related to the presence of hot and cold spots. Aside from the long-term cost benefits, radiant floor heating is silent heat, with no loud air ducts or furnaces to deal with.

Recently, radiant heating floor systems can be applied also to chill the environment in summer by using cold water instead of hot one. The water temperature required by the system is near 15-18°C to guarantee a decrease of ambient temperature. However, the design of the system must be accurately, and its operation temperature must be verified with dynamic simulation in order to avoid negative effects such as condensation of water vapour present in the air. For this reason, it is very difficult to use this system to chill thermal zones whose cooling power request is higher than 50 W/m^2. Moreover, radiant floor is not able to dehumidify the environment since they are not designed to achieve condensation and to evacuate it. In fact, this system in cooling mode require the presence of an independent dehumanisation system.

Fan coil

Fan coil units are used to introduce outdoor air into a space, circulate and filter air within a space, and to heat and cool the internal environment. "The basic components of a fan coil unit are a heating/cooling coil, fan section, and a filter. Units may stand alone within a single space or be ducted to serve multiple spaces, and can be controlled by a manual switch, thermostat, or building management system.

Fan coil units facilitate the transfer of heat to or from an occupied space by use of a closed loop water system including a heating and cooling coil. A coil consists of a tube usually made with copper, that passes through a series of aluminium fins. The copper tubes carry hot or chilled water that has been conditioned by a boiler, chiller, heat pump, or other device. The fins, in contact with the copper tube, increase the surface area on which heat transfer may occur, therefore increasing the total capacity of the coil" [Krueger, 2012].

The presence of a fan moves the air across a hot water or chilled water coil, addressing it towards the internal environment. Moreover, a recirculation system may be applied to save energy. In this case, ambient air returns back into the fan coil unit through a grille with a filer, it recirculates through the coils and is mixed with new conditioned air re-distributed into the space.

Fan coils are sized according to the internal loads and the used of spaces and their application guarantees the achievement of thermal comfort in summer and winter season, contributing also to improve internal air quality by adding fresh air to the internal spaces.

The application of fan coils is can be a good solution for service of offices buildings. In school it is preferred to not use other types of terminals, since fan coils require a periodic maintenance and cleaning operation of the internal fins. Moreover, their cage/envelope has some holes through which air passes and children may play with them or putting inside items, compromising their functioning.

Active and Passive ceiling beams

Active and passive beam systems provide an effective method for providing heating or cooling to a space while promoting a high level of occupant comfort and energy efficiency. Like radiant heating and cooling systems, active and passive beam systems use water to heat or chill spaces. Their application in buildings offer energy and space saving, but also a reduction of maintenance costs. However, these technologies deliver the majority of their cooling and heating through convection and not by radiation as in the case of radiant heat floor.

These systems are composed by a central generator that delivers cold or warm air to satisfy the requests of occupants and to balance thermal loads. As terminals, this system uses diffusers mounted in each thermal zone to distribute the conditioned air. In many cases, the amount of air required to cool or warm the space or the fluctuations of loads make the system design very difficult.

There are two types of system design such as active and passive beams. Hydronic heating or cooling where the hydronic systems are integrated with the primary ventilation system belong to the first category; while hybrid heating or cooling systems where water-based devices are used in conjunction with a scaled-down ventilation system (and manage the bulk of the sensible cooling load) belong to the second.

The application of these systems has some benefits in the improvement of thermal comfort and energy saving at the same time. School buildings (as office building) can use this system for space conditioning and take advantages since they do not compromise furniture distribution. However, active and passive beams are not very used in Italian school, since the request of cooling is very low because schools are closed in summer. In fact, in most cases, chilling system is not taken into account.

2.5.3. NATURAL VENTILATION

The use of natural ventilation to improve the quality of internal air and to chill the environment is the main strategy used by many buildings that belong to the second half of twentieth century. Nowadays, due to the climate change and the request of better indoor conditions, this strategy is not sufficient to achieve the minimum comfort imposed by standards. Therefore, in most cases, the combination of mechanical cooling system and natural ventilation mechanism is required, but not sufficient to guarantee the well-being of occupants. In fact, the two systems must be correctly sized and projected in order to work together.

Designers of ventilation systems have to project the plant considering the internal comfort for occupants, but at the same time, the energy saving. As known, the use of natural ventilation is a free strategy, that uses no energy; if combined with mechanical cooling system, the amount of energy consumed by building operation will surely increase respect to the application of just natural ventilation. Therefore, designers have to set the plant in order to reduce the use of mechanical system, while encouraging the use of natural ventilation where it is possible. Thus, the sensibility of designers on comfort and energy issues is very important to set the best system that guarantees comfort condition and uses less energy. Moreover, occupants must be educated to regulate the systems according to their needs, but also to adapt themselves to the environment conditions, for example to open windows before using mechanical ventilation system, or else to adapt their clothing to the seasonal temperature. Specially in school buildings that uses only natural ventilation to refresh air and chill the environment, children and teachers have pay attention on these problems.

As said, natural ventilation is a mechanism that uses no energy and therefore, it must be chosen as the main strategy to chill and refresh the air of internal spaces. One arguments against natural ventilation is the fact, that it can be very difficult to control the incoming air flux through the openings since it depends on many factors like wind pressure and wind speed, geometry of the openings, building orientation and many other; thus, it is not possible to keep stable indoor conditions as in mechanically ventilated buildings. Moreover, the flux and the frequency are not controlled by a specific device, but only users can regulate it; therefore, it is very important that occupants know exactly how the system works and how to set the best configuration to refresh air and improve the comfort conditions. Nevertheless, the design of spaces and the shape or the position of openings can induce natural ventilation.

The presence of windows on only one wall surface is the most common situation that can be found in many school buildings. The amount of air going through the window opening in single-sided ventilation will depend on the presence of wind, its speed next to the building and its direction that will cause turbulence and pressure variation, but also it depends on the difference in temperature between internal and external environment [Larsen, Heiselberg, 2007]. Therefore, the evaluation of air flux mainly depends on unsteady parameters, which make the prediction difficult. Basically, the airflow driven force depends on wind characteristics, thermal buoyancy or by their combination and the velocity of the flux varies according to the dominant force [Larsen, Heiselberg, 2007].

The cross-ventilation mechanism takes its name from the position of openings on two opposite wall surfaces. The main drive force is connected to wind characteristics such as its velocity and its orientation, which creates a variation in wind pressure on the facades where openings are placed. The volume air flow that is allowed to enter in the space is very large. Therefore, it can be a good strategy to refresh air in few minutes. Nevertheless, the shape of many buildings, schools and public buildings, doesn’t allow to place windows on two opposite due to the division of internal space and distribution systems.

Another mechanism to induce natural ventilation is the design of stack ventilation systems. This mechanism is primarily driven by warm air that rises to the top creating a pressure difference, which drives the ventilation. The best effect is obtained when the openings for natural ventilation are placed so that the wind pressure contributes to an increase in the driving pressure. Therefore, buildings that use this mechanism should have openings on the rooftop whose shape is similar to a chimney.

This particular technique is used in *nearly zero energy buildings* as a passive strategy that cool down the internal environment since it guarantees a good rate of air change if it is well dimensioned, without any supplementary energy cost.

Openings in the building envelope like windows and doors are designed in order to allow the air passage and solar gain, but there are other kind of openings of the external cladding, that are not projected since they are linked to the construction process and sometimes, not expected by designers. These openings are the main responsible of envelope air-permeability, that will cause firstly infiltration of air from inside to outside and secondly, an exchange of heat. This means that the presence of many *unwanted openings* contributes to increase the energy consumption in the heating season and in the cooling season. Infiltrations may be cause by system passages that break the continuity of the building envelope if they are not sealed properly or they can be generated by degradation of envelope materials, that can produce cracks or openings due to the thinning of some parts. Plastic materials are subjected to a fast degradation due to reaction with solar radiation, rain and weather conditions, that cause crazing, hardening and breakage. In fact, sealant and baskets of windows are made with plastic materials and they are one of the first element subjected to degradation. The absence of these elements on window closures generates infiltration of air from the external environment and contribute to increase local discomfort, especially in school buildings. In fact, in winter, the infiltration of cold air can be an annoying effect for students set near the window. On the other hand, in summer season, infiltrations contribute to dissipate heat stored inside the building if the room is not chilled by any mechanical system.

CHAPTER

3

Case study: school building in Melzo

3.1. BUILDING DESCRIPTION

The Secondary School "Piero Mascagni" is placed in Melzo in the province of Milano. It is composed by two main blocks, one for classrooms, laboratories and offices, and the other for the gym and school canteen.

The first block is divided in two floors where at the ground lever there are laboratories of art, music and informatic, the library and the administration offices. On the upper level there are twenty-four classrooms for frontal lectures.

The main building is distributed on two storeys, with a gross area of around 1800 m^2 each; the intended uses of the spaces, with their respective total surface, are reported in the following tables.

The building it is not surrounded by tall buildings or other kind of obstructions that can generate relevant shadows for during the day.

Figure 3 Ground floor function distribution

Ground floor		
	Laboratories	637 m^2
	Offices	211 m^2
	Library + storage	201 m^2
	Toilets	101 m^2
	Corridor	535 m^2

Table 19 Ground floor area

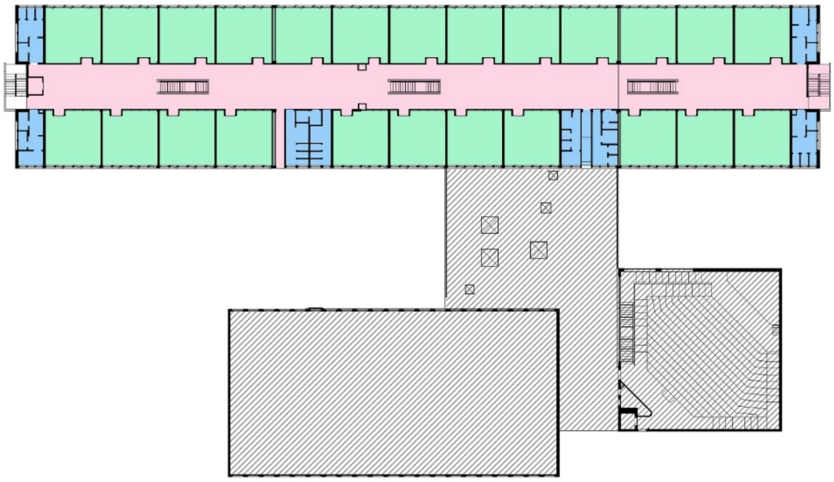


Figure 4 First floor function distribution

First floor		
	Classrooms	1080 m^2
	Toilets	153 m^2
	Corridor	548 m^2

Table 20 First floor area

Total surface		
Useful floor surface SU	3586	m^2
SLP	3979	m^2
H_0	3.5	m
H_1	3	m

Area total building		
A roof	2017	m^2
A ground	2017	m^2
A external walls	380	m^2
A windows	1477	m^2

Occupants' data	
Number of Students	600
Number of teachers	52
Number of Classrooms	24
Number of Laboratories	12
Number of students per classroom	25
Number of students per laboratories	25

Table 21 School data used to build IESve model

3.2. IESVE MODEL DESCRIPTION

The analyses of the school are based on specific 3D models made in IESve with the support of AutoCAD in some cases. Since the goal of this work is focused in particular on lecture spaces, each model was built considering only the classroom block which includes lecture places, laboratories, library, archives, offices and service and distribution spaces. Each strategy has its own building model that was designed and set with different levels of detail in the geometry and scheduling to achieve specific results.

The optimization process on the building envelope and the analyses on the internal comfort conditions have been divided into three steps, with growing level of detail:

- Model 1: Simplified classroom
- Model 2: School block
- Model 3: Four typical classroom and two laboratories

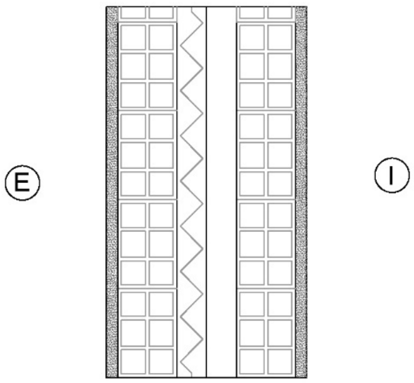
After the preliminary analyses the last model has been used to perform more analyses since its level of detail is considered sufficiently faithful to the existing building even if some simplification in geometry and scheduling were necessary. In particular, the net area of glazing surfaces was reduced at most of 4 cm in some corners in order to clarify the division of the window between the external wall. Also, skylights and chimneys placed on the room of the corridor were not designed in any models since the evaluation of thermal conditions in the corridor are not studied and previous analyses demonstrate that their presence was negligible in the total energy consumptions. In addition, the external shading system was not taken into account because it would affect the reliability of results. The rest of the geometry and distribution have been kept equal to the original project tables.

The variation of the space function is done on the third model where one laboratory and the library placed at the ground floor where changed into classroom to compare their results with the ones of other classroom at the first floor and decide which is the best place for lectures.

Baseline technologies

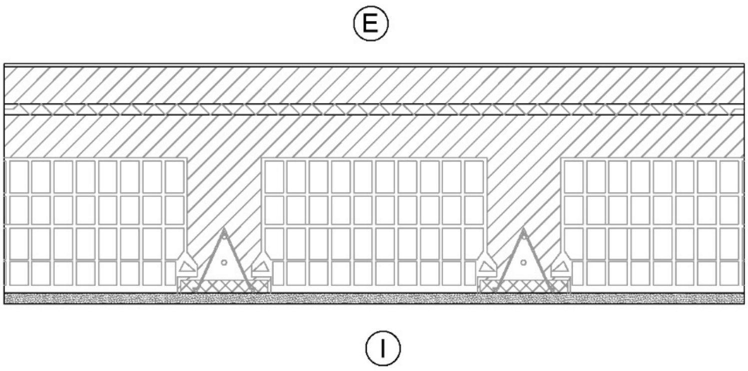
The baseline model is set on the existing building and that uses the construction technology of 1970’ which involves mainly the use of concrete and clay bricks with a little part of insulation material.

This technology is not performant from the energy point of view, in particular during the heating season since the presence of insulation is not sufficient in this kind of climate zone.



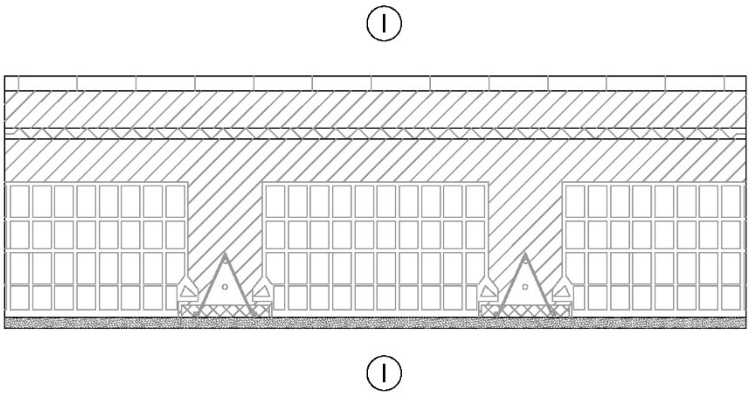
EXTERNAL WALL	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m²K/W]	[kg/m3]	[kJ/kg K]	[W/m²K]
ext			0.04			0.64
External layer	15	1	0.02	1800	850	
Hollow brick	80	0.4	0.20	1200	850	
Insulating layer	40	0.05	0.80	30	850	
Cavity	40		0.16			
Hollow brick	80	0.4	0.20	1200	850	
Plaster	10	0.7	0.01	1400	850	
int			0.13			

Table 22 Baseline external wall technology



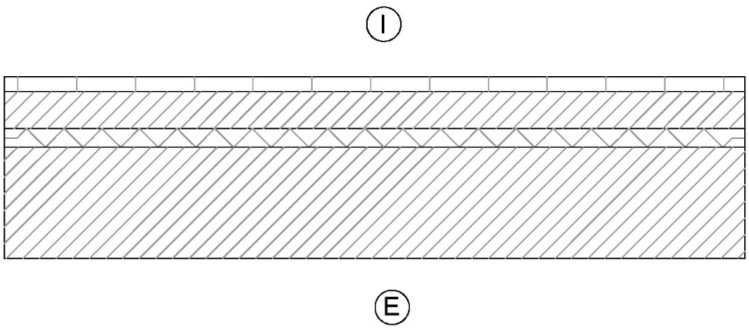
ROOF	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m²K/W]	[kg/m3]	[kJ/kg K]	[W/m²K]
ext	-	-	0.04	-	-	0.99
rain protection	4	0.23	0.02	1500	1300	
screed	50	1.4	0.04	2000	850	
insulating layer	15	0.04	0.38	30	850	
Reinforced brick-concrete slab	240	0.6	0.40	1200	850	
Plaster	10	0.7	0.01	1400	850	
int	-	-	0.13	-	-	

Table 23 Baseline roof technology



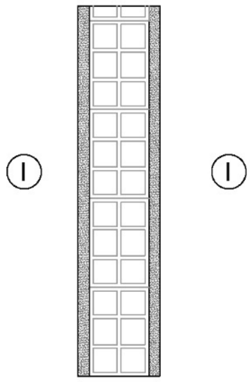
INTERNAL SLAB	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m²K/W]	[kg/m3]	[kJ/kg K]	[W/m²K]
int			0.13			0.91
Flooring	20	1.2	0.02	2000	850	
Screed	50	1.4	0.04	2000	850	
Insulating layer	15	0.04	0.38	30	850	
Reinforced brick-concrete slab	240	0.6	0.40	1200	850	
Plaster	10	0.7	0.01	1400	850	
int			0.13			

Table 24 Baseline internal slab technology



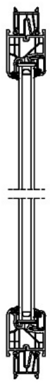
GROUND SLAB	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m²K/W]	[kg/m3]	[kJ/kg K]	[W/m²K]
ext			0.04			1.10
Reinforced concrete	150	2.3	0.07	2400	850	
Insulating layer	25	0.04	0.63	30	850	
Screed	50	1.4	0.04	2000	850	
Flooring	20	1.2	0.02	2000	850	
int			0.13			

Table 25 Baseline ground slab technology



INTERNAL WALL	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m^2K/W]	[kg/m3]	[kJ/kg K]	[W/m^2K]
INT			0.13			2.05
Plaster	10	0.7	0.01	1400	850	
Hollow brick	80	0.4	0.20	1200	850	
Plaster	10	0.7	0.01	1400	850	
int			0.13			

Table 26 Baseline internal wall technology



EXTERNAL WINDOW	Area	t	R	g-value	U
	%	[mm]	[m^2K/W]	[-]	[W/m^2K]
Clear glass		6	-	0.77	2.91
Air cavity		10	-		
Clear glass		6	-		
Metal without thermal break	30 %	60	0.01	-	5.56
Total			0.342		3.65

Table 27 Baseline external window technology

Occupancy schedule

The occupancy schedules are based on the real school calendar of Lombardy 2017-2018 considering the summer break from June to September, Christmas holydays and national/regional festivity.

This schedule is applied to classrooms, laboratories, library and drawings archives since they are almost used by students and teachers. Office and administration services are based on a different schedule that considers also the operation time during June, July and September.

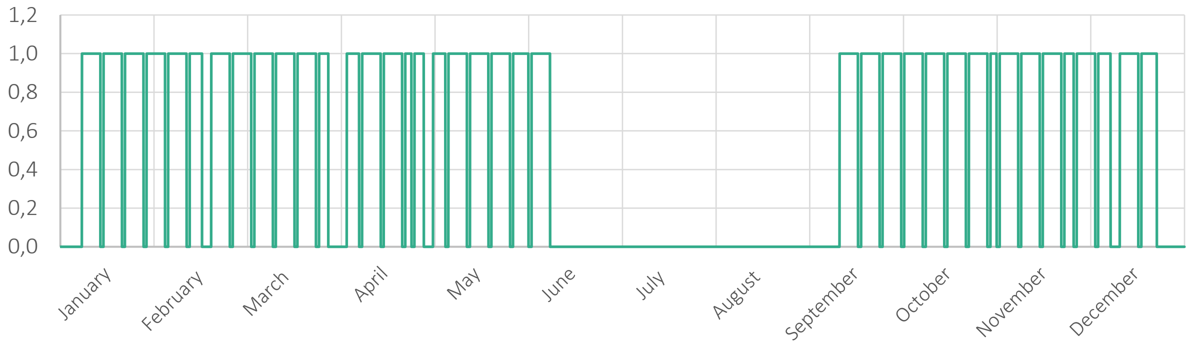


Chart 13 Year occupation schedule for students and teachers

The schedules related to the occupied hours are almost equal for the weekdays Monday-Friday where lessons are taken during the morning and during the afternoon; the same trend is kept on Saturday morning with no occupancy in the afternoon.

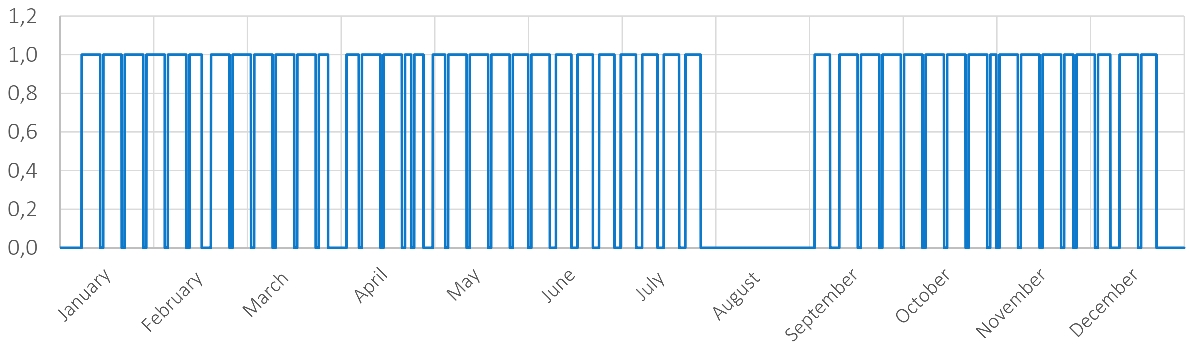


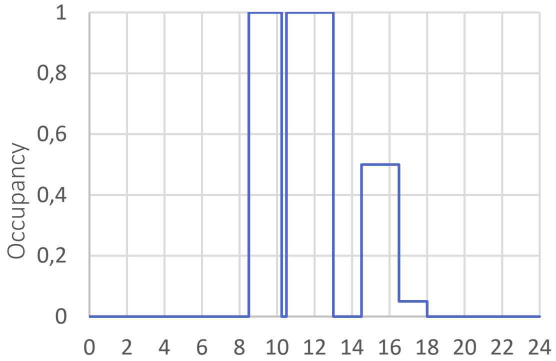
Chart 14 Year occupation schedule for administration offices

The daily schedules for occupancy are based on a realistic situation in which lessons start at 8.30 AM and finish at 13:00 with a middle break from 10:15 to 10:30. According to the school regulation, there are some courses where the lessons are taken only during morning from Monday to Saturday and some other that have lessons also in the afternoon from 14:30 to 16:30 from Monday to Friday.

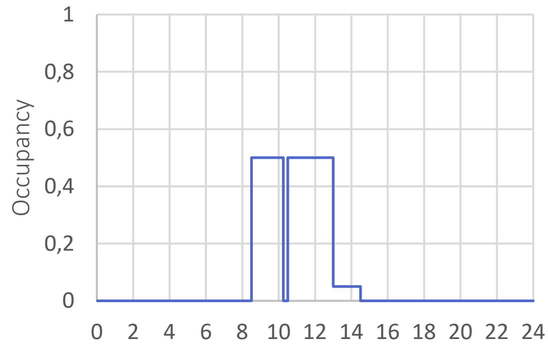
At the end of each lesson, for classes, it is considered a small supplementary occupation rate that is related to cleaning operations.

CLASSROOM daily schedule

Monday-Friday



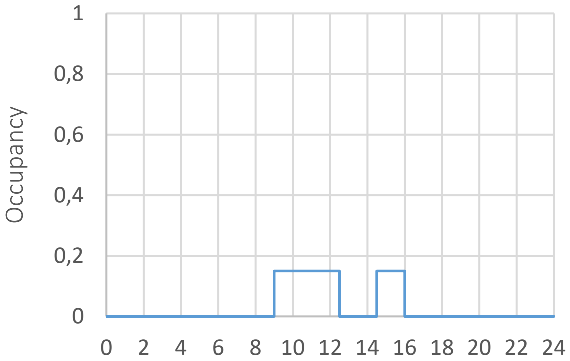
Saturday



T_{set} 20-26°C; ventilation 3.5 ach

LIBRARY daily schedule

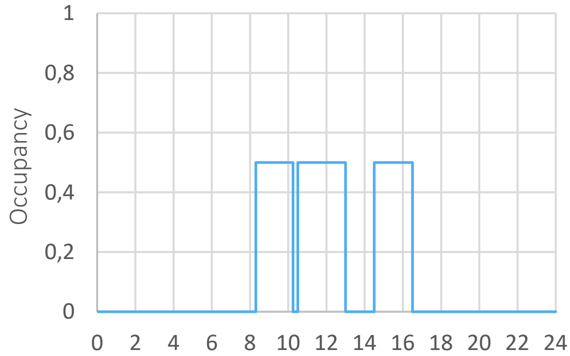
Monday-Friday



Tset 20-26°C; ventilation 3.5 ach

LABORATORY daily schedule

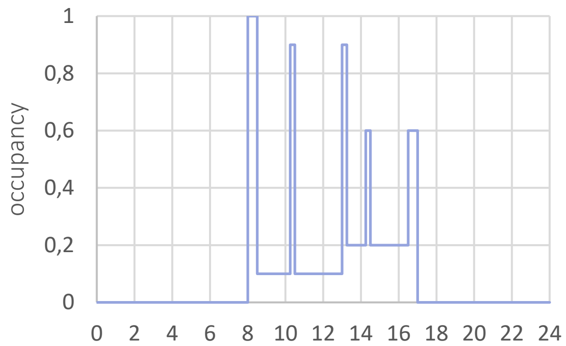
Monday-Friday



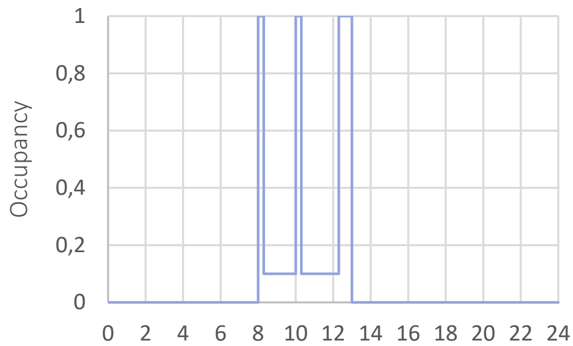
Tset 18-26°C; ventilation 2.5 ach

CORRIDOR daily schedule

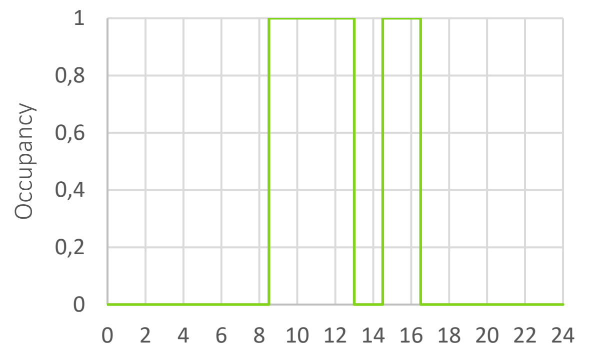
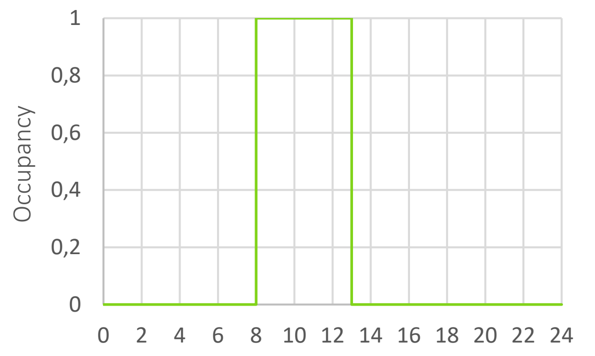
Monday-Friday



Saturday



T_{set} 18-26°C; ventilation 2.5 ach

<table>
<tr><th colspan="2">OFFICES daily schedule</th></tr>
<tr><th>Monday-Friday</th><th>Saturday</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">T_{set} 21-26°C; ventilation 1.5 ach</td></tr>
</table>

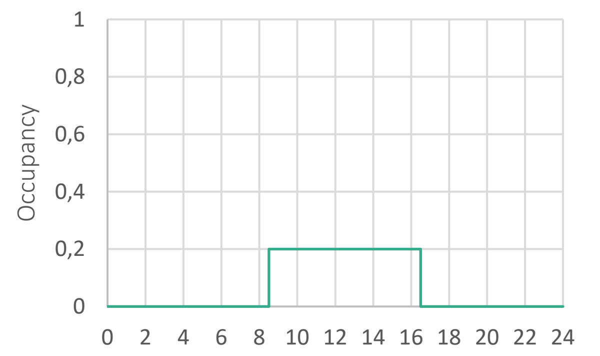
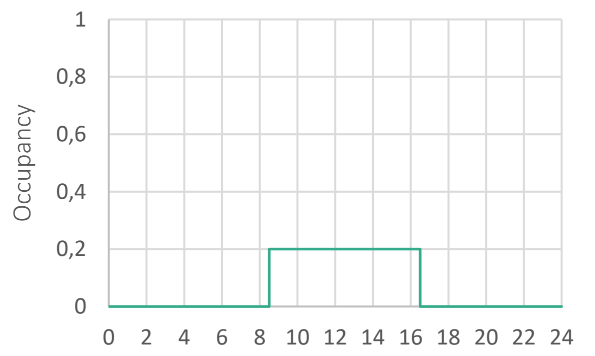
<table>
<tr><th colspan="2">TOILETS daily schedule</th></tr>
<tr><th>Monday-Friday</th><th>Saturday</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Tset 22-27°C; ventilation 3.5 ach</td></tr>
</table>

Table 28 Data for occupancy schedule

Form standard UNI EN ISO 11300-1 for climate zone E, it is possible to define the standard period in which the heating system must be activated.

Heating season: 15th October – 15th April

Non-Heating season: 15th April – 30th September

Cooling and heating systems Parameters

Primary energy coefficients DGR 967/2015 and from DM 26/06/2015

$$fPE_{th} = 1.05\ kWh_{PE}/kWh_{th}$$

$$fPE_{ele} = 2.42\ kWh_{PE}/kWh_{ele}$$

Cost assessment coefficients

$$c_{ng} = 0.06\ €/kWh_{ng}$$

$$c_{ele} = 0.20\ €/kWh_{ele}$$

3.3. OPTIMIZATION STRATEGIES

3.3.1. ENVELOPE OPTIMIZATION STRATEGY

In order to establish the possible optimization strategy some free-floating simulations were run. The absence of thermal systems for heating and cooling in the simulation generate outputs useful to analyse the influence of conduction exchanges between the building and the external environment.

At the first stage, the analysis detected the influence of gains and losses whose results have been divided for Heating and Non-heating season. The pie chart is done in order to evaluate the percentage of each contribution on the total result; while the column chart wants to underline gains (positive numbers) and losses (negative numbers) through the building. In this way, it is possible to test the variation of each contribution on the Heating and Non-heating season and the monthly variation. Then, the analysis focuses on the external conduction gain and on elements, that contribute to increase this gain comparing them with the influenced area.

Moreover, it was analysed the hourly temperature variation considering the operative temperature instead of air temperature. According to ASHRAE, operative temperature is "the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment". In fact, comfort condition of internal spaces is mainly influenced by air temperature and mean radiant temperature. These two parameters can be combined to get the operative temperature that is the real temperature perceived by occupants.

$$t_0 = \frac{h_{CV}\, t_{air} + h_R\, t_{MR}}{h_{CR}}$$

Where

h_{CV} is the convective heat transfer coefficient that was assumed equal to 2.5 W/m^{2}K

t_{air} is the air temperature

h_R is the radiant heat transfer coefficient 5.7 W/m^{2}K

t_{MR} is the mean radiant temperature

h_{CR} is the sum of convective and radiant heat transfer coefficients

Model 1: Simplified classroom

The first model is the simplest one. Since the lecture block of the existing building is composed by twenty-four classrooms based on a class-module with standard dimensions of the entire space, window and door, it is decided to analyse only two of those thermal zones. The two classrooms with standard dimensions are placed on the ground and the first level as the existing building and South oriented. The construction technologies match the baseline solutions and the geometry of each component like door and windows follow the original position, but the shading device was no considered in order to avoid any fake results. The rest of the building was simulated in IES with an adjacent building close to the two classrooms with the same thermal conditions.

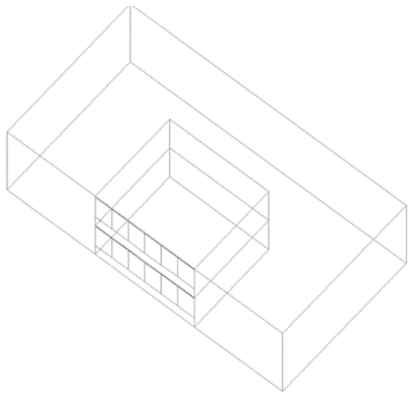


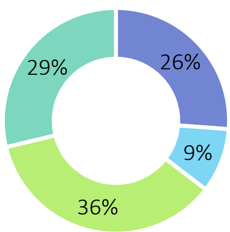
Figure 5 Model 1 geometry

The occupancy schedule where set on a real case in which the school can be occupied during morning and afternoon and closed in the weekend (Saturday and Sunday); the summer and winter break were considered but not very précised. Also, national, regional and other holydays and closure days were not taken into account.

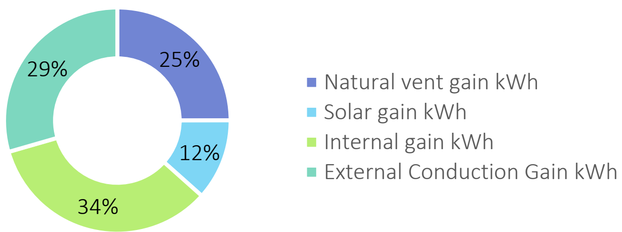
With the free-floating analysis it is possible to analyse gain and losses of the building model for winter and summer period. The gain charts show the percentage of the contribution of natural ventilation related to air changes, solar gain, internal gain due to people and lighting and the external conduction gain; the internal conduction gain was not included into the diagrams because its contribution was close to zero and thus, negligible. Each contribution is calculated as an energy sum of the two thermal zones. The internal gains and natural ventilation gains, which cover more than half of the total contribution, are fixed since they are linked to the occupancy schedule and parameters imposed by standards to guarantee a good air quality; thus, they can't be changed or improved. The charts show that the percentage of their contribution is almost the same along the year with a little increment in winter. About 30% of the total gains is related to the external conduction, without any variation from summer to winter; the other part is related to solar gain that comes inside the room thanks to the presence of windows. In this case, the charts highlight an increment of 3% from winter to summer period because of the intensity of Sun rays, higher in summer.

According to the results, the envelope of the building can be optimized in order to reduce the external conduction and solar gain. The first contribution has negative effects in winter because it allows thermal losses and positive in summer, since it gives internal heat to external environment. On the other hand, the second contribution, the solar gain, is a free energy heat source in the cool season but it must be avoided in summer in order to reduce the heat gain as much as possible.

Gains: Heating season



Gains: Cooling season



Gain comparison

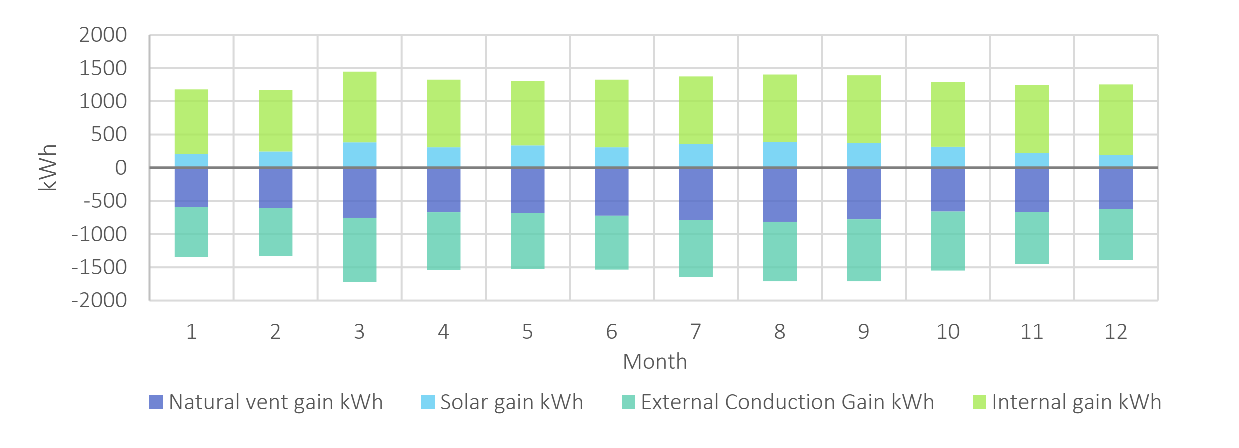


Table 29 Model 1 gain analysis results

The external conduction gain is generated by the building surfaces in contact with the external environment as opaque walls, glazing, roof and ground slab. The following charts show the influence of each element on the external conduction: the major contribution is done by windows since the glazed surface is more relevant and by the roof.

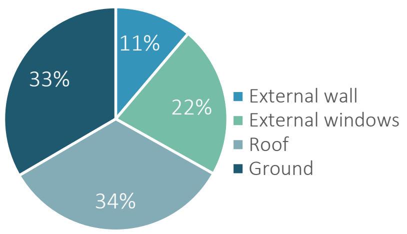
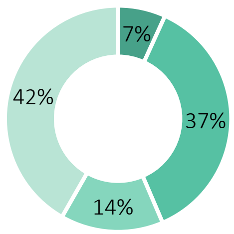
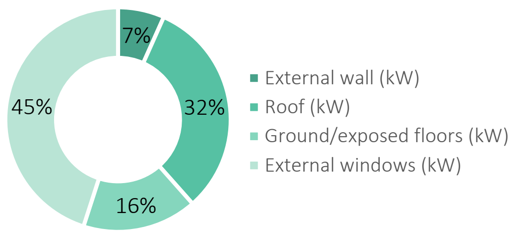
Areas	Conduction gains: heating season	Conduction gains: cooling season
		

Table 30 Model 1 external conduction gain analysis results

Observations for Model 1 strategy

Form the results obtained by this preliminary analysis the possible strategy to achieve better internal environment quality, improve comfort condition for occupants and saving energy start with the optimization of the envelope. This strategy consists of applying some operations that will decrease the external conduction.

For this model the list of priorities for action is:

1. Windows change
2. Roof insulation
3. Shading the external windows
4. Ground insulation
5. External wall insulation

Model 2: Total building

The second strategy consists on analysing the total building set as a sum of different thermal zones. The level of details in the model is increased respect to the previous case; windows are set in the correct way and the geometry of the building is close to the existing one. The occupancy schedule of spaces is based on the real calendar 2017-2018 of secondary schools in Milano.

The charts of the gain demonstrate that the higher contribution is due to the external conduction gain that influence the 38% in winter and 39% in summer of the total gain.

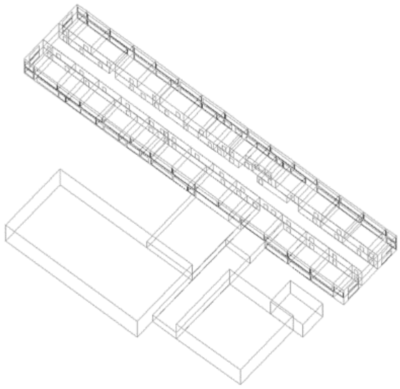


Figure 6 Model 2 geometry

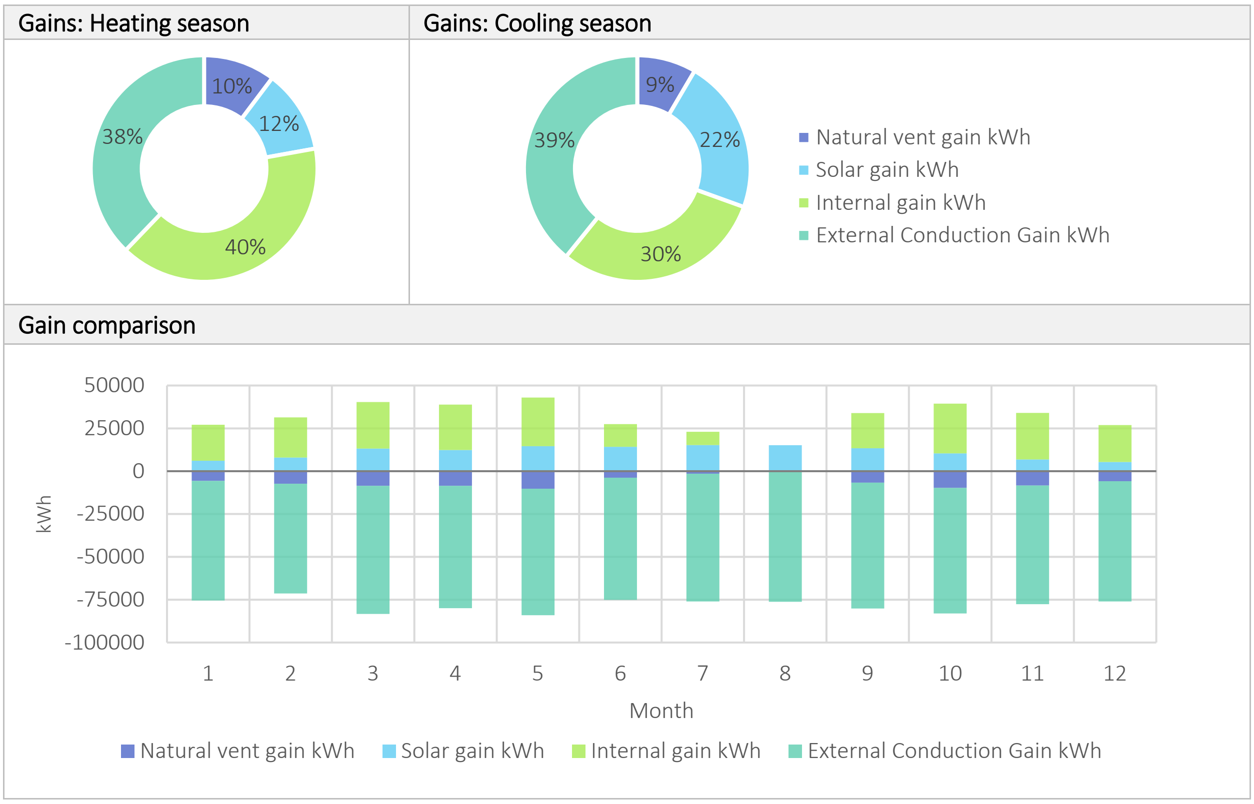


Table 31 Model 2 gain analysis results

Studying the external conduction gain, it is possible to work out the energy lost by conduction for each construction element. In winter, the greatest losses are due to the presence of windows which contribute to lose 55% of the total energy even if the occupied area is only the 14% of the total external building surface; while the low-insulated roof dissipates 20% of the energy, according to its large surface. In summer, the energy lost by these elements is a bit more different: 48% of the energy lost by glazed surface and 31% from the roof. In both seasons, the influence of external wall is very low since its area is not much extended. On the other hand, the ground surface covers the more than one third of the global external surface, but its losses are only the 22% of the total kWh amount. This effect is strictly connected to the inertia of the ground that is different from the inertia of air and. Also, the fluctuation of ground temperature is lower respect to air temperature; thus, losses due to the difference in temperature between building and environment are reduced.

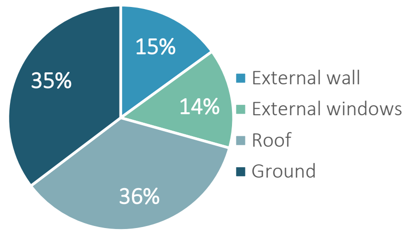
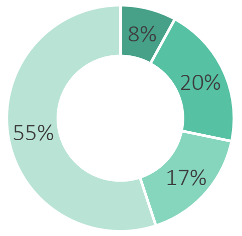
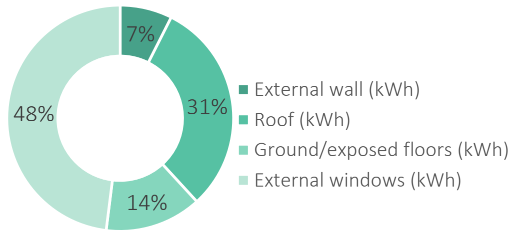
Areas	Conduction gains: heating season	Conduction gains: cooling season
		

Table 32 Model 2 external conduction gain analysis results

Observations for Model 2 strategy

The analysis on this model is useful to understand the real influence of external conduction gain/loss since the geometry of the model is faithful to the existing building. In fact, the percentage of energy lost by each construction component is more reliable than the previous strategy and they can be used to set the list of intervention to apply at the whole building.

Thus, the list of priorities for action in this case would be:

1. Window change
2. Solar shading
3. Roof insulation
4. Ground insulation
5. External wall insulation

Model 3: Four typical classroom and two laboratories

The third strategy uses the same model of the Model 2 with the same level of accuracy in the geometry, scheduling for occupancy and ventilation rate. In this case, the analysis was done on four classrooms and two laboratories where students spent most of their time. In order to establish the best position for lecture the functions of some thermal zones like library and archives or laboratories are modified into classroom. Therefore, the objects of this analysis are four classrooms and two laboratories highlighted in the figure that are placed at the first and ground floor facing North and South.

Figure 7 Model 3 geometry

Classrooms N.0 and S.0

Two laboratories of the ground floor have been changed into classroom in order to evaluate which is the best position for lectures; thus, classroom N.0 and S.0 whose original function were library and archive, have been transformed into classroom.

The charts of the hourly temperature registered inside the spaces are useful to analyse one of the comfort parameter in the middle season since it is quite obviously that the building requires the presence of a heating system for winter season, from November to February. In fact, the temperature of classroom N.0 (North oriented) in the Non-heating season is almost in the comfort range 19-26 °C, but there are some hours of underheating at the end of April and at the beginning of October and some hours of overheating in May, June and in the middle of September. Analysing the Heating season (rose areas) there are some peaks in which the internal temperature reaches the comfort values. In particular, these peaks are registered in the transition phase from Winter to Spring and in Autumn.

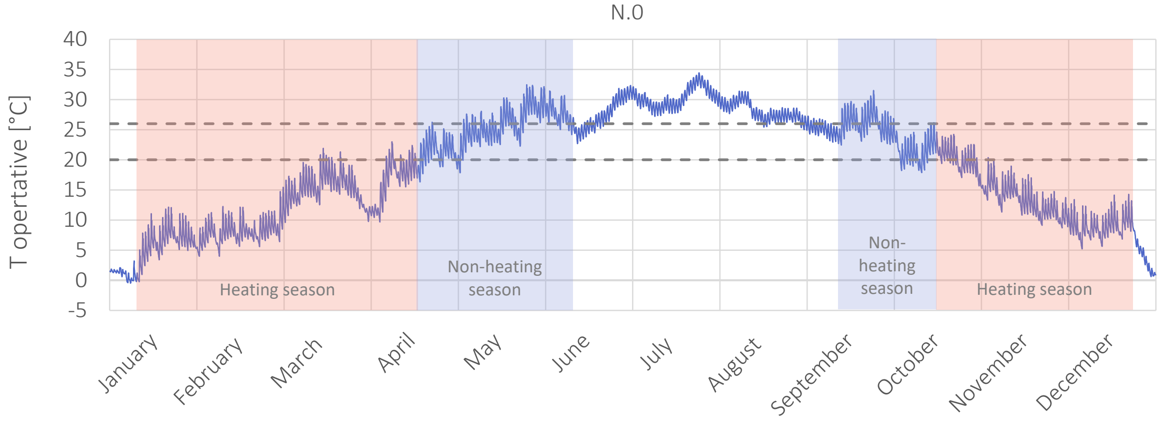


Chart 15 Operative temperature of classroom N.0

The temperature variation of the classroom S.0 has the same trend of the previous thermal zone, but its values are a bit higher since this room faces South. In fact, the Non-heating season presents less hours in which internal temperature is lower than the comfort value and high number of peaks of overheating, registered in May, June and September. As in the previous case of classroom N.0, the hourly temperature chart of classroom S.0 shows that there are some hours in March, April, October and November in which the internal temperature is in the comfort range even if there is no system activated. In particular, October has most of the occupied hours in the comfort range thanks to the presence of internal gain and solar gain due to the South orientation.

This means that the division of Heating and Non-heating season (from 15th of October to 15th of April and vice versa) imposed by Italian law is not always the best method to achieve internal comfort and energy saving.

The spaces marked my white areas represent Christmas holydays and summer break where the school is closed. Therefore, these periods are not taken into account in the following evaluations.

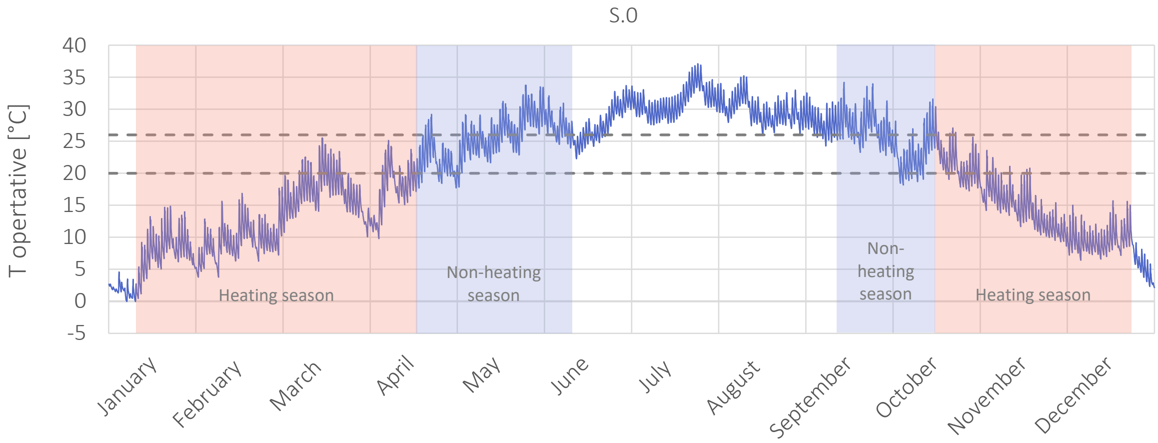


Chart 16 Operative temperature of classroom S.0

From the gain analysis it is possible to establish which parameter generates the highest contribution. In the Heating season, internal gains play the greatest role, but they can't be avoided or reduced since they are linked to the occupancy rate and lighting system. The second greatest parameter that influence the global balance is the external conduction gain that represents an energy lost along the year, in this climate conditions. As expected the solar gain has a bigger influence in classroom S.0 due to its orientation towards South. In fact, it generates the 20% of the balance and it is a good and passive strategy to heat up the space during the cool season. Natural ventilation gain and internal conduction gain represents the smallest contribution, almost equal for the two thermal zones. In particular, natural ventilation corresponds to an energy lost in both Heating and Non-heating season. Obviously, the presence of heat losses has a positive effect only in summer or in the middle season where it contributes to chill the space. Since the minimum ventilation rate that guarantee a good level of internal air quality is imposed by law, this parameter can't be optimized. As an alternative it is possible to refresh internal air with a mechanical ventilation system with heat recover and compare its energy consumptions with the energy lost by natural ventilation.

In the Non-heating season, the external conduction gain generates the biggest loss of energy with 38% in classroom N.0 and 34% in the other. Opposed to the Heating season, here it has a good influence thanks on the negative temperature difference from internal and external environment, that allows to dissipate heat stored inside the room. As expected, solar gain is bigger respect to the heating season since in the Sun rays are more direct and solar altitude increases in the central months of the year. Natural ventilation gain is almost the same for both classrooms and the internal conduction gains has increased a little bit due to the difference in temperature between internal spaces, in particular between the classroom and the corridor. In fact, temperature of the corridor is lower respect to classrooms because it is not reached by solar rays and also because its occupation time is much lower than the classroom one.

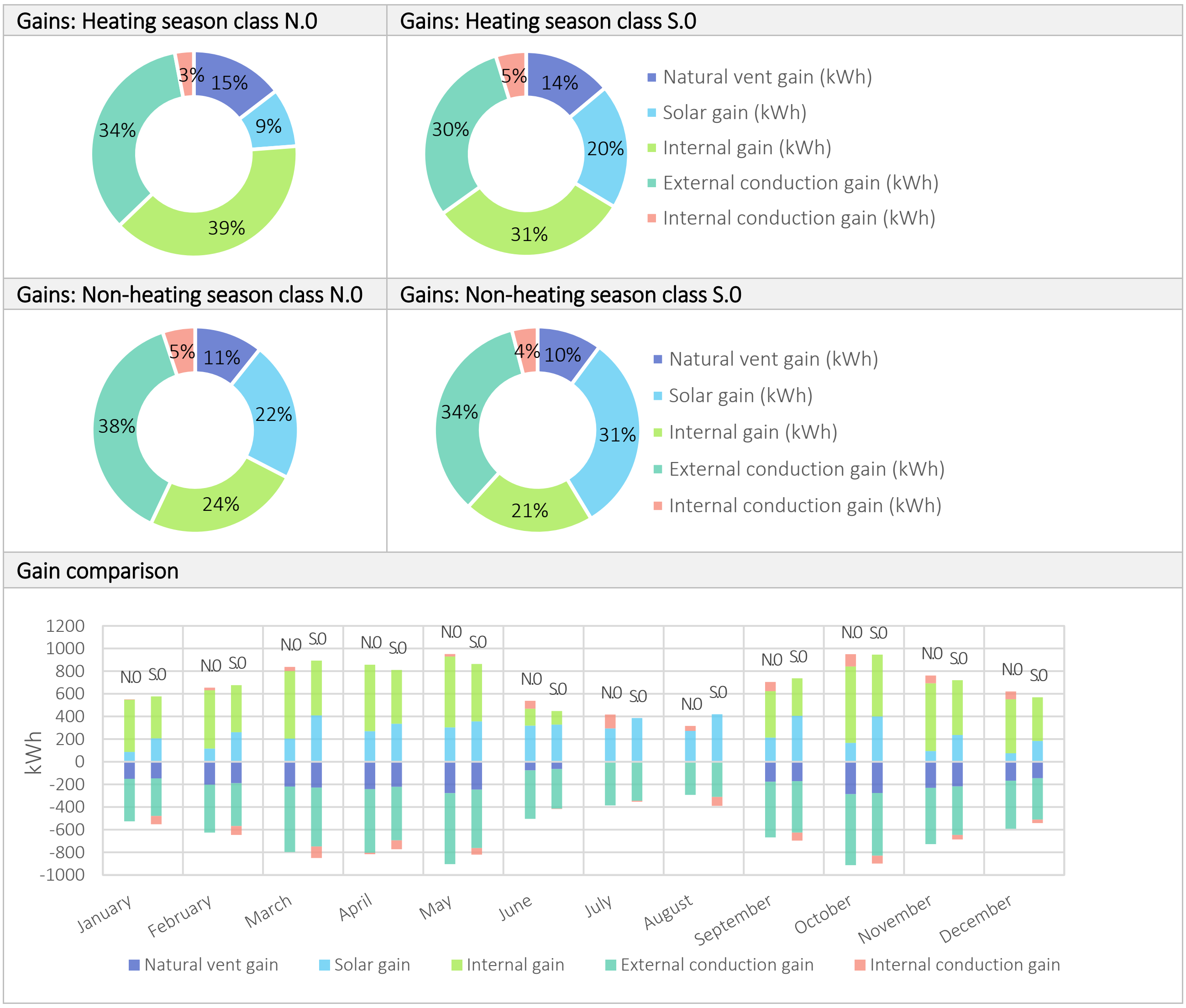


Table 33 Model 3 N.0 S.0 gain analysis results

According to the gain analyses, the highest contribution on the global balance is represented by the external conduction gain and it can be reduced by an envelope optimization.

Focusing the analysis on the external conduction gain it is possible to underline that the presence of windows with low performance that generate the 72% for the total losses for the classroom North oriented and 69% for the other with South exposition even if the area covered by glazing is only 20% of the total exposed surface. The ground floor, whose surface is the biggest, dissipates only 20-30% of the total energy; in particular, charts underline that the ground floor loses more energy in the South classroom respect to the North one. This effect it linked to the difference in temperature between the ground (whose temperature is constant) and classroom which is bigger for rooms South oriented. Thus, higher ΔT implies higher thermal losses.

The external condition gain related to the opaque façade is very low since its area is not very extended and its thermal characteristics like thermal transmittance and thermal inertia are much better respect to the poor thermal characteristics of glazing.

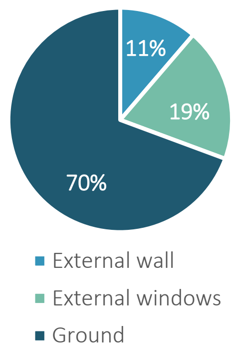
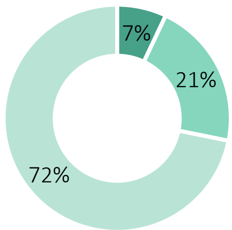
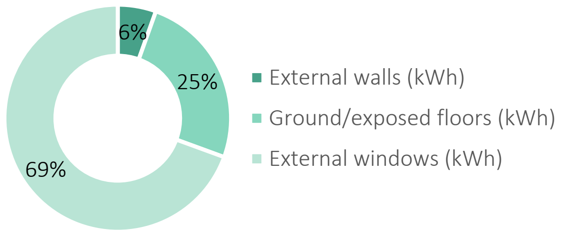
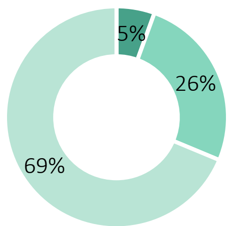
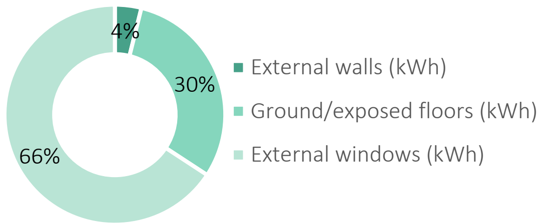
<table>
<tr><th rowspan="2">Areas</th><th colspan="2">Conduction gains</th></tr>
<tr><th>Heating season classroom N.0</th><th>Heating season classroom S.0</th></tr>
<tr><td rowspan="4">
</td><td>
</td><td>
</td></tr>
<tr><th>Non-heating season classroom N.0</th><th>Non-heating season classroom S.0</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Table 34 Model 3 N.0 S.0 external conduction gain analysis results

Classrooms N.1 and S.1

These two classrooms are placed at the first floor of the school block; class N.1 faces Nord, while S.1 faces South. The hourly internal air temperature chart is important to understand the temperature variation in the Non-heating season and analyse the temperature peaks in these periods.

As expected, higher temperature values are reached in the South class respect to the other. In particular, the internal air temperature of classroom N.1 in the middle season is almost in the comfort zone 19-26 °C with some lower peaks at the end of April and higher peaks between May and June. On September the internal temperature can satisfy occupants' expectation, but in October there is a significant decrease of temperature that would create discomfort for some hours.

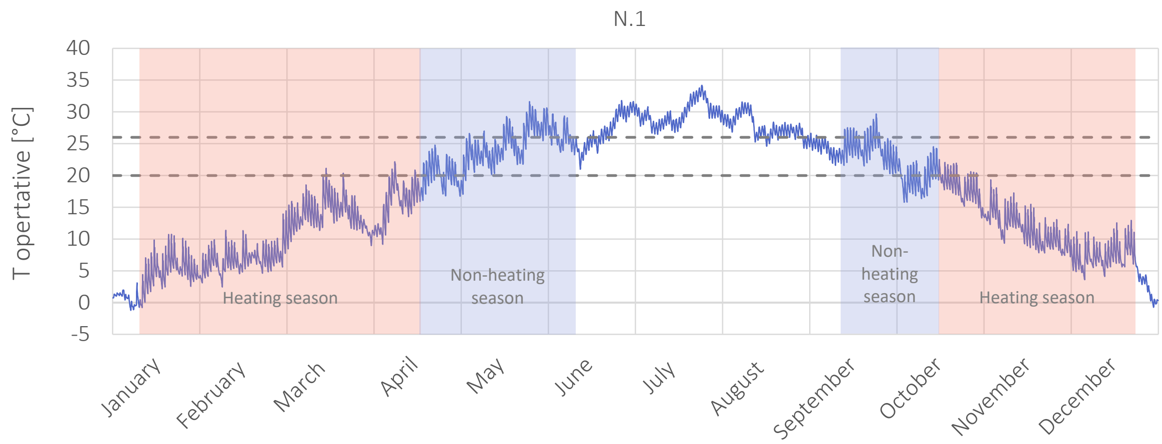


Chart 17 Operative temperature of classroom N.1

The trend of internal temperature related to Class S.1, with South exposition, is a bit higher and its peaks of variation are more extended than the previous one. Consequently, the internal temperature in the middle season is in the comfort area except for some days at the end of March, where it decreases until 16°C, but then increasing again. The highest peak of the middle season for this thermal zone has been recorded at the end of May where temperature reaches 32°C. Also, in September the internal temperature presents some peaks above the comfort range, but it decreases with the beginning of October. In the middle of this month there are some hours of overheating, where temperature is equal to 28 and 29°C without the activation of heating systems.

From the charts it is clear that these thermal zones require the presence of heating system from October to April and they should be separated for the south and north thermal zones.

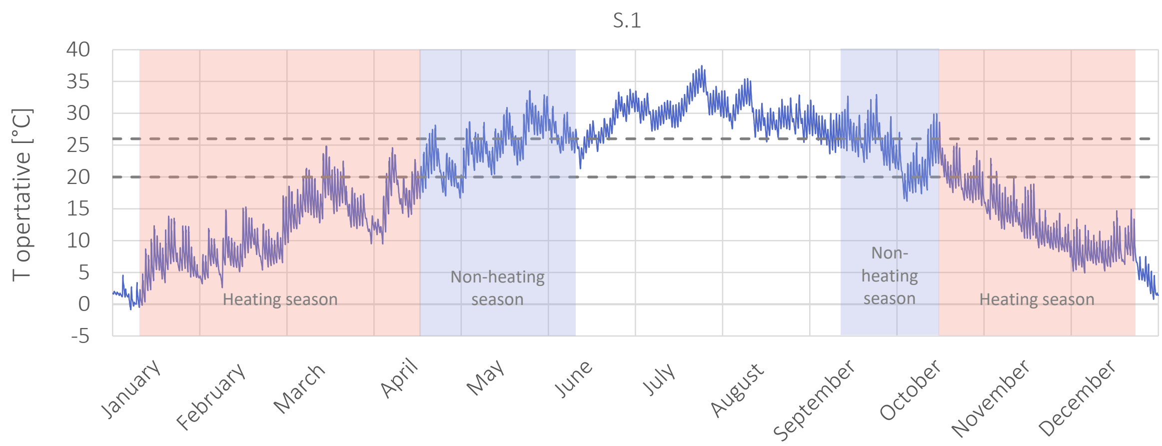


Chart 18 Operative temperature of classroom S.1

Focusing the analysis on gains and losses of the two classrooms it is possible to underline that the external conduction gains is the highest contribution which is almost equal for the two spaced, in winter and summer season. This loss covers more than one third of the total energy and the greatest part of the losses associated to these thermal zones, as already underlined by the previous analyses.

The solar gain is a free energy that contributes to heat up the internal environment in winter even if it is not very influent on the balance. Its value is lower for the classroom with North exposition, (only 8 % since only diffuse radiation reaches these parts) and higher for the classroom that faces South (22%). In Non-heating season its value increases due to the rise of Sun altitude at the beginning of summer period.

The internal conduction gain is higher in winter respect to summer. This value represents the heat transmitted by conduction through internal walls, partitions, floors and ceilings. The charts underline that the internal conduction gain values are higher in the Heating season respect to the Non-heating one. This effect is due to the negative difference in temperature of the classroom at the ground floor which are warmer than the first-floor classroom. On the other hand, in summer the temperature difference between first-floor classrooms and ground-floor ones is not always negative, thus the balance of their gain and losses is very low that influences the total energy gain as 1 or 2%.

Ventilation gain and internal gain are values that can't be optimized since they are related to fixed parameter imposed by low or linked to the occupancy rate.

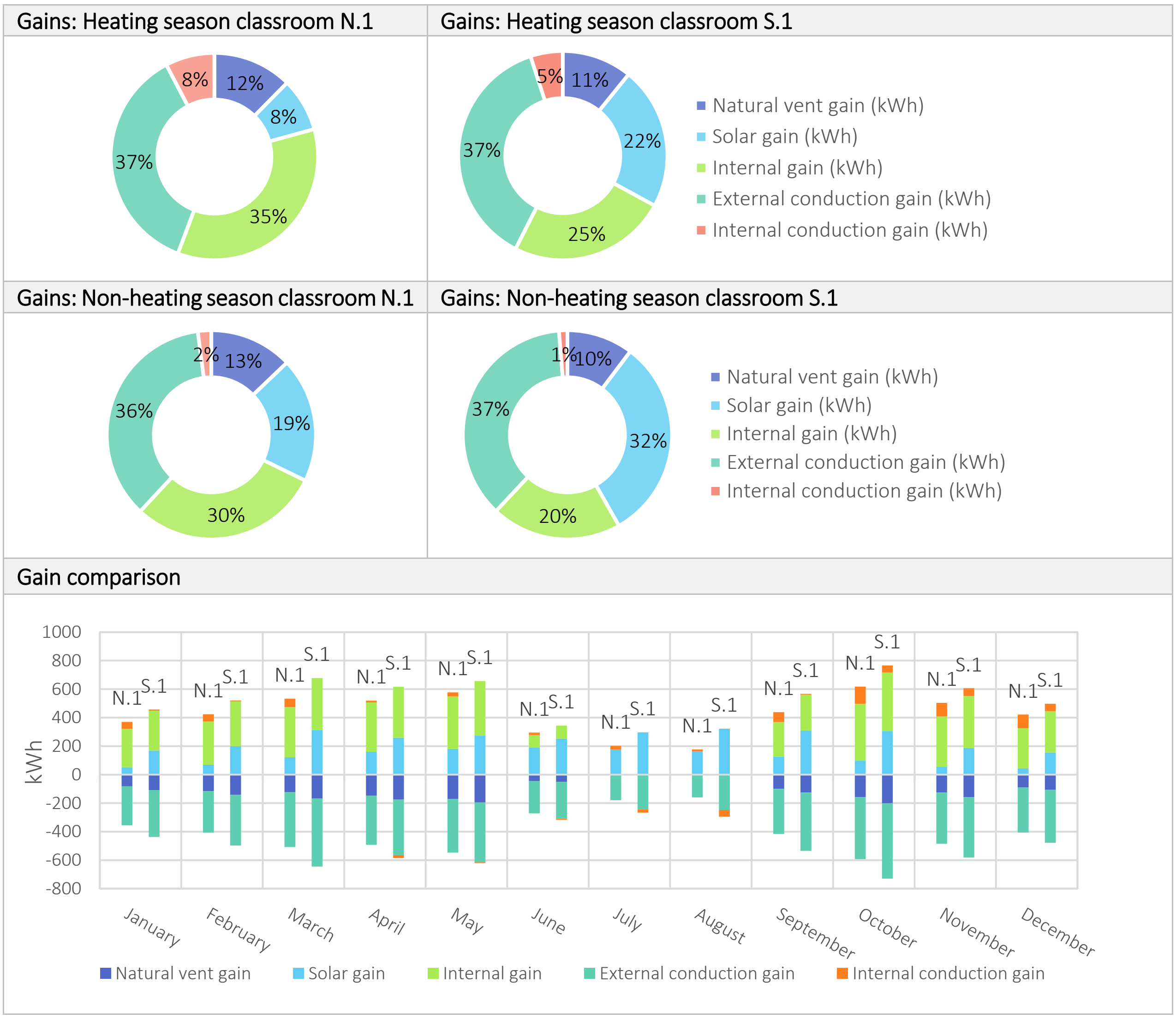


Table 35 Model 3 N.1 S.1 gain analysis results

The following charts show the external conduction gains. In particular they underline that the highest contribution (thermal losses by conduction) is due to the presence of windows with very low thermal performances even if their surface is only 18% of the total. The second highest contribution on thermal losses is represented by the non-insulated roof since its area covers more than one half of the total exposed room surface.

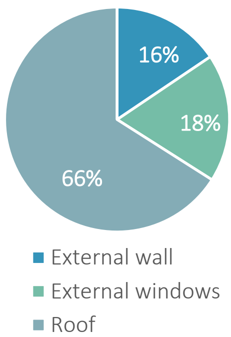
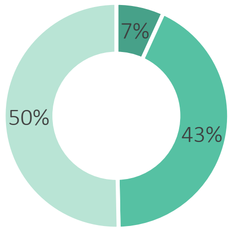
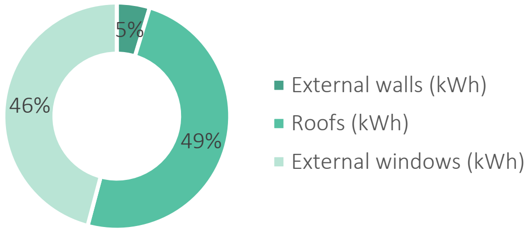
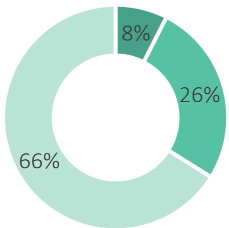
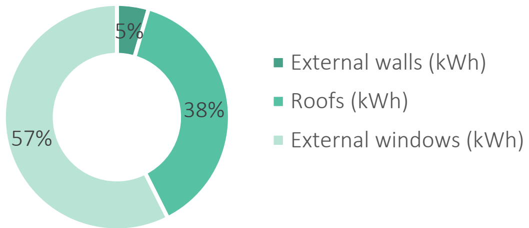
Areas	Conduction gains	
	Heating season classroom N.1	Heating season classroom S.1
		
	Non-heating season classroom N.1	Non-heating season classroom S.1
		

Table 36 Model 3 N.1 S.1 external conduction gain analysis results

Laboratories N.0L and S.0L

Laboratories N.1L and S.1L are placed at the ground floor. Their occupancy parameters are different respect to the parameter used for classrooms since their function is different. In fact, laboratories are generally use less than lecture spaces, but they have to be considered in the analyses in order to set the best optimization strategy that guarantees a good level of internal comfort for all spaces used by students.

In fact, the internal temperature is strictly connected to internal gains like the presence of people, lighting system and computers. The following charts show that the hourly temperature trends for laboratories N.0L and S.0L are lower than the one registered for classrooms.

The Non-heating season temperature is almost in the comfort range in both laboratories, in particular in May. Peaks under the comfort level are registered in April where the lowest internal temperature reached is equal to 15.2 °C for laboratory N.0L at the 15th of April, just at the beginning of the Non-heating season imposed by law. In fact, the chart shows that in the second half of April at the beginning of the day temperature is under the comfort range; then, the presence of internal gains and the influence of solar gain rise the internal temperature until it reaches the comfort area. Again, the charts show underheating peaks in October, where temperature decreases according to the reduction of external temperature in Autumn. Peaks of overheating are present at the end of May, June and September with higher values for laboratory S.0L that faces South.

In the Heating season the internal temperature is outside the comfort areas except for few hours registered in March, April and in October, where temperature increase and reaches comfort values. The number of these peaks are much lower compared to classrooms' one.

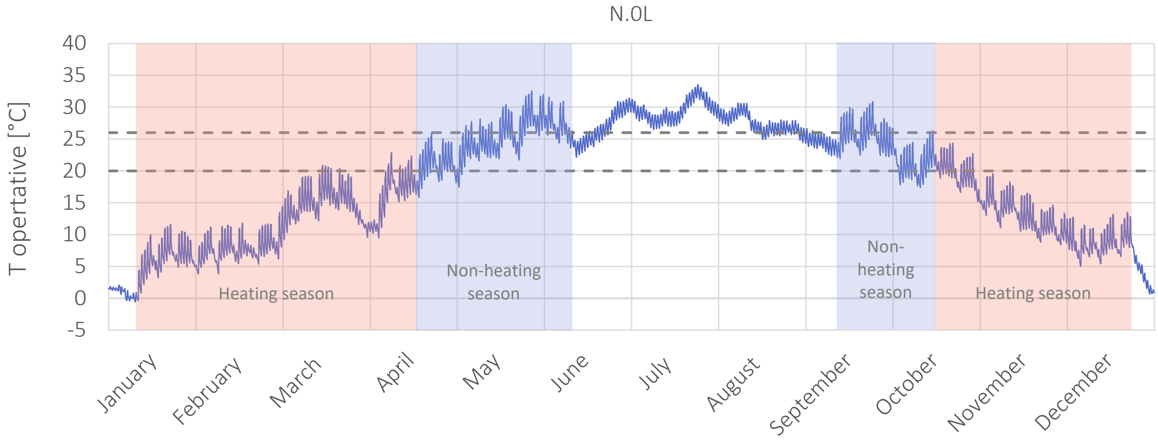


Chart 19 Operative temperature of classroom N.0L

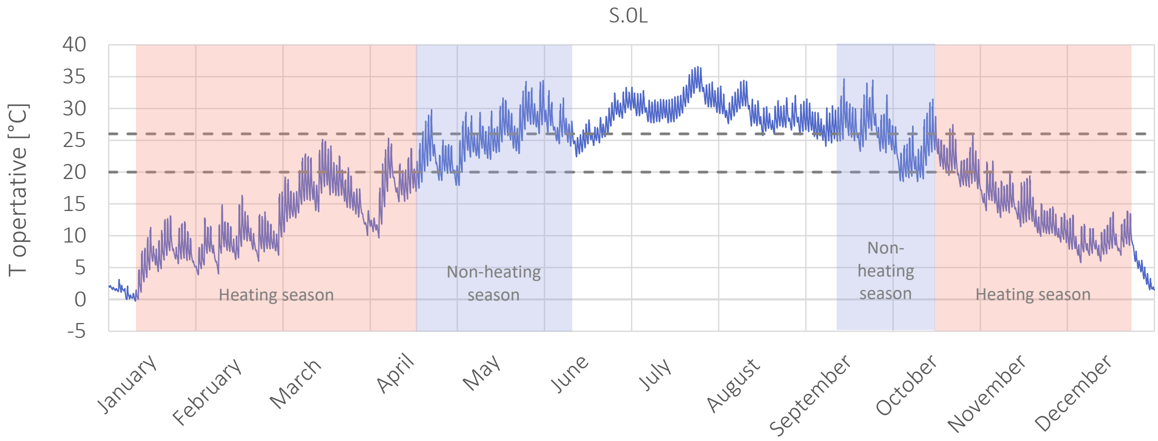
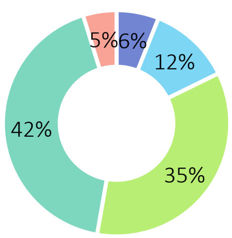
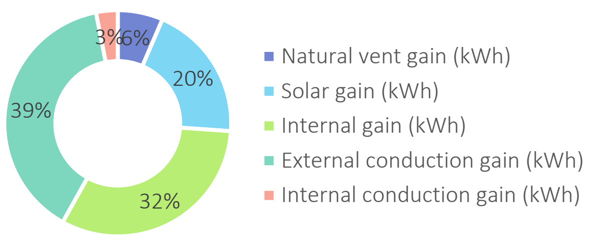


Chart 20 Operative temperature of classroom S.0L

Like in the gain analyses related to classroom N.0, S.0, N.1 and S.1, the highest contribution is given by the external conduction gain which influence the 42% and 44% in N.0L and 39% in S.0L. The second highest parameter that influences the balance is the solar gain whose contribution is greater in laboratory S.0L respect to laboratory N.0L since it faces South.

Gains: Heating season classroom N.0L	Gains: Heating season classroom S.0L





Gains: Non-heating season classroom N.0L	Gains: Non-heating season classroom S.0L

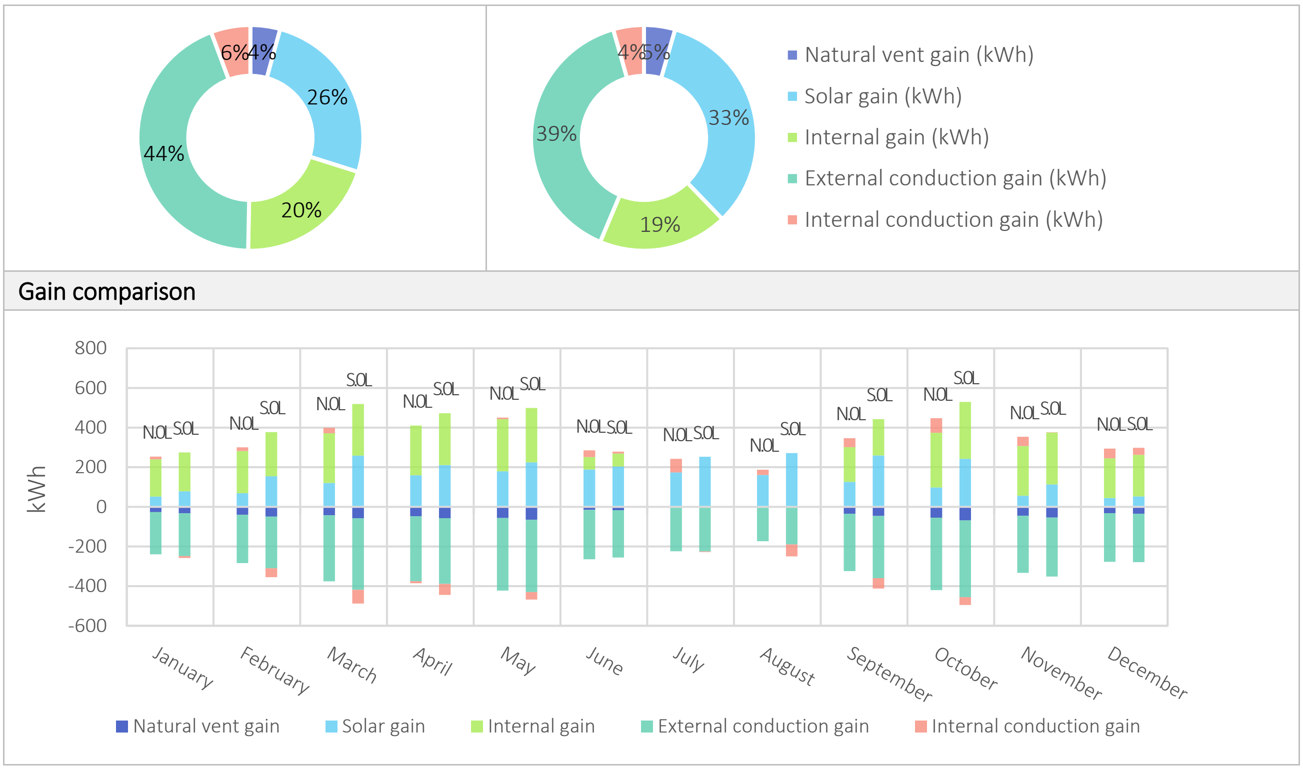


Table 37 Model 3 N.0L S.0L gain analysis results

Also in this case, the presence of windows with high value of thermal transmittance causes a huge thermal loss in both laboratories, in Heating and Non-heating seasons. The ground floor dissipates from 21 to 26% in N.0L, while about one third of the total energy in S.0L. The influence of the external wall is very little since its area is not extended.

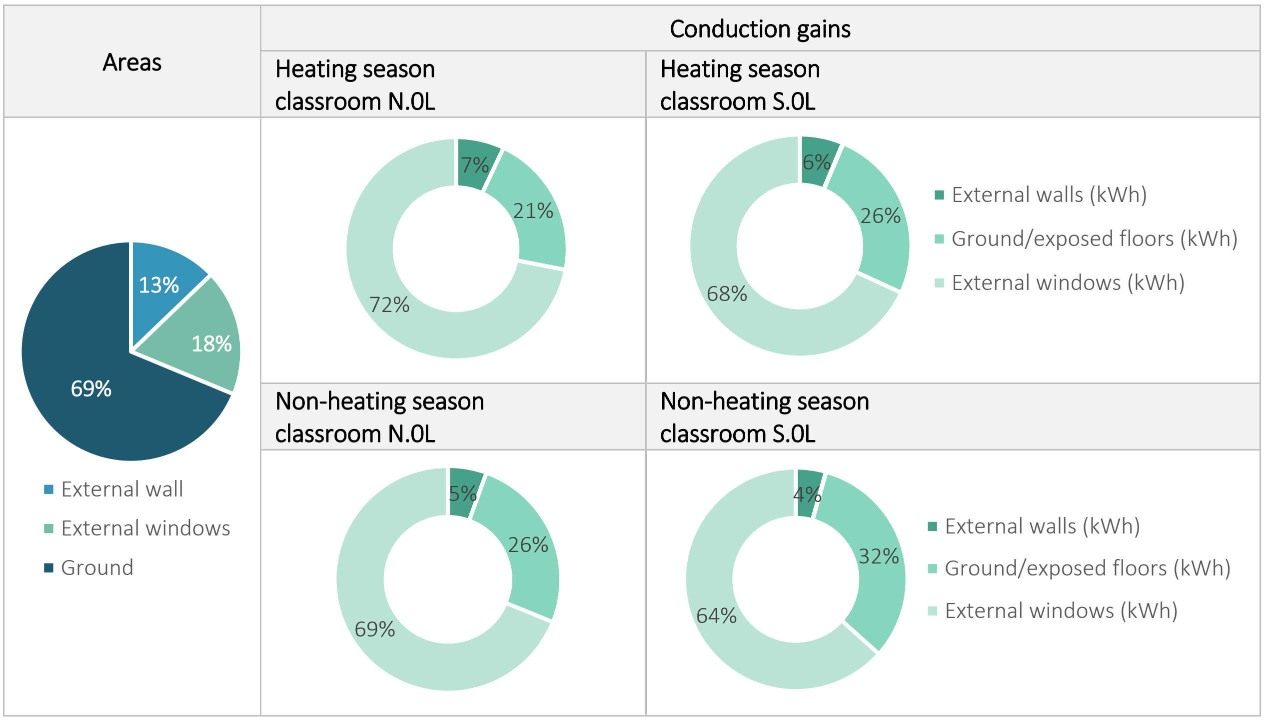


Table 38 Model 3 N.LO S.0L external conduction gain analysis results

Peak comparison

After the analysis on energy gains and losses on whole year, it is analysed the power generated of the thermal zones N.0, S.0, N.1, S.1, N.0L and N.0L during the worst day. This analysis is useful to study the daily variation of gain and losses of a single room, compare the trends of many thermal zones avoiding the influence of the geometry and it can be used as a reference baseline trend test the optimization effectiveness of further analyses.

The calculation of the worst day was done according to the highest value of hourly internal temperature of thermal zones on the occupied days; holydays and summer break are no taken into account since the school is closed and there is no request of comfort conditions. The worst day analysis on the six thermal zones provides the following results:

Thermal zone	Worst day	Internal temperature
N.0	17^{th} of May	31.65 °C
S.0	26^{th} of May	33.26 °C
N.1	26^{th} of May	32.52 °C
S.1	26^{th} of May	33.95 °C
N.0L	28^{th} of May	31.85 °C
S.0L	14^{th} of September	33.66 °C

Table 39 Worst day results according to the position of the thermal zone

The highest value of internal temperature is recorded in classroom S.1 at the 26^{th} of May, therefore this day has been chosen as the reference day for all the thermal zones and, for this day, it is analysed the daily power variation in kW/m^2 and in kW/m^3.

The power trend showed by the charts represent the sum of Natural ventilation gain, Solar gain, Internal gain, External conduction gain and Internal conduction gain. Due to the presence of these parameters the trend of the power is close to zero when the school is closed (from 18 to 8) since internal gains and solar gains are zero and the unique source of energy losses is represented by internal and external conduction. From 8 to 13.30 the classroom is used by students and teachers and in the afternoon from 14.30 to 16.30 by only half of the students. The trend presents also some decrescent peaks at 10.15 and 13.30; they correspond to periods in which classroom or laboratory are empty due to the middle morning break and lunch break. The highest peak is reached at 13.00 where internal gains and the solar gains are maximum.

The trend of pawer expressed in kW/m^2 with the highest value of gain and loss is related to class S.1, placed at the first floor and South oriented, while the lower values have been generated by laboratory N.0L, at the ground floor that faces North. For laboratory N.0L it is possible to underline that at 13.00 the power is not increased like in classroom S.1 because the laboratory is not hit by direct solar radiation. In fact, the thermal zones oriented toward North (N.0, N.1 and N.0L) present a flatter trends respect to those spaces that face South.

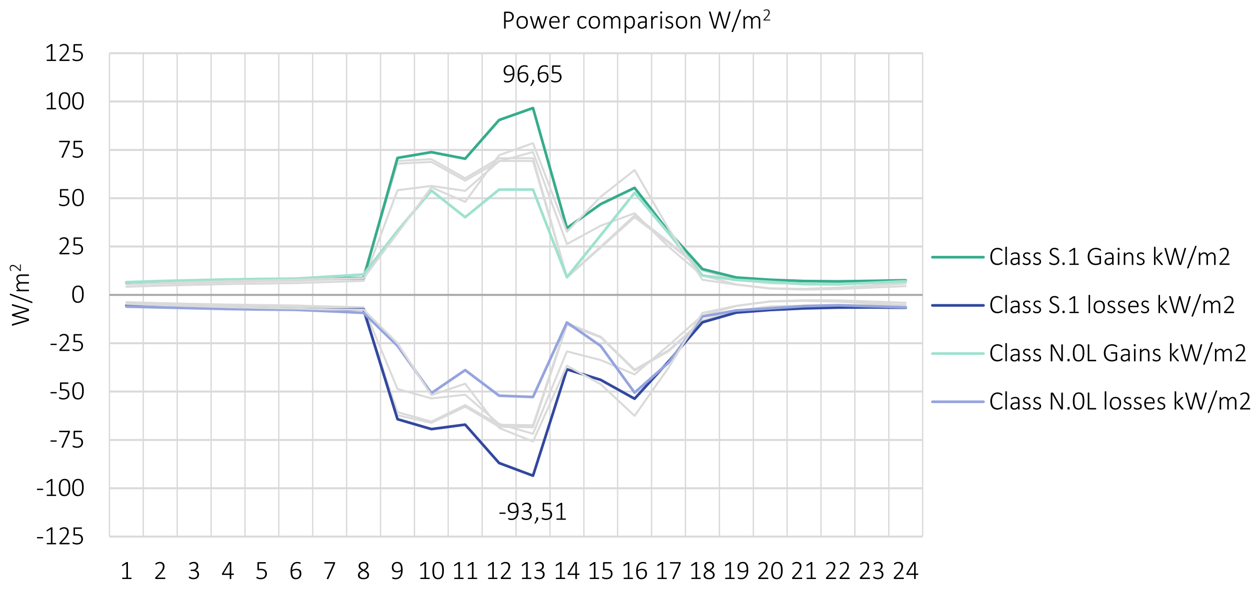


Chart 21 Daily variation of the peak power (m^2)

The analyses of the power expressed in kW/m^3 was done because the internal high of rooms at the ground floor is not the same of the one at the first floor. In fact, the trends of power related to the volume are quite different respect to the previous chart. Again, classroom D and laboratory E have registered the highest and the lowest peaks among the trends considered. The power variation of classroom A, close to the one of classroom C in the previous chart, is now shifted up since the highs of these space are different.

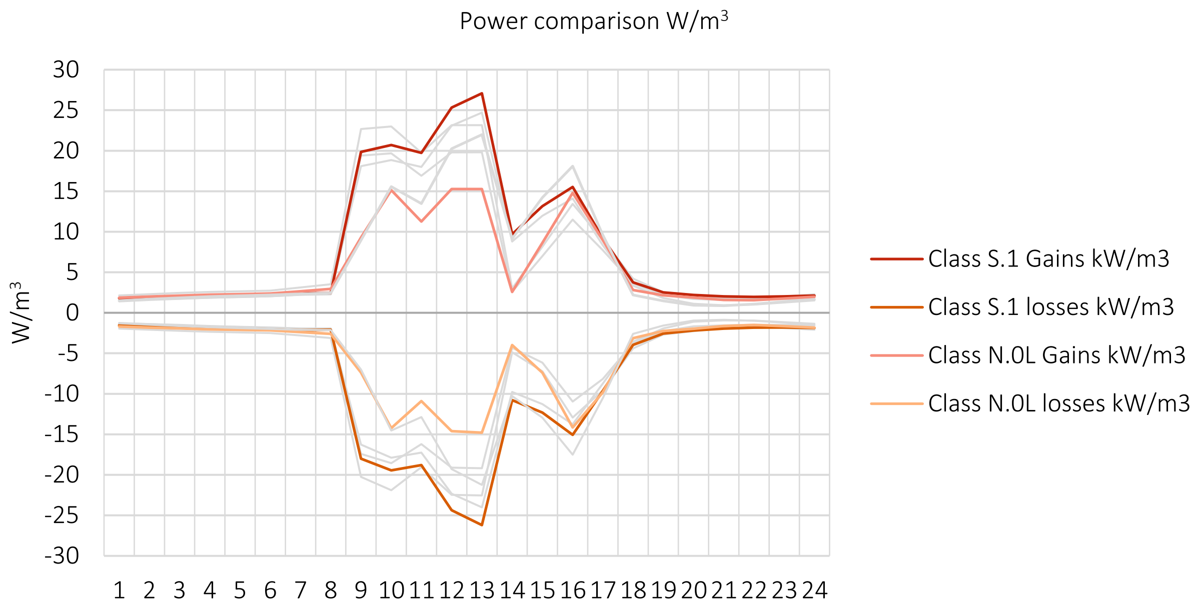


Chart 22 Daily variation of the peak power (m^3)

Observations for Model 3 strategy

The third and last strategy demonstrates that in the six cases analysed the highest influence is related to external conduction thermal losses, in particular due to windows whose area is not very large but its thermal resistance very low that generates an important loss of heat. Thus, the optimization strategy in terms of energy reduction can be defined as:

1. Window change
2. Roof insulation
3. Solar shading
4. Ground insulation
5. External wall insulation

3.3.2. COMFORT OPTIMIZATION STRATEGIES: FURTHER ANALYSES

The application of the adaptive approach described by UNI 15251 and ASHRAE 55 on the case study is useful to evaluate the comfort condition of the internal environment considering the adaptation of human body to the variation of thermal parameters of the environment. This approach is used in Non-heating season to understand if the comfort of internal environment can be achieved without the use of mechanical cooling system. Thanks to the absence of thermal systems in the simulations it is possible to analyse the real influence of gains on the internal temperature and establish the period in which the internal temperature of the spaces is in the comfort range and therefore avoid (or limit) the use of cooling systems. This method can be applied only for summer and middle season: consequently, it is calculated the frequency of internal comfort temperature when the external temperature is between 15 and 30 °C, with an approximation of ±0.5 °C. For these preliminary analyses the limit of the comfort range chosen is the equal to the values obtained by comfort category III.

The monthly comfort hours registered in each room are compared with the monthly occupied hour in which the school is used by students and teachers, according to the occupancy schedule, considering also cleaning and administration stuff.

The internal comfort assessment goes on with the evaluation of humidity and it is calculate the hours in which the humidity ratio or the moisture content is in the comfort range. In order to have a slender calculation, the analysis on humidity was done only when internal temperature is between 15 and 30 °C, with an approximation of ±0.5 °C.

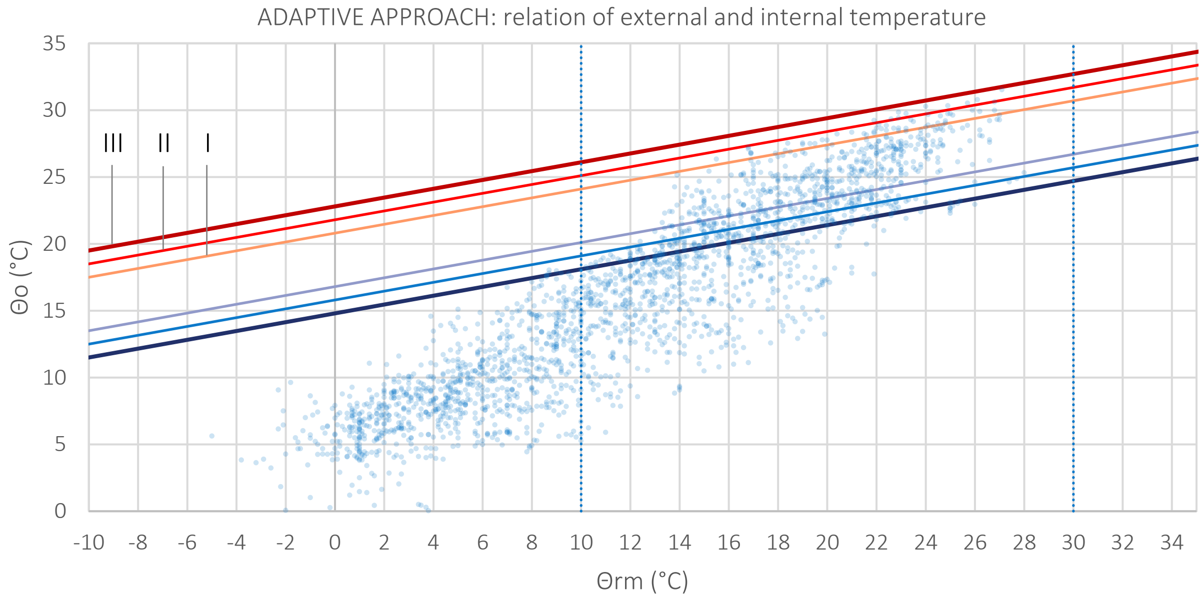


Chart 23 Hourly operative temperature distribution according to the Adaptive approach

Moreover, Predicted Mean Vote and Percentage of Discomfort for two months of the middle season March and May have been plotted in order to understand if occupants are in comfort conditions without the presence of thermal systems. Obviously in these preliminary analyses, it is useless to investigate winter and summer months where the internal temperature without thermal system is not in the comfort range, as the experience suggests. The PMV and PD monthly variation is based on the daily average which takes into account only the occupied hours imposed by schedules, without considering holydays, weekends and hours of closure (from 18 to 8). At this stage, the outputs related to PMV and PD considers occupants as a unique group without considering any difference between female and male or the type of clothing.

The analyses made on three models focus on the frequency of adaptive comfort temperature, frequency of comfort relative humidity, PMV and PD.

Model 1

The evaluation of comfort condition is done considering the internal temperature with adaptive approach, internal humidity and PMV PD indices.

The frequency charts of comfort hours related to the internal temperature shows that it is required to set a heating and cooling systems. In fact, respect to the total occupied hours the percentage of comfort hours doesn't reach high values. The peak is registered in the midseason, in April May and October where the percentage of comfort hours is between 33 and 48 %. Charts shows also that the internal temperature of the classroom at the first floor has registered higher values than the one at the ground level; nevertheless, the difference between the two classes is just around 7% and still not sufficient to reach a comfort internal environment.

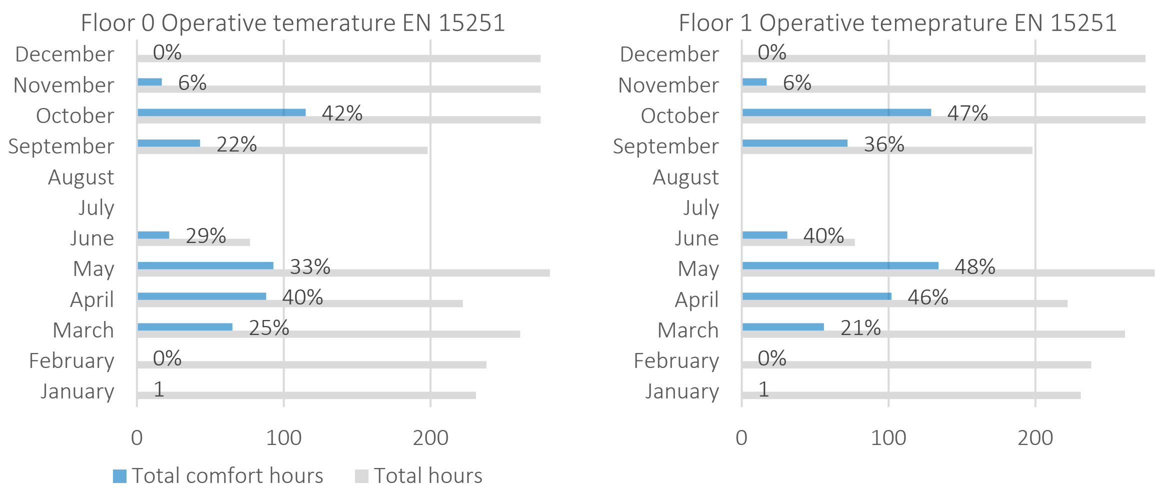


Chart 24 Model 1 Frequency of comfort operative temperature according to the adaptive approach

The hours of comfort humidity are almost the same for the ground and first level with the same trend. The European approach shows the same results of the ground floor with a unique variation in March, where the percentage of comfort hours falls from 28% to 18%. A good level of comfort condition is reached in summer months May, June and September, where the percentage of comfort hours is very close to the occupied hours. The middle season months April and October which are interested by seasonal variation show that about half of the occupied hours have a comfort level of humidity, while in winter season this percentage is almost equal to zero.

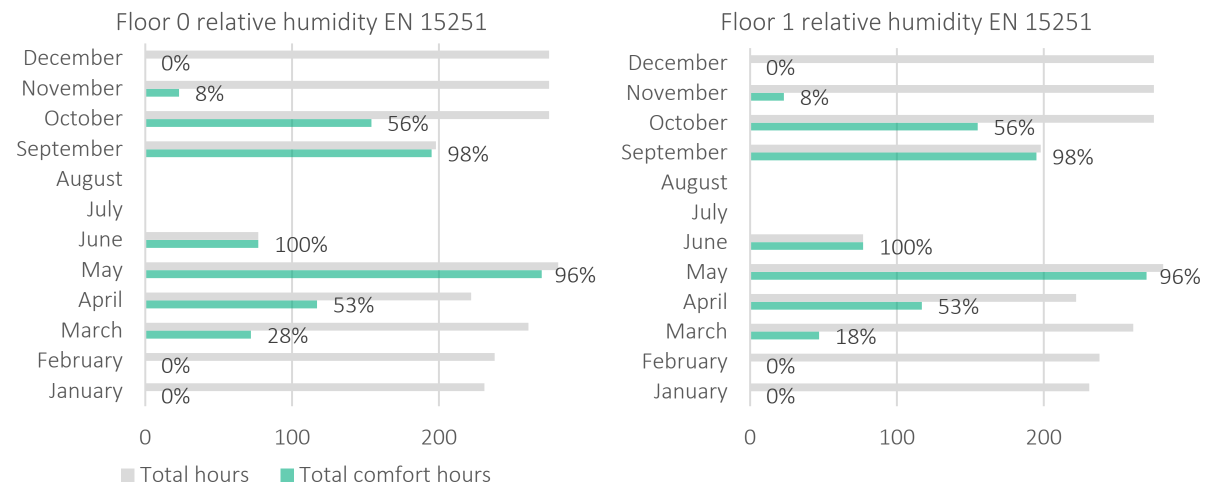


Chart 15 Model 1 Frequency of comfort relative humidity according to the adaptive approach

The PMV and PD diagrams are useful to understand the internal comfort of occupants, in particular for students. Charts show that values of the two classrooms follow the same trend; values of the thermal zone placed at the ground floor are almost a bit higher than the other at the first floor, except for the Percentage of Discomfort in March, where the trend is not the same for the two classrooms. The trend of PMV and PD have some peaks at the weekend or holydays where the values fall to zero since the school is closed.

Form the PMV analysis it is possible to see that the values recorded in March are almost in the comfort range of category III (±0.7 from EN 15251) except for some days, where values present a small variation respect to the acceptable area. Instead, the PMV average calculated in May is completely outside the comfort range of category III. The higher peak is registered at the end of the month since the outside temperature increases and therefore the internal environment is not comfortable for occupants.

The PD chart has the same trend of the previous one. In March the percentage of not satisfied people is nearly acceptable since most of the hours are in the comfort range of category III with some peaks at the beginning and in the middle of the month where the percentage increase. For this month, the PD trend of classroom at the ground floor and the other at the first level is not the same; in some days is the values are higher at the ground level and sometimes at the first floor. As expected, May has higher discomfort percentage respect to March. The trend of the two thermal zones is clearly defined with greater values for the classroom at the ground floor.

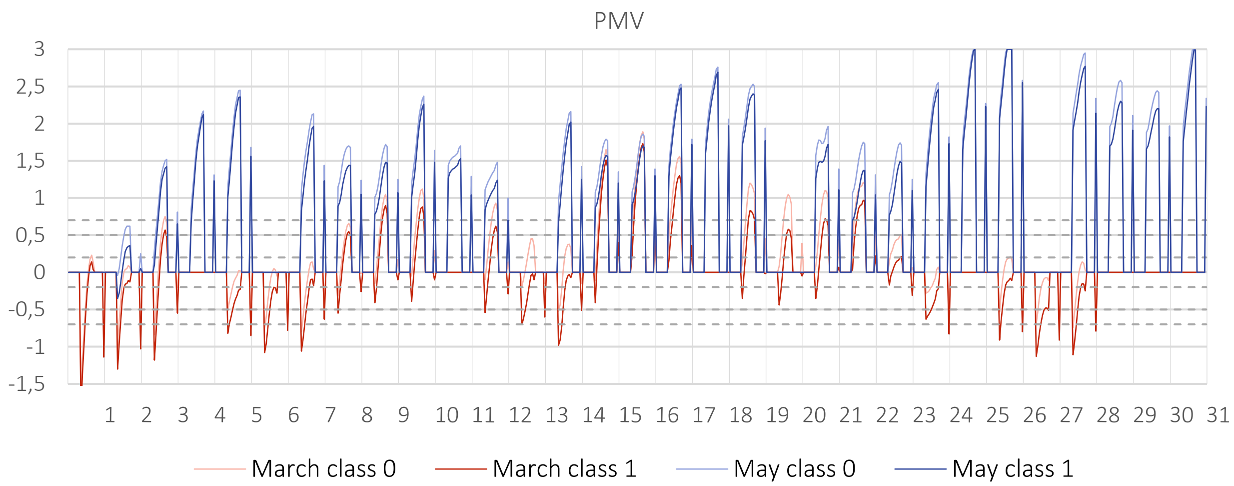


Chart 26 Model 1 Hourly variation of PMV in march and may

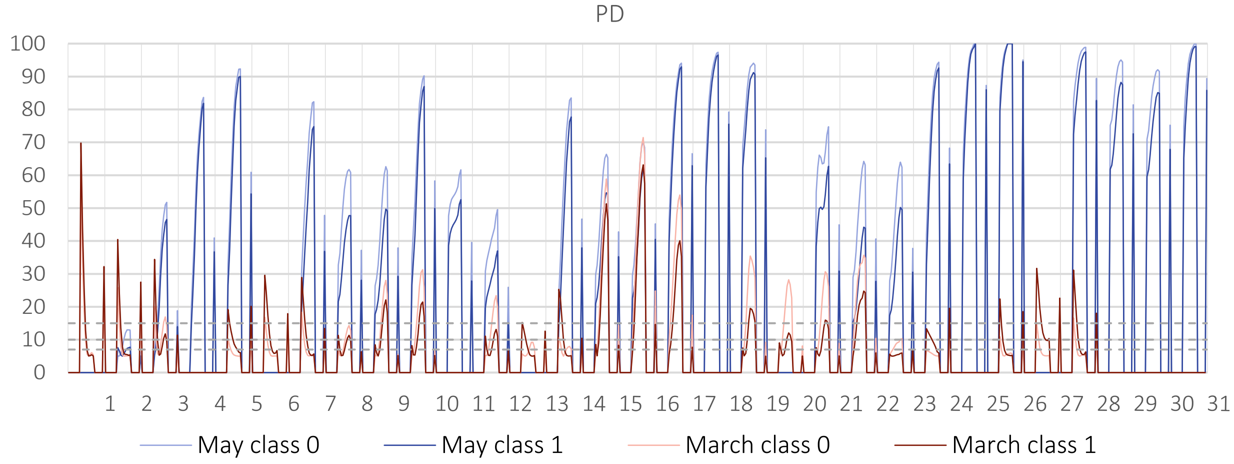


Chart 27 Model 1 Hourly variation of PD in march and may

Observations of Model 1

The evaluation of comfort paramteres related to the simplest model worked out resuts not reliable; therefore, this model can't be used to assess comfort of the whole building.

Model 2

Since this model is designed as an assemblage of thermal zones, it not possible to define a space which represents faithfully the entire building. The average values of PMV, PD and the frequency calculation of comfort internal temperature and comfort humidity was not developed for this model because the results wouldn't represent the real situation of the building. Also, an average value of comfort is not useful since the thermal zones included into the model have very different schedule and occupancy rate. Comfort analysis can provide reliable results if it is done with a single thermal zone; therefore, it was skipped for Model 2 and it is done for Model 3 that focuses on single spaces.

Model 3

This model focuses the analysis of internal comfort on four classrooms N.0, S.0, N.1, S.1 and two laboratories N.0L, S.0L, the same thermal zones of the envelope optimization strategy.

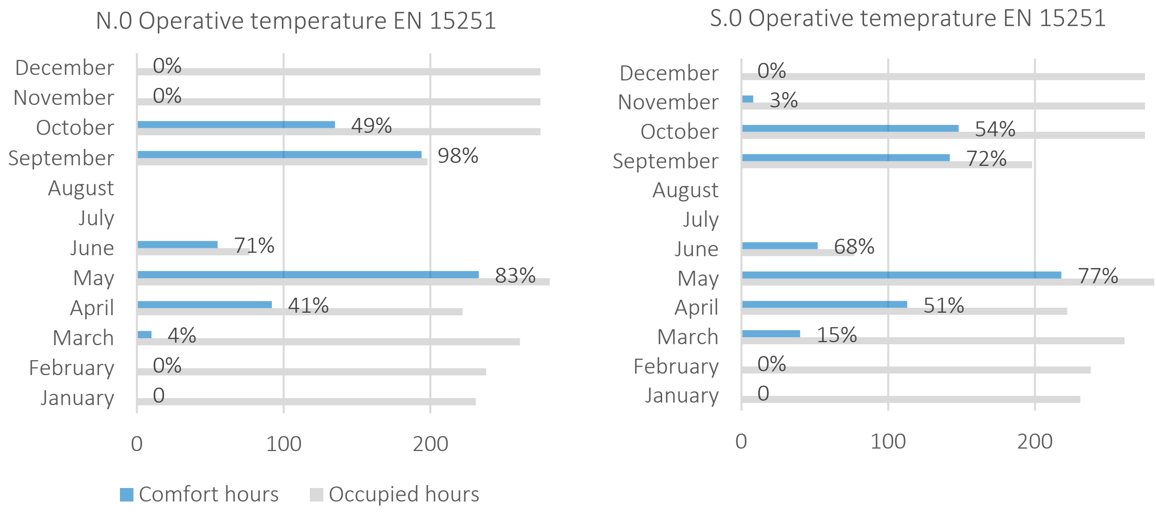
Comfort temperature frequency

The calculation of the hours in which the internal temperature values are in the acceptable range established by the adaptive approach demonstrates that the highest comfort temperature hours are reached in May, June and September. In these months the percentage of comfort hours varies between 84% and 100%.

Comparing classroom N.0, North oriented and classroom S.0, South oriented it is possible to underline that comfort hours registered in March, April and October are higher in classroom S.0 since the Solar gain contribute to warm up the space. On the other side, in summer months, May, June and September the number of comfort hours is greater for classroom N.0 because the temperature has been mitigated by the contact with ground and its ceiling is not direct in touch with solar rays, that would overheat the thermal zone like classroom S.0.

The internal temperature of the two thermal zones N.1 and S.1 shows its higher peak in the central months May, June and September. The best conditions are reached in June in classroom N.1 because it faces North and in summer period it guarantee a good level of internal comfort temperature. As explained in the previous case of classroom N.0 and S.0, in the middle season the best conditions are achieved in classroom S.1 with South exposition in which internal temperature is warmed by solar gain. Opposite, in the middle/summer period, the best comfort condition is reached in classroom with North exposition.

The same considerations can be done for the two laboratories.



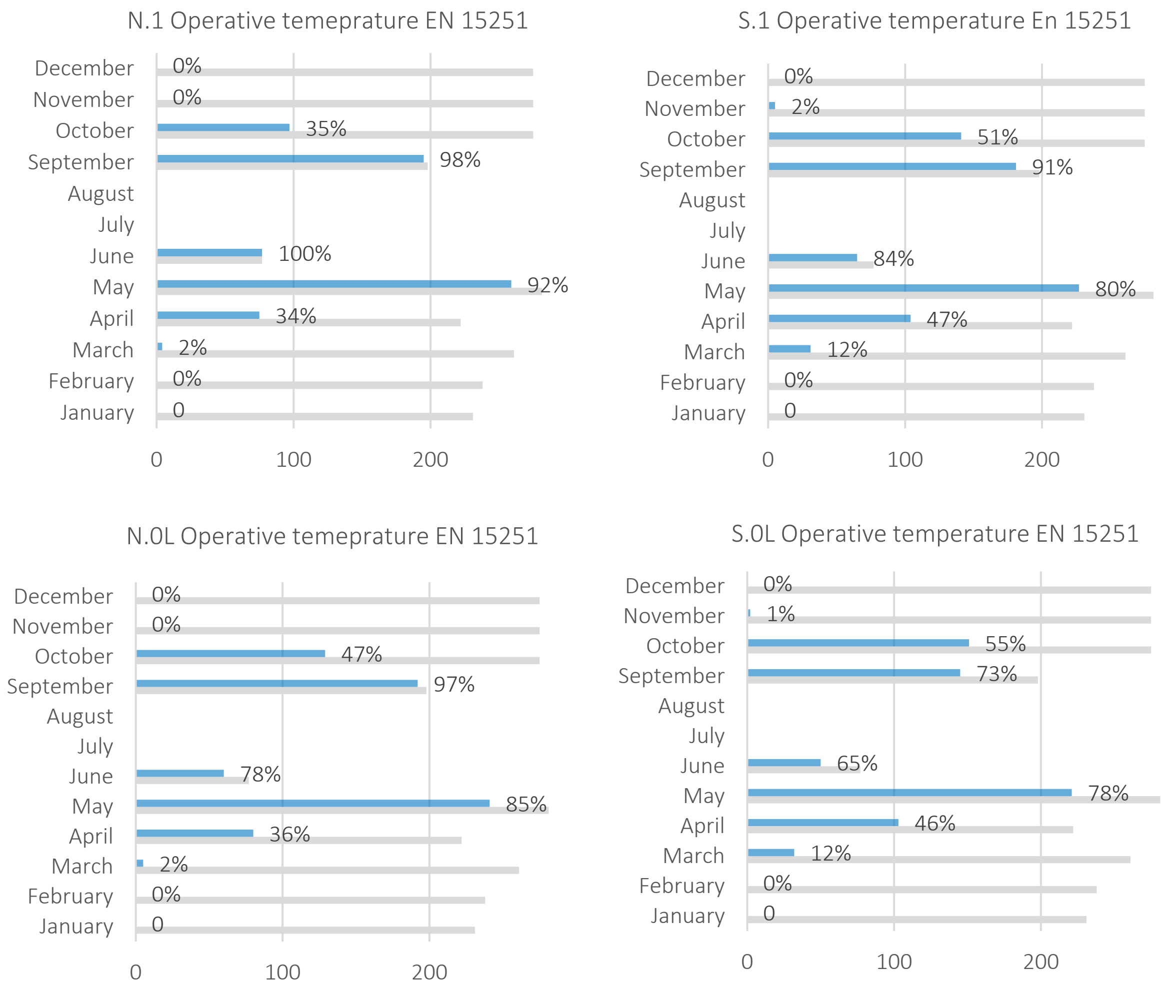


Chart 28 Model 3 Frequency of comfort operative temperature according to the adaptive approach

The results of the adaptive approach for the middle/summer season months have been compared with the static method in order to test the difference between them. In particular, the analysis is made on the number of comfort hours calculated according to the adaptive approach and the static one for six classrooms. The static approach is the older method and the easier one, that is explained by the standard UNI EN ISO 7730 where the comfort range of temperature is set between 20 °C and 26°C.

As expected, the static approach is more restrictive in all cases than the adaptive since it is based on fixed values and the percentage of comfort hours is around half of the occupied hours in the best cases.

In May, the best position for classroom is at the first floor facing North; in fact, the percentage of comfort hours for class N.1 is 61% of the occupied hours, while the worst position is at the ground floor towards South, where there is only the 38% of comfort hours. Probably, the best case is placed at the first floor with North orientation because the external conduction losses are higher at the top level (roof dissipate more heat respect to the ground since it is in contact with air) and the presence of only diffuse radiation doesn't rise solar gain very much.

In June, comfort values are very low since the presence of internal gains, high external temperature and solar gain contribute to rise the internal temperature of classroom. According to the charts, the higher value of comfort is reached in class N.1 and S.1 with 34% of comfort hours, while the lower value was registered in class S.0 with only 12%.

The results in September is similar to results of May, even if the variation among the cases is more effective. In particular, the highest value has been registered for class N.1 in which the 80% of occupied hours are in comfort range of temperature, while the worst is related to classroom S.0L and S.0 with 24% and 25% of comfort hours. In the other classrooms the comfort percentage is between 45% and 60%.

More in general, the difference between the two methods is quite clear, since their results are very different. The following table define the *best* and the *worst* thermal zone of the two calculation methods according to the result obtained. Notice that *best* and *worst* mean the best and the worst case among the results. They are don't mean absolutely best and absolutely worst thermal conditions.

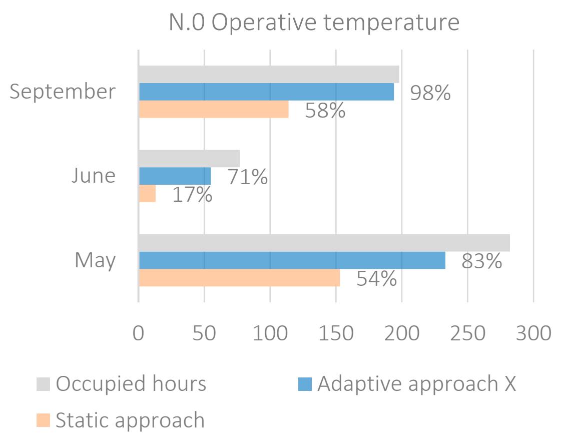
The static approach defines the best position for classroom at the first floor, in particular, for class N.1 even if the percentage of comfort hours with no conditioning systems is not very high. Opposite, the worst position is related to classroom at the ground floor, S.0.

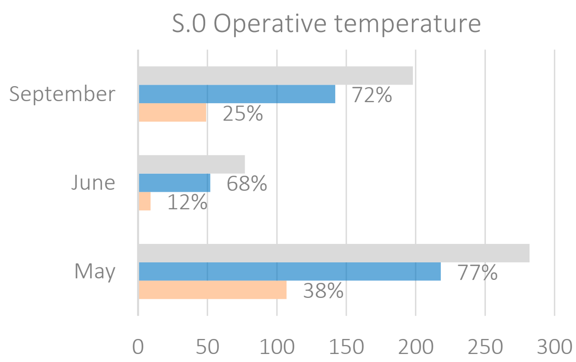
On the other hand, the adaptive approach described by EN 15251 identifies the best position in classroom N.0 and the worst on the opposite edge of building, in classroom S.0L.

The two methods are aligned in the definition of the best and worst orientation (the best towards North and the worst towards South) and in the definition of the best and worst floor, even if the percentage of comfort hours are very different.

	UNI EN ISO 7730		UNI EN 15251	
	Best	Worst	Best	Worst
May	N.1	S.0	N.1	S.0
June	N.1 - S.1	S.0	N.1	S.0L
September	N.1	S.0 - S.0L	N.0 - N.1	S.0 - S.0L

Table 40 Comparison of the best thermal zone according to the adaptive and non-adaptive approach





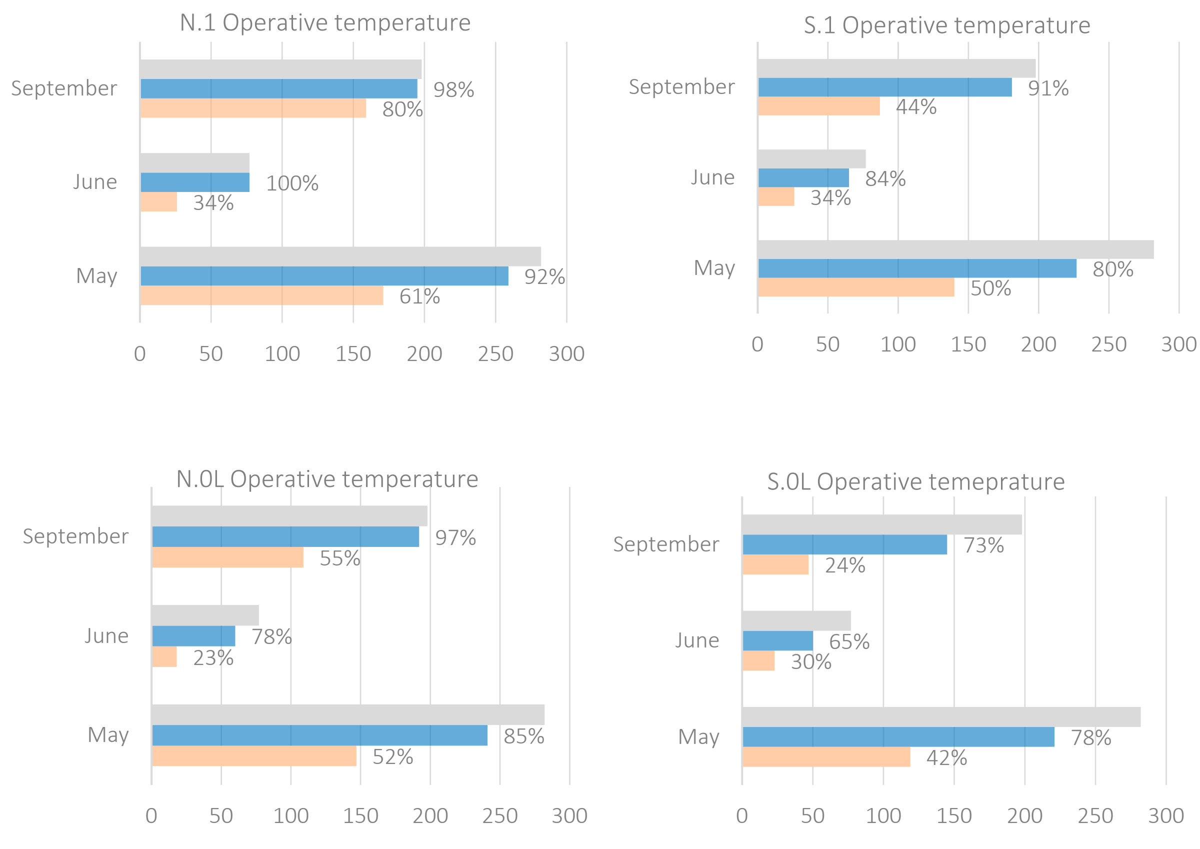


Chart 29 Comparison between adaptive and non-adaptive frequency of comfort operative temperature

Comfort humidity frequency

The evaluation of internal humidity shows that the number comfort hours are higher and almost equal for central months May, June and September where the percentage is between 87 and 96%. In the middle season there is a steep fall of comfort percentage in both classroom, even if the values are a little higher for classroom S.0. This is probably liked to the internal temperature which is greater in classroom S.0 respect to N.0.

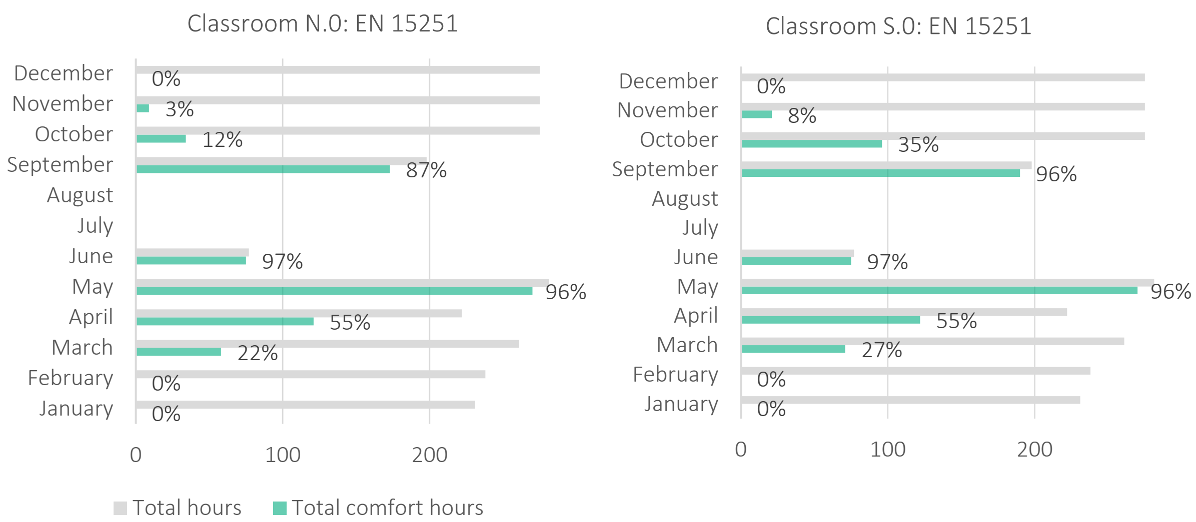


Chart 30 Model 3 Frequency of comfort relative humidity according to the adaptive approach

Comfort comparison

The comfort analysis of the thermal zones N.0, S.0, N.1, S.1, N.0L and S.0L is done considering the Predict Mean Vote and the Percentage of Discomfort people. In both cases, the trend of daily average PMV or PD was studied and reported in the following charts.

The Percentage of Discomfort charts show that all thermal zones have basically the same trend as concave shape in March and increasing line in May.

Focusing on March, values are higher at the beginning of the month where the percentage of discomfort varies from 60% to 80% and at the end, from 70% to 80% since internal temperature is too low. In the middle of the month, values decrease until the limit of category II, but then it increases again. Nevertheless, the diagram of freefloating analysis demonstrates that people are not satisfied of the internal environment conditions.

In May, the situation is different. In the first half of the month, trends of all thermal zones are almost in the comfort range between category II and III with some peaks over this limit for classrooms B and F. Then, internal temperature of the space increase and at the same time the percentage of people not satisfied of the igro-thermal conditions. Values under the limit of category I are not present for this month

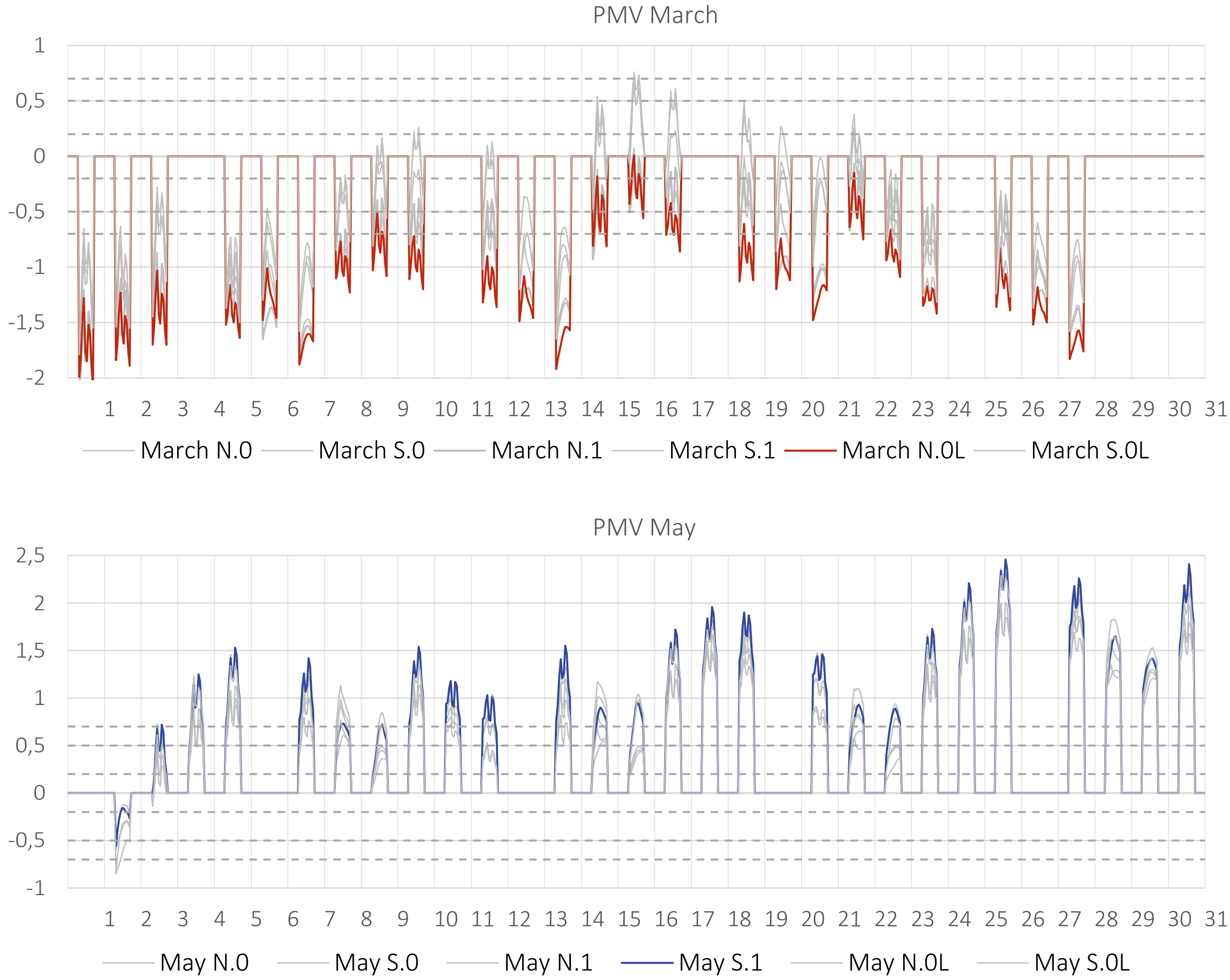
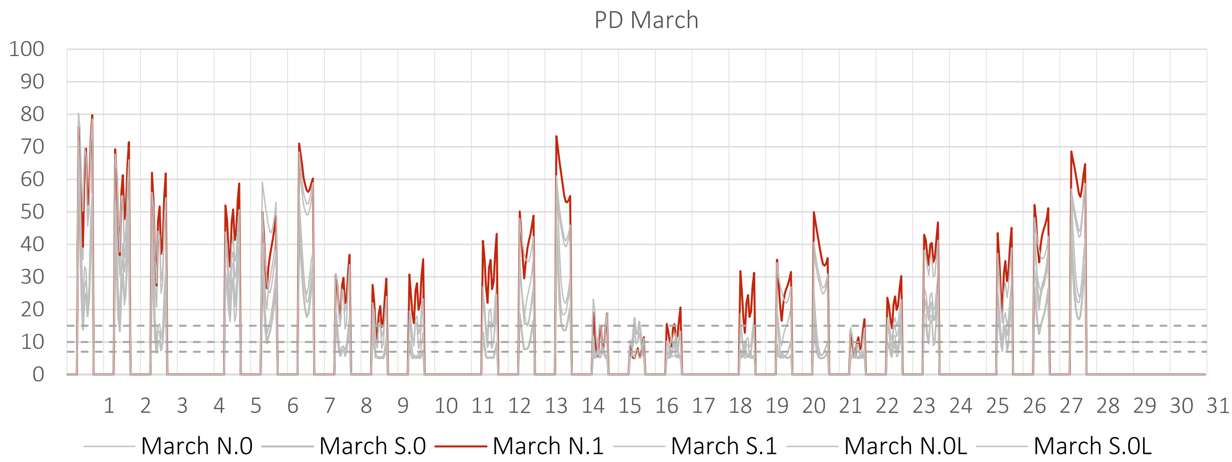


Chart 31 Model 3 hourly PMV in march and may according to the thermal zones



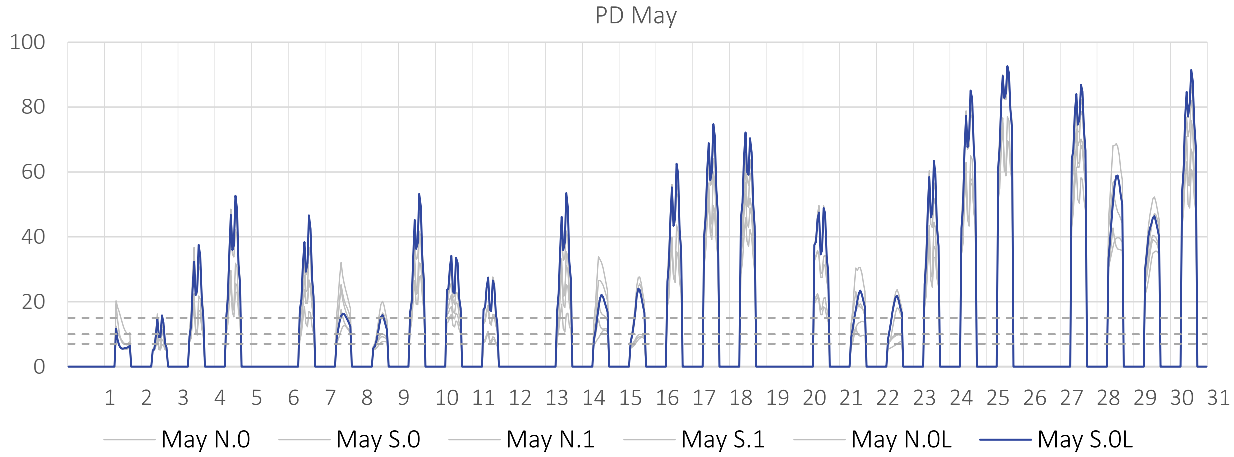


Chart 32 Model 3 hourly PD in march and may according to the thermal zones

Observation of Model 3

The third model is the more reliable in terms of output results since it is based on the most detailed model in the geometry and scheduling. Also, comparing the charts of thermal discomfort, PMV and PD of model 1 and 3 the differences are quite big. Therefore, Model 3 will be used in further analyses to assess thermal comfort for occupants.

3.3.3. COMPARISON OF THE OPTIMIZATION STRATEGIES AND BEST MODEL CHOICE

The three strategies analysed in this section are based on different models and different level of detail in the geometry, scheduling and parameters, while the building technology is the same for every case.

The model 1 is the simplest and the roughest in the simplification of the building geometry and the occupancy schedule, therefore its results in the evaluation of gains and losses are not reliable. The model 2 is more accurate since it considers the whole building and its shape is very close to the existing building. In fact, the results associated to this model evaluate gains and losses of the classroom block without differencing lecture room, library, laboratories and other function spaces that are present inside the classroom block. In the end, model 3 has the same geometry of model 2 but its results are focused on four classrooms and two laboratories with different orientation and floor level. Since the results associate to this model are more accurate than the others, it is not possible to choose which room could represent the classroom block and then define a strategy to optimize the building envelope.

Due to these considerations, the strategy related to model 2 has been chosen in order to define the sequence of envelope optimization, while model 3 to assess comfort.

	Model 1	Model 2	Model 3
1°	Windows change	Window change	Window change
2°	Roof insulation	Solar shading	Roof insulation
3°	Solar shading	Roof insulation	Solar shading
4°	Ground insulation	Ground insulation	Ground insulation
5°	External wall insulation	External wall insulation	External wall insulation
	NOT USED	ENVELOPE OPTIMIZATION	COMFORT OPTIMIZATION

Table 41 Comparison between the strategies of the three models

CHAPTER

4

IESve Simulations and building optimization

Baseline simulation

The envelope optimization process starts with the evaluation of the baseline simulation in which it was considered the model 2 for the geometry with the baseline technology constructions. In addition to the previous analyses, the conditioning system has been activated according to the Heating period established by UNI EN ISO 11300 that fix it from 15th of October to 15th of April. For simplicity the cooling season has been set as the complementary period of heating season without considering holydays and summer break.

The baseline thermal plant is composed by a boiler powered by natural gas that provides hot water for the heating system and a chiller for the cooling system that uses electricity. At this stage, standard IES parameters for conditioning system are used to evaluate the baseline simulation and the optimization choices.

Heating system	
Source	Natural Gas
Seasonal η	0.75
Delivery η	0.9216
sCOP	0.6912

Cooling system	
Source	Electricity
Nominal EER	2.5
Seasonal EER	2
Delivery ε	0.8
SSEER	1.3539

Table 42 Heating and cooling system baseline IES parameters

The evaluation of the systems consumptions was done considering the total Primary Energy used by heating and cooling systems. According to UNI EN 15603, the total Primary Energy "is the energy that has not been subjected to any conversion or transformation process". The value of tot PE includes renewable and non-renewable sources, but also the energy used for the production, transport, extraction and so on. Thus, this value can be very different if it is calculated for different nations.

The calculation method of total Primary Energy consumed by the heating plants (boiler) and cooling plants (chiller) consists in the use of conversion coefficients $f_{P,tot}$ form D.M. 26 6 2015.

$$tot\ PE = \sum_i Q_i \cdot f_{PE,tot}$$

The baseline simulation shows that the building is heating oriented, since the great part of energy consumption is related to the boiler energy. In fact, 96% of the total PE is used by the heating system, while only 4% by the cooling one. The result of total PE of the baseline simulation will be used and compared with results of the optimization process simulations in order to understand the percentage of energy saved by the variation of specific parameters.

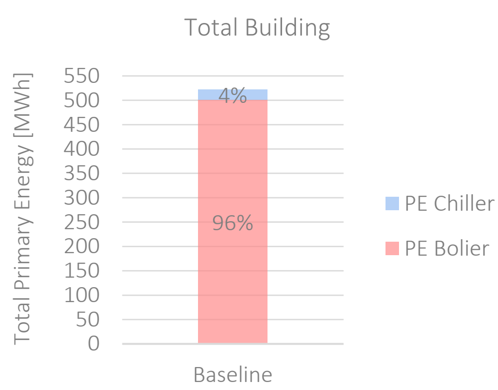


Chart 33 Baseline primary energy results

On the other hand, gains of the baseline simulation were analysed, in particular the solar gain and the external conduction which is divided into the contribution due to external walls, roof, ground and windows. This result is different from the external conduction gains analyses without conditioning systems. In fact, the presence of heating and cooling plants to control internal temperature, generates a decrease in the conduction losses form window, from 48%-55% to 39%-43%, while roof and ground losses have been increased from 20%-31% to 29%-22%, and from 17%-14% to 25%-29% for the ground.

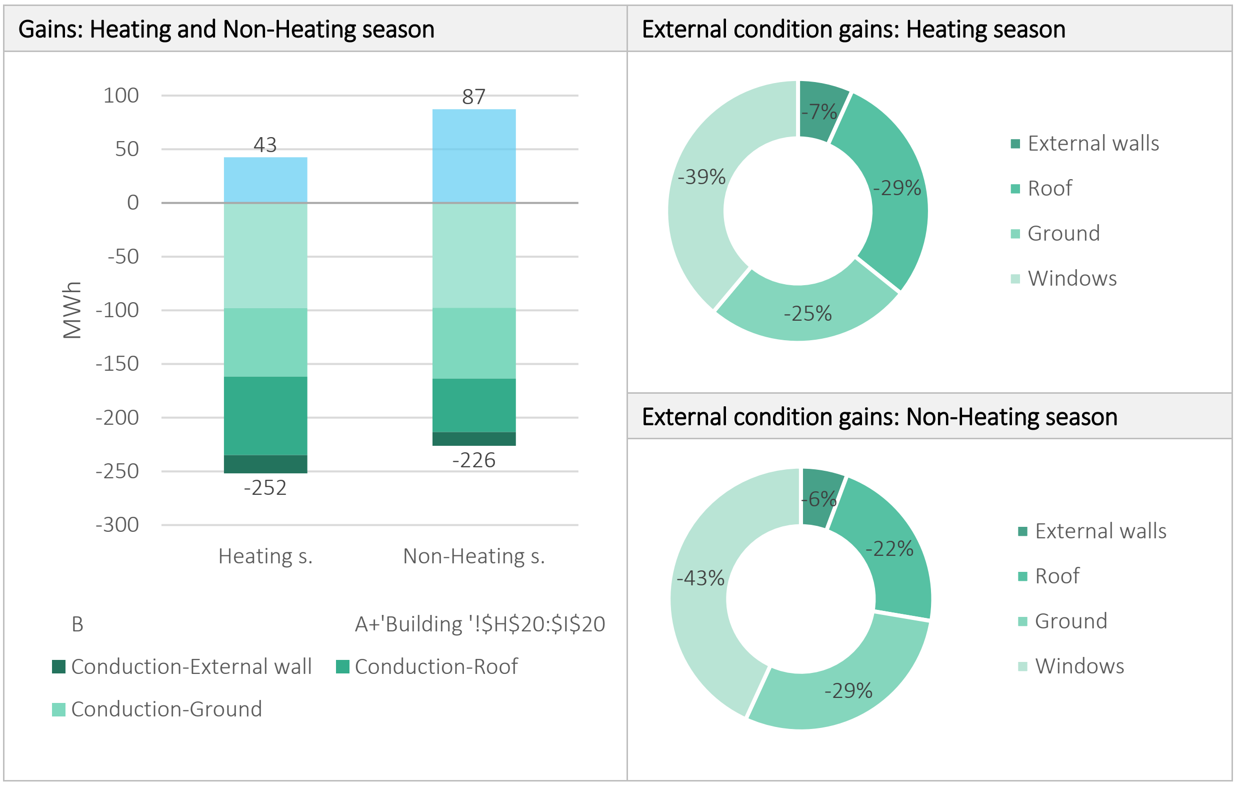


Table 43 Baseline simulation gains

Gains	Heating season [MWh]	Non-Heating season [MWh]
Solar gain	43	87
Conduction-Windows	-98	-98
Conduction-Ground	-64	-66
Conduction-Roof	-73	-50
Conduction-External wall	-17	-13

Table 44 Baseline simulation gains data

4.1. ENVELOPE OPTIMIZATION SIMULATIONS

The simulations for the building envelope optimization was done on the Model 2 which considers the whole building and its results are set as a sum of all thermal zones. Schedule for occupancy rate, internal gains and ventilation has been set faithfully to standards and school calendar.

According to the results of the preliminary analysis, the optimization process follows the sequence list of the chapter 3.2.3 related to Model 2. The evaluation of energy saving was done comparing together the results of optimized parameters with the baseline simulation. Then, the effect generated by the change of each parameter was analysed considering the variation of gains and losses.

For each step of the list of sequence, the first simulation is done considering the minimum standard parameters required by the D.M. 26/6/2015 for building renovation. On the other hands, the second and the third simulation consider an improvement of the standard parameters.

The influence of each optimized parameter on the whole building consumption has been analysed comparing the total Primary Energy used by the systems.

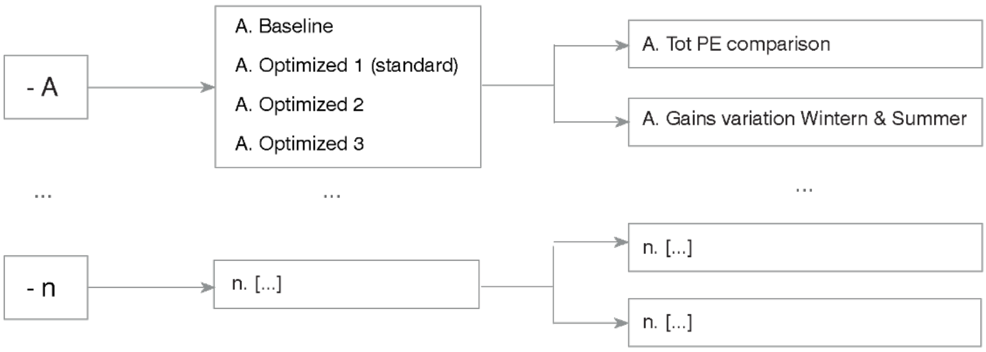


Figure 8 Optimization scheme

Windows change

The first operation to improve the quality of the external building envelope and decrease the energy consumption consists in changing the external windows. This stage of optimization process considers three types of window with different characteristics of glasses and frame. Each new window has built with wooden frame with the external surface cladded with aluminium sheet.

The influence of these windows with different performance characteristics has been analysed comparing the total Primary Energy used by heating and cooling systems and then the gains compared with the baseline simulation.

WINDOW 1	t	Resistance	ε_O	ε_i	g-glass	Ug	Uw
	[mm]	[m^{2}K/W]	[-]	[-]		[W/m^{2}K]	[W/m^{2}K]
Clear float glass	6	0.780	0.837	0.837	0.6983	1.40	1.45
Argon	16	1.1597					
Low-E glass	6	0.780	0.157	0.837			

WINDOW 2	t	Resistance	ε_O	ε_i	g-glass	Ug	Uw
	[mm]	[m²K/W]	[-]	[-]	[-]	[W/m²K]	[W/m²K]
Clear float glass	6	0.780	0.837	0.837	0.5471	1.05	1.21
Argon	16	1.1597					
Clear float glass	6	0.690	0.837	0.837			
Argon	16	1.1597					
Low-E glass	6	0.690	0.157	0.837			

WINDOW 3	t	Resistance	ε_O	ε_i	g-glass	Ug	Uw
	[mm]	[m²K/W]	[-]	[-]	[-]	[W/m²K]	[W/m²K]
Clear float glass	6	0.780	0.837	0.837	0.5841	0.82	0.98
Argon	16	1.1597					
Low-E glass	6	0.690	0.157	0.837			
Argon	16	1.1597					
Low-E glass	6	0.690	0.157	0.837			

Table 45 Window optimization parameters

After, it is analysed the influence of each optimized U value on the external conduction loss and the solar gain. From the charts it is possible to highlight that the improvement of window thermal transmittance has a big influence on the reduction of external conduction. In fact, the use of the lowest Ug generates a decrease of this parameter equal to 19% in winter and 43% in summer. Also, the with the standard U (U=1.4 W/m^{2}K) there is a significant energy reduction related to the external conduction of the 11% in winter and 33% in summer.

Focusing on the solar gain, the charts show that the improvement of window performance generates a rise of solar gain in both seasons. This is a useful effect of the optimization of the heating period since solar gain contribute to warm the internal environment and reduce the energy consumed by boilers. In fact, standard U-window generate a rise of 63% of solar gain in winter and 33% in summer. The best U-window instead, has a different behaviour; it will generate an increment of 37% in winter and only 12% in summer because of the presence of triple gazed with two cavities filled with Argon.

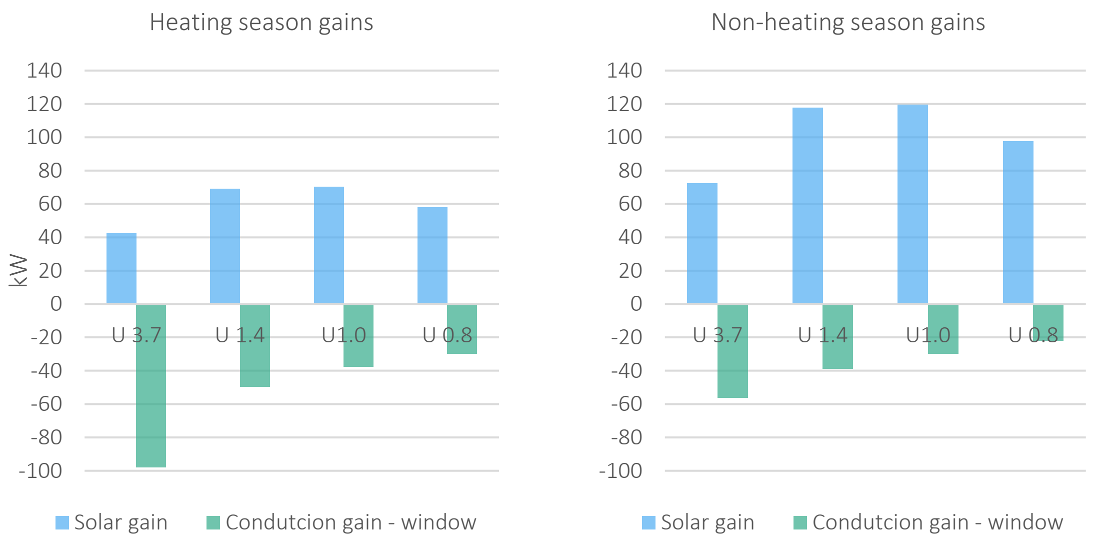


Chart 34 Widow optimization gain result

U	Heating season				Non-heating season			
	Solar gain		Conduction gain-window		Solar gain		Conduction gain-window	
	MWh	Δ	MWh	Δ	MWh	Δ	MWh	Δ
U 3.7	43		-98		72		-56	
U 1.4	69	+63%	-50	-49%	118	+63%	-39	-31%
U 1.0	70	+65%	-38	-61%	120	+66%	-30	-47%
U 0.8	58	+37%	-30	-69%	98	+35%	-22	-61%

Table 46 Window optimization gain results

Comparing the total Primary Energy consumed by the whole building, expressed in MWh, it is possible to underline that the improvement of window performance determines a reduction of the boiler consumption, but at the same time an increment of the energy used to chill the environment. From the Baseline to the best optimized window thermal transmittance the energy saved is equal to the 10%; while the application of the standard performance windows will provide a saving of 7%.

Basically, from this chart it is possible to underline that improving the performance of windows, the energy consumed by the heating system will decrease, while there is an increment of the energy used to cool down the internal environment in summer months.

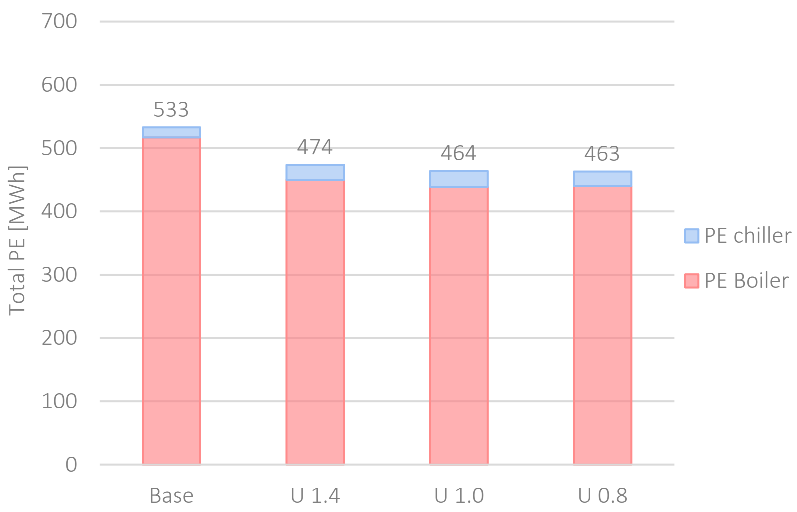


Chart 35 Widow optimization primary energy result

	Base	U 1.4	U 1.0	U 0.8
PE Bolier [MWh]	517	450	439	440
PE Chiller [MWh]	16	24	25	23
Total PE	533	474	464	463
Δ		11%	13%	13%

Table 47 Window optimization primary energy results

Windows and shading devices

The second step of the optimization focuses on the combination of windows and shading devices. These simulations have been done considering the combination of the previous window thermal transmittances and the use of internal blind (made by light coloured textile material) and/or external louvres with different inclination of lamellas.

Windows with internal blinds

The first group of simulation was done considering the effect of U-window variation and the presence of internal blinds.

Analysing the results of external conduction through windows and the solar gain and comparing them with the previous case, it is possible to underline that there is a reduction of about 20% of solar gain in both seasons and with all three cases. This effect is generated by the presence of internal curtains that blocks part of the solar radiation, avoiding glare. The conduction losses through window is almost the same of the previous case without shading devices, where the difference is only 1% in Heating season and around 3-4% in Non-heating season. Therefore, the influence of internal blinds on the external conduction is negligible.

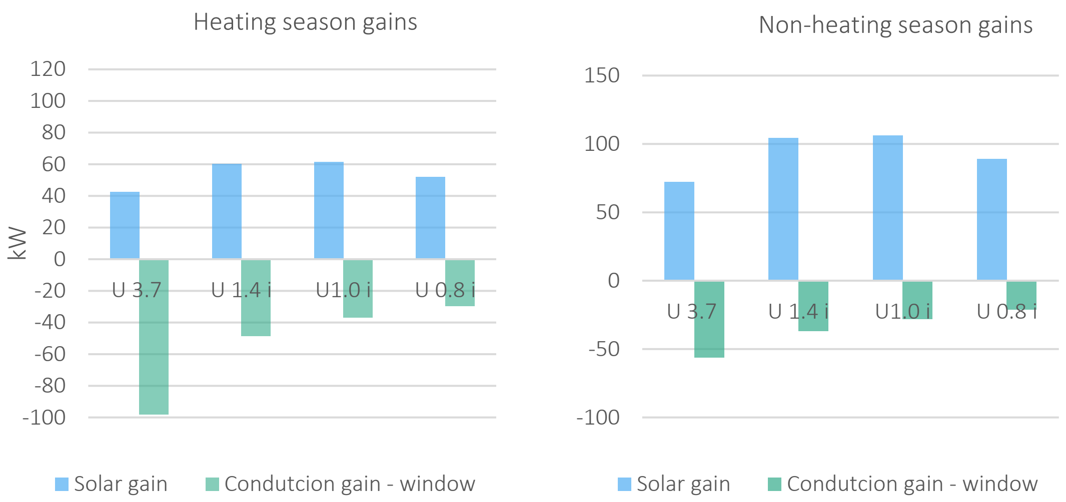


Chart 36 Widow and internal blinds optimization gain result

U	Heating season				Non-heating season			
	Solar gain		Conduction gain-window		Solar gain		Conduction gain-window	
	MWh	Δ	MWh	Δ	MWh	Δ	MWh	Δ
U 3.7	43		-98		72		-56	
U 1.4 i	60	**+42%**	-49	**-50%**	104	**+45%**	-37	**-35%**
U1.0 i	61	**+44%**	-37	**-62%**	106	**+47%**	-28	**-50%**
U 0.8 i	52	**+22%**	-29	**-70%**	89	**+23%**	-21	**-63%**

Table 48 Window and internal blinds optimization gain results

Form the chart of the total Primary Energy consumption expressed in MWh it is possible to underline that the use of shading systems determines, in general, a good reduction respect to the baseline construction; in particular this reduction is related to the energy consumed by chiller. The use of shading devices to avoid glare and annoying Sun light effects (like reflectance) generates a reduction of solar gain. In summer it is a good strategy that determines a reduction of overheating, a decrease of internal temperature and thus a lower chiller consumption. On the other hand, in winter, solar gain is a free source of heat that can be used to rise the internal temperature, but it can be reduced by the use of solar screeds. Due to this fact, there is a little increase of boiler energy.

Comparing the total PE chart with the one of the previous analysis, that there is an improvement in both cases of internal blinds and internal blinds plus external louvres respect to the simulation without shading devices.

The application of only internal blinds generates an energy saving equal to 8% combined with the standard U-Window, while 9% and 10% with more performant glazing. In fact, in all three cases, there is an improvement of 1% respect to the previous analyses in which the optimization was done only on the U value of windows.

The other three simulation results are based on the combination of internal blinds and external louvres and their results show that there is again a little improvement. In fact, the standard U-window with the two shading screed contribute to reduce the energy consumption of 9% of the total energy and the other window types of 11% in both cases.

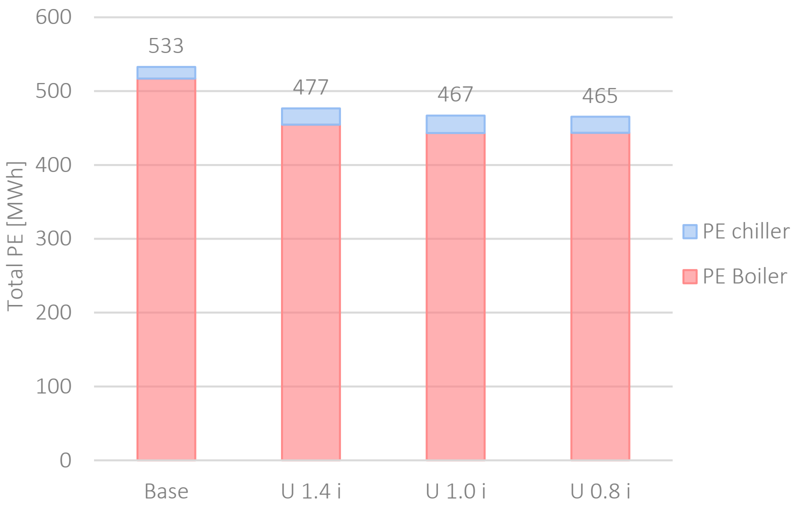


Chart 37 Widow and internal blinds optimization primary energy result

	Base	U 1.4 i	U 1.0 i	U 0.8 i
PE Bolier [MWh]	517	455	443	443
PE Chiller [MWh]	16	22	24	22
Total PE	533	477	467	465
Δ		11%	12%	13%

Table 49 Window and internal blinds optimization primary energy results

Windows with internal blinds and external louvers

The second group of simulation consider the combination of different U-window with internal and external shading devices.

The following charts show that solar gain is kept almost equal to the baseline case, while it is reduced respect to the first group of simulation with only internal blinds. The use of standard performance window (U_w=1.4 W/m^{2}K) combined with internal and external shading generate an increase of solar gain equal to 10% in the heating season and 7% in Non-heating one respect to the baseline, while the best case generates a reduction of 7% and 10%. Also in this case, the influence of shading on conduction gain through window is low. Its variation is equal to 2% in Heating season and about 5-10% in Non-heating season, respect to the case with no shading.

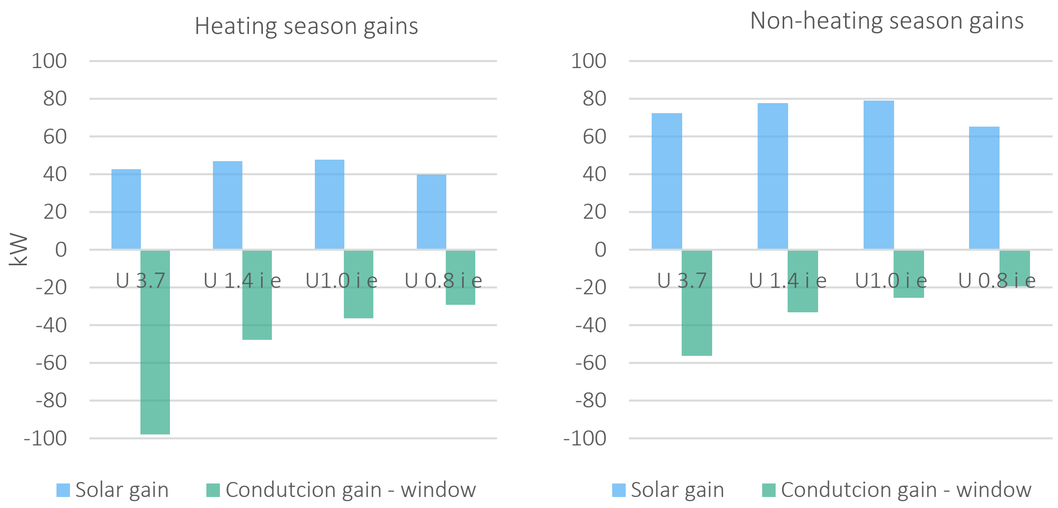


Chart 38 Widow and external louvers optimization gain result

U	Heating season				Non-heating season			
	Solar gain		Conduction gain-window		Solar gain		Conduction gain-window	
	MWh	Δ	MWh	Δ	MWh	Δ	MWh	Δ
U 3.7	43		-98		72		-56	
U 1.4 i e	47	**+10%**	-48	**-51%**	78	**+7%**	-33	**-41%**
U 1.0 i e	48	**+12%**	-36	**-63%**	79	**+9%**	-25	**-55%**
U 0.8 i e	40	**-7%**	-29	**-70%**	65	**-10%**	-19	**-66%**

Table 50 Window and external louvers optimization gain results

The presence of external and internal shading devices generates a decrease of total Primary Energy. The standard window with both solar screeds guarantees to save the 8% of the total PE respect to the baseline and the best window with two shading layers of 11%. In particular, there is a significant reduction of the energy consumed by heating plants, while there is a little increase of the chiller consumption. This effect is aligned with the gain analysis. In fact, since the variation of solar gain is not very different from the baseline, the energy consumed by the cooling system can only be almost similar.

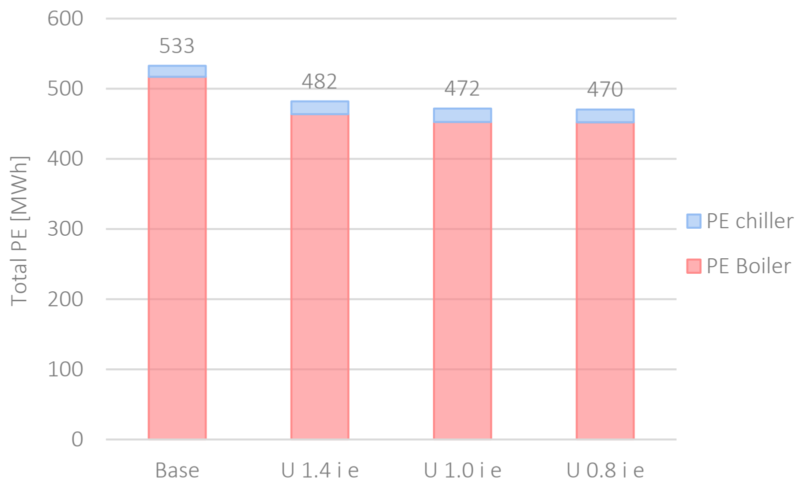


Chart 39 Widow and external louvers optimization primary energy result

	Base	U 1.4 i e	U 1.0 i e	U 0.8 i e
PE Bolier [MWh]	517	464	452	452
PE Chiller [MWh]	16	18	19	18
Total PE	533	482	472	470
Δ		10%	11%	12%

Table 51 Window and external louvers optimization primary energy results

Roof

The aim of the optimization is not the total change of the envelope, but the building renovation, thus the structural part of the roof kept equal to the original. The variation is related to the non-structural part like screed, insulation and external finishing. This group of simulations considers different type of construction with a variation of insulation thickness and concrete screed. Moreover, it is considered that the roof can be used only for maintenance and inspections, thus flooring and other kind of finishing are not necessary.

Due to it large surface, it is expected that the variation of insulation thickness will generate a consistent energy saving.

ROOF 1	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m^2K/W]	[kg/m^3]	[kJ/kg K]	[W/m^2K]
ext			0.04			0.24
rain protection	4	0.23	0.02	1500	1300	
screed	50	1.4	0.04	2000	850	
insulating layer Glasswool	100	0.04	4.00	30	850	
Reinforced brick-concrete slab	240	0.6	0.40	1200	850	
Plaster	10	0.7	0.01	1400	850	
int			0.13			

ROOF 2	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m^2K/W]	[kg/m^3]	[kJ/kg K]	[W/m^2K]
ext			0.04			0.15
rain protection	4	0.23	0.02	1500	1300	
screed	50	1.4	0.04	2000	850	
insulating layer Glasswool	160	0.04	6.25	30	850	
Reinforced brick-concrete slab	240	0.6	0.40	1200	850	
Plaster	10	0.7	0.01	1400	850	
int			0.13			

ROOF 3	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m^2K/W]	[kg/m^3]	[kJ/kg K]	[W/m^2K]
ext			0.04			0.10
rain protection	4	0.23	0.02	1500	1300	
screed	70	1.4	0.05	2000	850	
insulating layer: glass fiber	200	0.035	9.14	30	850	

Reinforced brick-concrete slab	240	0.6	0.40	1200	850	
Plaster	10	0.7	0.01	1400	850	
int			0.13			

Table 52 Roof optimization parameters

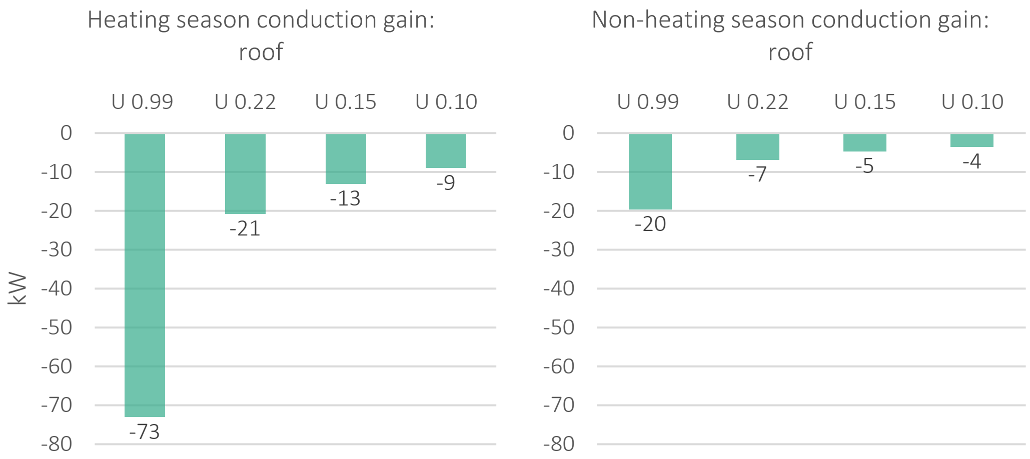


Chart 40 Roof optimization gain result

U	Heating season		Non-heating season	
	Conduction gain-roof		Conduction gain-roof	
	MWh	Δ	MWh	Δ
U 0.99	-73		-20	
U 0.22	-21	-72%	-7	-65%
U 0.15	-13	-82%	-5	-76%
U 0.10	-9	-88%	-4	-82%

Table 53 Roof optimization gain results

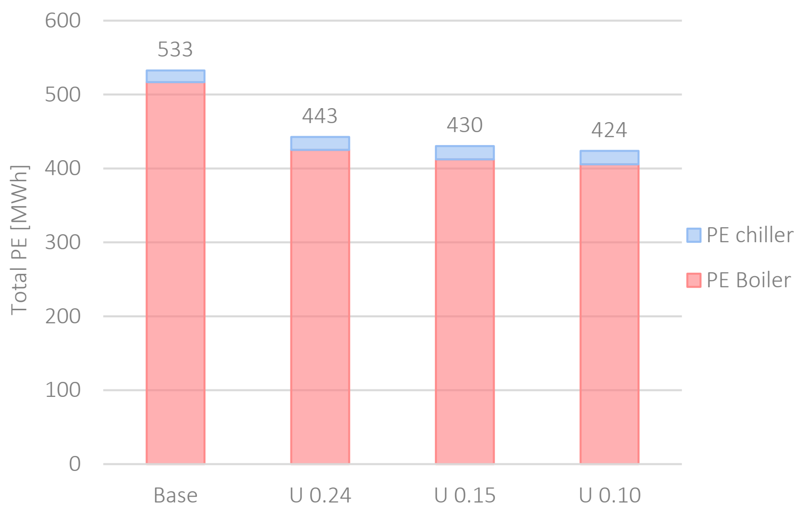


Chart 41 Roof optimization primary energy result

	Base	U 0.22	U 0.15	U 0.10
PE Bolier [MWh]	517	425	412	406
PE Chiller [MWh]	16	18	18	18

Total PE	533	443	430	424
Δ		17%	19%	20%

Table 54 Roof optimization primary energy results

Ground

The improvement of ground floor thermal characteristics can be achieved by the use of insulation, placed on the inner surface of the slab. Moreover, it is necessary to remove the existing barriers and place a new vapour barrier and waterproof layer to avoid condensation.

GROUND 1	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m²K/W]	[kg/m³]	[kJ/kg K]	[W/m²K]
ext			0.04			0.29
Reinforced concrete slab	800	2.3	0.65	2400	850	
Insulating layer	100	0.036	2.50	30	850	
Screed	70	1.4	0.05	2000	850	
Flooring	50	1.0	0.04	2000	850	
int			0.13			

GROUND 2	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m²K/W]	[kg/m³]	[kJ/kg K]	[W/m²K]
ext			0.04			0.24
Reinforced concrete slab	800	2.3	0.65	2400	850	
Insulating layer	120	0.036	3.00	30	850	
Screed	70	1.4	0.05	2000	850	
Flooring	50	1.0	0.04	2000	850	
int			0.13			

GROUND 3	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m²K/W]	[kg/m³]	[kJ/kg K]	[W/m²K]
ext			0.04			0.17
Reinforced concrete slab	800	2.3	0.35	2400	850	
Insulating layer	120	0.04	3.33	30	850	
Screed	120	1400	0.00	2000	850	
Insulating layer	60	0.04	2.00	30	850	
Screed	50	1.4	0.04	2000	850	
Flooring	25	1.2	0.02	2000	850	
int			0.13			

Table 55 Ground optimization parameters

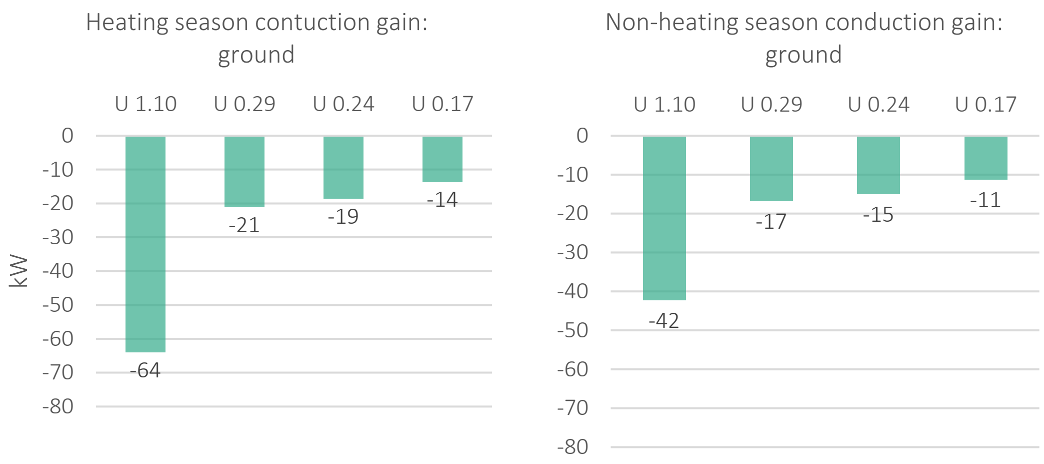


Chart 42 Ground optimization gain result

U	Heating season		Non-heating season	
	Conduction gain-roof		Conduction gain-roof	
	MWh	Δ	MWh	Δ
U 1.10	-64		-42	
U 0.29	-21	**-67%**	-17	**-60%**
U 0.24	-19	**-71%**	-15	**-65%**
U 0.17	-14	**-79%**	-11	**-73%**

Table 56 Ground optimization gain results

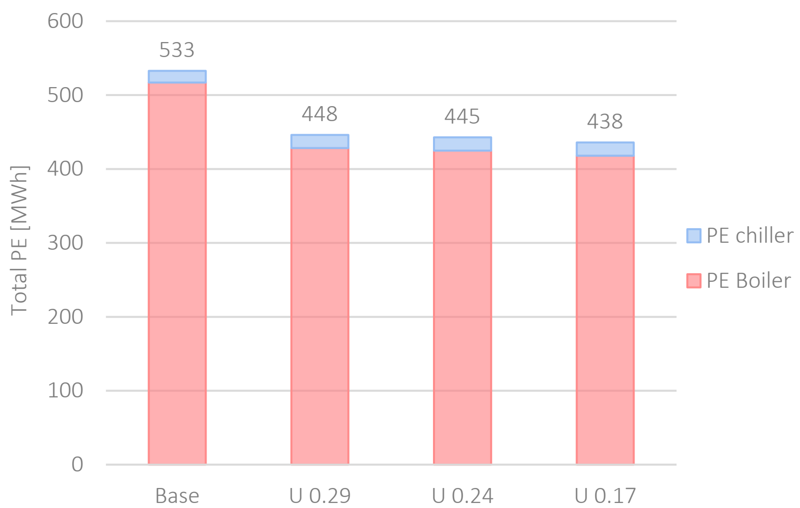


Chart 43 Ground optimization primary energy result

	Base	U 0.29	U 0.24	U 0.17
PE Bolier [MWh]	517	428	425	418
PE Chiller [MWh]	16	19	20	20
Total PE	533	448	445	438
Δ		16%	17%	18%

Table 57 Ground optimization primary energy results

External walls

To improve the quality of the external walls without changing the structural part, new layers of insulation has been added, even if the external wall surface is not very extended in this project. Therefore, it is not expected a huge improvement on energy saving with the application of these strategies.

Usually, the best choice is to add insulation panels on the external walls surface, that reduce degradation phenomena like vapour condensation and mould growth and avoid thermal bridges thanks to the continuity of the material. Form the economic point of view, this kind of intervention is one of cheapest since it guarantees a rise of envelope thermal and aesthetic quality. External wall 1 and 3 consider the original construction technology with an improvement of the insulation layer on the external face.

Another possible strategy consists in the application of insulation on the internal surface of walls. This technique is very useful for ancient building renovations, where the external surface is historically significant and cannot be covered. This intervention is not very expensive, but it is not able to solve thermal bridges and risks of condensation and mould growth. Moreover, the presence of a new material layer on internal surfaces generates a reduction of space. External wall 2 was designed with this strategy.

EXTERNAL WALL 1	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m^{2}K/W]	[kg/m^3]	[kJ/kg K]	[W/m^{2}K]
ext			0.04			0.24
External plaster	15	1	0.02	1800	850	
Insulating layer: EPS	100	0.04	2.63	25	1400	
Hollow brick	80	0.4	0.20	1200	850	
Insulating layer	40	0.05	0.80	30	850	
Cavity	40		0.16			
Hollow brick	80	0.4	0.20	1200	850	
Plaster	10	0.7	0.01	1400	850	
int			0.13			

EXTERNAL WALL 2	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m^{2}K/W]	[kg/m^3]	[kJ/kg K]	[W/m^{2}K]
ext			0.04			0.21
External layer	15	1	0.02	1800	850	
Hollow brick	80	0.4	0.20	1200	850	
Insulating layer	40	0.05	0.80	30	850	
Cavity	40		0.16			
Hollow brick	80	0.4	0.20	1200	850	
Insulating layer: glasswool	120	0.04	3.00	25	1400	
Plaster	10	0.7	0.01	1400	850	
int			0.13		850	

EXTERNAL WALL 3	t	λ	R	ρ	cp	U
	[mm]	[W/mK]	[m^{2}K/W]	[kg/m^3]	[kJ/kg K]	[W/m^{2}K]
ext			0.04			0.16
External layer	15	1	0.02	1800	850	
Insulating layer: Mineral wool	160	0.035	4.57	25	1400	

Hollow brick	80	0.4	0.20	1200	850	
Insulating layer	40	0.05	0.80	30	850	
Cavity	40		0.16			
Hollow brick	80	0.4	0.20	1200	850	
Plaster	10	0.7	0.01	1400	850	
int			0.13			

Table 58 External wall optimization parameters

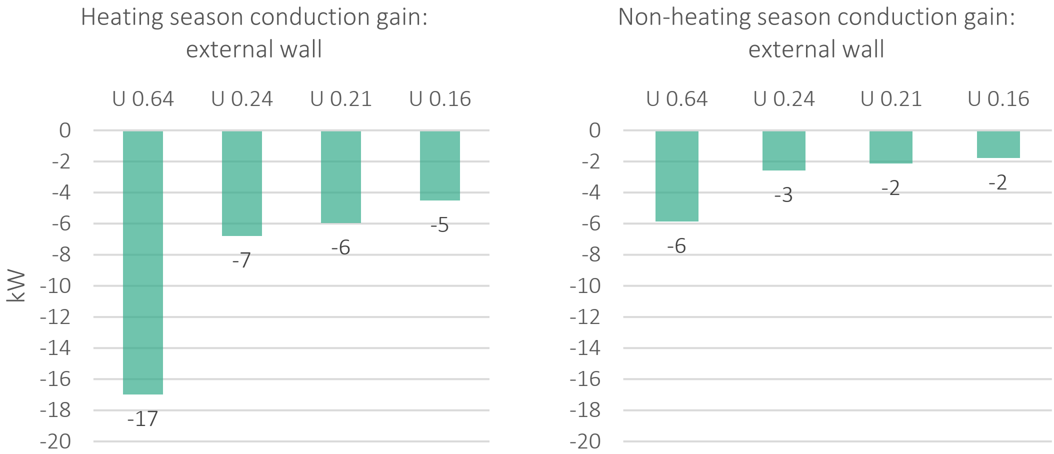


Chart 44 External wall optimization gain result

U	Heating season		Non-heating season	
	Conduction gain-external wall		Conduction gain-external wall	
	MWh	Δ	MWh	Δ
U 0.64	-17		-6	
U 0.24	-7	**-60%**	-3	**-56%**
U 0.21	-6	**-65%**	-2	**-63%**
U 0.16	-5	**-73%**	-2	**-69%**

Table 59 External wall optimization gain results

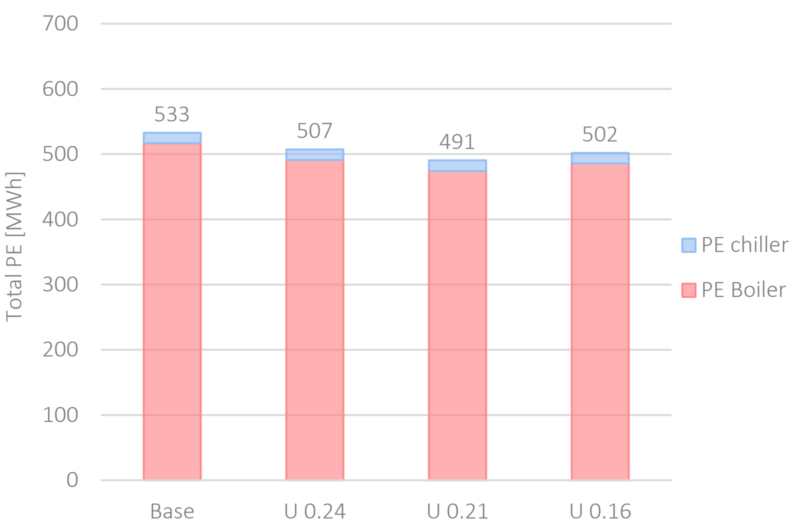


Chart 45 External wall optimization primary energy result

	Base	U 0.24	U 0.21	U 0.16
PE Bolier [MWh]	517	491	474	486
PE Chiller [MWh]	16	16	17	16
Total PE	533	507	491	502
Δ		5%	8%	6%

Table 60 External wall optimization primary energy results

Combinations

After testing the influence of single optimized parameter, it is studied the effect generated by the combination of some of them and compared the percentage of energy saving with the baseline building.

For this step, seventeen simulations were run and divided in four groups.

Group 1 - Standard, best, intermediate cases

This group contains three simulations. The first is the combination of all standard parameters with only internal blinds and it is very useful to calculate how much energy it is possible to save if the contractors decide to use the project that is based on DM 26 6 2015; the second uses all best U values combined with both internal and external shading devices in order to reduce gains as much as possible and the third is the combination of all intermediate parameters.

N°	U windows	blinds	louvers	U roof	U ground	U external wall
Case 1	1.4	yes	no	0.24	0.29	0.24
Case 2	0.8	yes	yes	0.10	0.17	0.16
Case 3	1.0	yes	yes	0.15	0.24	0.21

Table 61 Group 1 thermal transmittance combinations

The chart and the table of the three cases show that there is a huge reduction of boiler energy in all cases. In fact, the reduction of the energy used by the heating system is almost one-half respect to the baseline in the first case (the one with standard parameters), about 65% in the second case with best parameters and 60% in the third that uses intermediate U values. As expected, the chiller energy has increased respect to the baseline due to the improvement of thermal resistence of the construction layers. In all three cases the increment of the chiller energy is significant.

In general, the application of standard project, case 1, guarantees a reduction of 37% of the total PE, while with the best project, case 2, it is possible to save 47% respect to the original building and 44% with case 3.

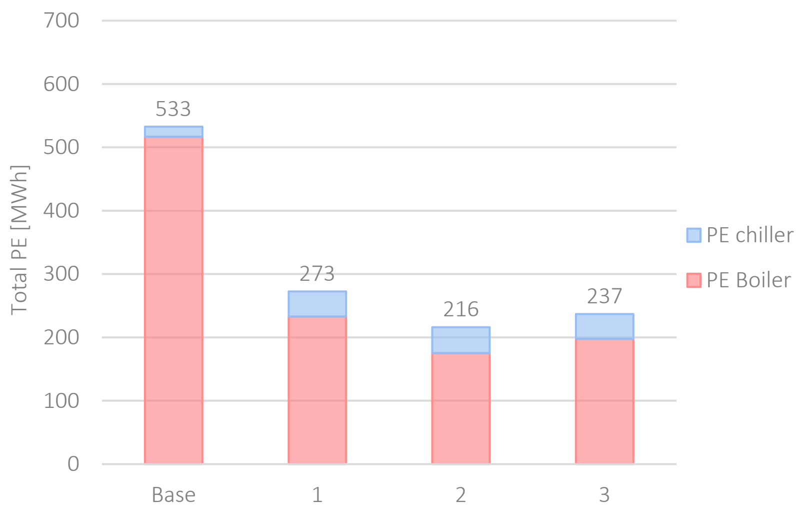


Chart 46 Group 1 primary energy result

	BASE	Case 1	Case 2	Case 3
PE Bolier [MWh]	517	233	175	198
PE Chiller [MWh]	16	40	41	39
Total PE	533	273	216	237
Reduction		49%	60%	56%

Table 62 Group 1 primary energy results

Group 2 - fixed ground parameter

The second group of simulations is composed by six cases (4-9) in which the thermal transmittance of the ground floor is kept constant and equal to the standard value. In fact, in many cases the consolidation of the ground floor during a building renovation is quite difficult since it is not always possible to substitute materials and waterproof barriers, add new layers on the outer surface of the slab or act on the ventilation system; moreover, it is very difficult to solve thermal bridges without a drastic intervention. Therefore, this group of simulations considers a minimum intervention to improve the thermal quality of the ground floor that is *balanced* by the use of performant windows (U from 0.8 to 1.0 W/m^{2}K) with always internal blinds, with or without external shading, well insulated roof and external walls.

N°	U windows	blinds	louvers	U roof	U ground	U external wall
Case 4	0.8	yes	no	0.10	0.29	0.24
Case 5	1.0	yes	no	0.15	0.29	0.24
Case 6	1.0	yes	yes	0.10	0.29	0.24
Case 7	0.8	yes	no	0.10	0.29	0.16
Case 8	0.8	yes	no	0.15	0.29	0.21
Case 9	1.0	yes	yes	0.10	0.29	0.16

Table 63 Group 2 thermal transmittance combinations

In all cases there is a reduction of the total primary energy higher then one half of the baseline. The best combination of this group is the case 7 which uses the best construction options for window roof and external walls and provide a reduction of 57% of the energy used by the original building. The chart highlights also that the improvement of external wall thermal transmittance (case 6 and 9) from the standard value to the best optimized has a very little influence on the energy consumption due to its reduced surface.

Also in these cases, the huge reduction of the energy consumption corresponds to an increment of the chiller energy since the thermal mass of the building has increased.

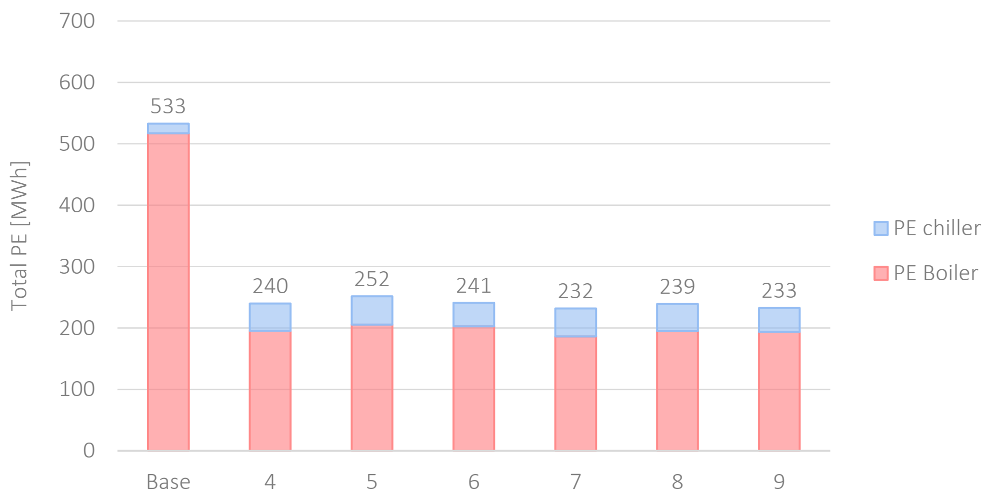


Chart 47 Group 2 primary energy result

	BASE	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
PE Bolier [MWh]	517	195	206	203	186	195	194
PE Chiller [MWh]	16	45	46	38	46	44	39
Total PE	533	240	252	241	232	239	233
Reduction		55%	53%	55%	57%	55%	56%

Table 64 Group 2 primary energy results

Group 3 - fixed roof

The third group contains simulations with fixed U value of the roof, the intermediate one, and combined with performant and standard window and with the intermediate and standard value of the ground and the external wall.

The two simulations have the same value of primary energy consumption even if the energy used by the boiler and the chiller is different. In fact, the chart shows that case 10 has higher heating consumption and lower chiller consumption respect to case 11. This *balance* is related to the use of some performant elements like windows combined with other low performant constructions. In the end, the application of the cases guarantees a reduction of energy consumption equal to 56% respect to the original building.

N°	U windows	blinds	louvers	U roof	U ground	U external wall
Case 10	1.4	yes	yes	0.15	0.17	0.16
Case 11	0.8	yes	no	0.15	0.24	0.21

Table 65 Group 3 thermal transmittance combinations

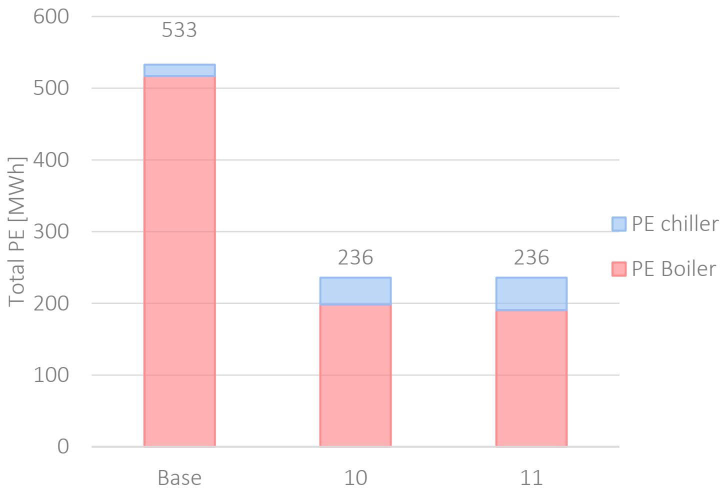


Chart 48 Group 3 primary energy result

	BASE	Case 10	Case 11
PE Bolier [MWh]	517	198	191
PE Chiller [MWh]	16	38	45
Total PE	533	236	236
Reduction		56%	56%

Table 66 Group 3 primary energy results

Group 4 - with baseline ground and external walls

The fourth group of simulations consider a partial building renovation of the building in which the ground floor and external walls are kept equal to their original construction. In fact, the previous analyses on the external conduction gain/loss demonstrate that the external wall has not significant contribution on the total external conduction due to its reduced surface.

The combination cases of the previous groups are some possible main goals for the renovation project that must be completed in some years, according to the financial sources. This group of simulations evaluates the energy saved if cases are partially applied. In order to have slender calculation, this group considers only case 2, case 7 and case 10, as main goals, which are the best combination of optimized elements of the previous three groups. These combinations are partially applied on the software model in order to understand how much energy can be saved after the application of some optimization steps. Therefore, each goal case is evaluated with the baseline construction of the ground and external walls.

The chart and the table show that the optimization of only window and roof can guarantee a reduction of 30-34% of the primary energy respect to the baseline. The improvement of the ground in addition to window and roof can increase the energy saved until one half of the original value.

Simulations related to case 2 and 7 are almost equal in the construction except for the presence of external shading whose contribution in energy saving is not so relevant as the previous analyses have shown; in fact, they both consider the best U value for windows and roof, while best and standard values for the ground. Thus, the results of simulation of cases 12 and 14 are very close. On the other hand, cases 13 and 15 are a bit different since the ground floor construction is different.

Simulations related to case 10 considers the application standard window with an intermediate value for the roof and the best one for the ground. Therefore, simulations of case 16 and 17 (with ground and external wall equal to the original building) registered higher energy consumption respect to case 12, 14 and 16. Thus, the application of the best ground combined with standard and intermediate window and roof is not able to save the same energy of the application of best windows and roof.

N°	Goal case	U windows	blinds	louvers	U roof	U ground	U external wall
Case 12	Case 2	0.8	yes	yes	0.1	base	base
Case 13		0.8	yes	yes	0.1	0.17	base
Case 14	Case 7	0.8	yes	no	0.1	base	base
Case 15		0.8	yes	no	0.1	0.29	base
Case 16	Case 10	1.4	yes	yes	0.15	base	base
Case 17		1.4	yes	yes	0.15	0.17	base

Table 67 Group 4 thermal transmittance combinations

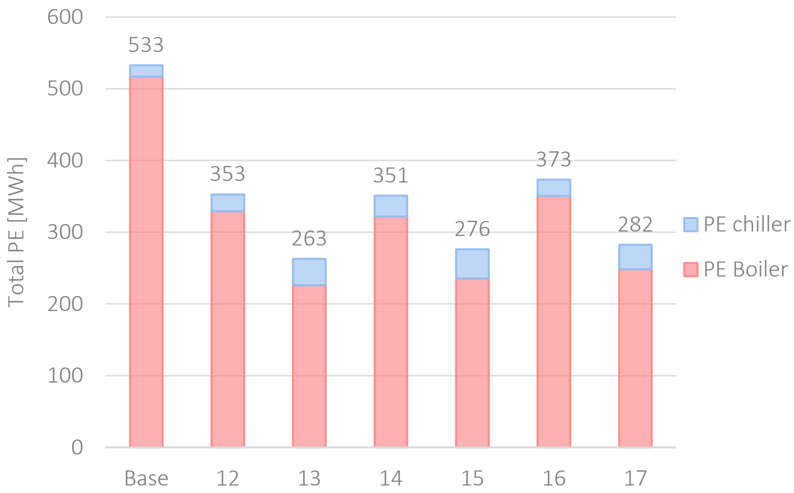


Chart 49 Group 4 primary energy result

	BASE	Case 12	Case 13	Case 14	Case 15	Case 16	Case 17
PE Bolier [MWh]	517	329	226	322	235	351	249
PE Chiller [MWh]	16	24	37	29	41	23	34
Total PE [MWh]	533	353	263	351	276	373	282
Reduction		34%	51%	34%	48%	30%	47%

Table 68 Group 4 primary energy results

4.2. SYSTEMS OPTIMIZATION

The building renovation process foresees the improvement of the conditioning systems among the optimization steps, considering also the type of terminals and distribution systems.

According to the previous simulation on the envelope optimization, the baseline heating and cooling systems consider traditional boiler and chiller whose performance is not very significant. This baseline system is associated to fan coil terminal placed in each thermal zone that are used to warm and chill the environment. Respect to the baseline, the first simulation analyses the influence of distribution system by the change of terminal typology, keeping the same energy generators.

Then, subsequent simulations consider the use of heat pumps instead of traditional boiler and chiller. In particular, the conditioning system is set on electric heat pump with air source EHP-A, electric heat pump with water source EHP-A and natural gas heat pump with water source GAHP-W. In the case of electric heat pumps, the terminals are radiant heating floor for winter and split systems to chill the environment in summer. On the other hand, simulations with natural gas heat pump considers a unique system with radiant beams for heating and cooling. The choice of terminal has done according to the function of the building (secondary school) and the type of comfort expected by occupants as reported in the chapter 4.2.

Values of efficiency, seasonal efficiently, performance of distribution systems and other parameters used in the software simulation are reported in the table.

Five simulations have been run for each cases of envelope combinations. They include the baseline simulation with the traditional system, the change of distribution plant, the application of electric air-source heat pump, application of the electric water source heat pump and natural gas heat pump (the simulations where the original generator is changed into a heat pump, auxiliary ventilation for air change has been set).

At this stage, the heating and cooling season are set according to the standard D.M. 26 6 2015.

Electric Heat Pump air source EHP-A			
ERAC2-Q /XL-CA 3222			
Heating		Cooling	
Energy source	Electricity	Energy source	Electricity
Seasonal η	3.46	Nominal EER	2.5
Delivery η	0.9216	Seasonal EER	4.59
sCOP	3.1888	Delivery ε	1.0554
	air	SSEER	3.1073

Electric Heat Pump water source EHP-W			
FOCS2-W /CA / H 4802			
Heating		Cooling	
Energy source	Electricity	Energy source	Electricity
Seasonal η	4.35	Nominal EER	2.5
Delivery η	0.8923	Seasonal EER	6.17
sCOP	3.88	Delivery ε	1.4395
	water	SSEER	5.1707

Natural gas Heat Pump water source GAHP-W			
ROBUR GAHP WS			
Heating		Cooling	
Energy source	Natural gas	Energy source	Electricity
Seasonal η	1.74	Nominal EER	2.5
Delivery η	0.8923	Seasonal EER	2
sCOP	1.5526	Delivery ε	0.88
	water	SSEER	1.3539

Table 69 Heat pumps data

Baseline construction

The improvement of systems with the baseline envelope can generate a big reduction of the primary energy consumption. The best result is obtained by the application of electric water source heat pump that provides a huge amount of energy saving, equal to 58% of the baseline consumption. Also, the application of other generators like electric air-source and natural gas heat pumps contribute to decrease the energy consumption of 48% and 53% with respect to the baseline systems.

Results of EHP-W has been checked with manual calculation in excel and the results worked out by the software IES have been almost verified.

The renovation of only distribution system can get little benefits on the total amount of energy consumed by the building. In fact, the substitution of ducts and channels can decrease the number of leakages and weak point that may dissipate and waste energy. According to the results showed by the chart, there is a little decrease of the total primary energy equal to 4%.

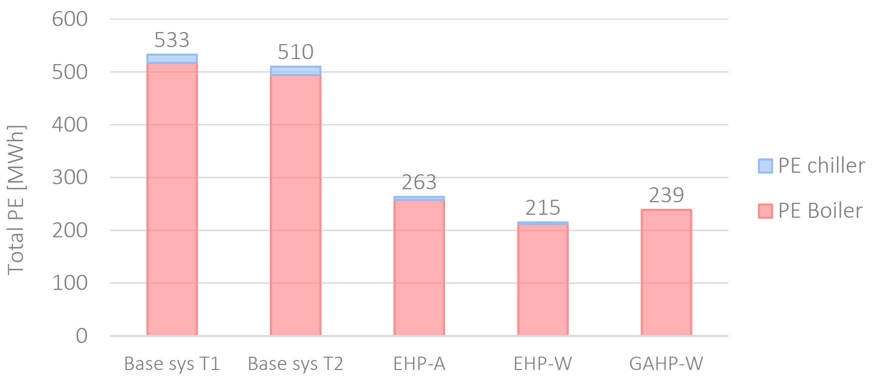


Chart 50 Baseline construction system optimization primary energy result

Baseline	Base sys T1	Base sys T2	EHP-A	EHP-W	GAHP-W
	Fan coil	Radiator	Radiant floor		Radiant ceiling
PE Bolier [MWh]	517	494	258	212	239
PE Chiller [MWh]	16	16	6	3	0
Total PE [MWh]	533	510	263	215	239
PE reduction		4%	48%	58%	53%

Table 70 Baseline construction systems optimization primary energy results

Case 1

The substitution of systems according to the building construction of case 1 has provided almost the same results of the baseline envelope in terms of energy saved. In fact, the greatest saving is related to the application of electric water source heat pump, that provides 61% savings. The other two types of generators, guarantee a reduction of primary energy equal to 50% with the electric air source heat pump and 52% with natural gas one.

Respect to the baseline construction that is made with traditional technologies of 1970', case 1 construction considers a standard thermal performance of the envelope. Comparing the percentage of energy saving of the baseline construction and case 1, there is a difference of 2-3%. This difference is connected to the improvement of thermal insulation that have a high impact in the reduction of energy used by boiler in the winter season.

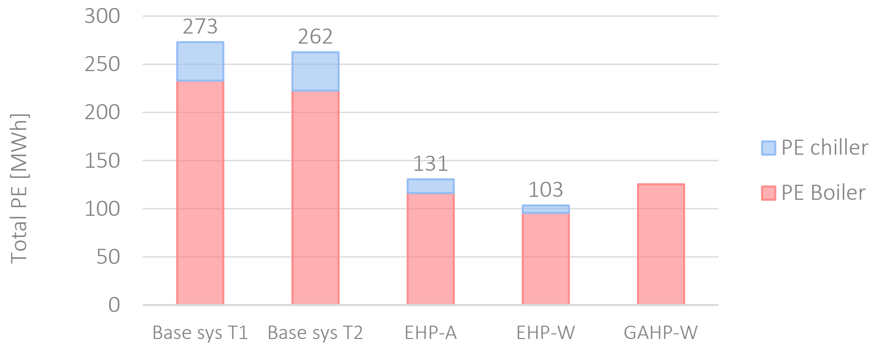


Chart 51 Case 1 construction system optimization primary energy result

Case 1	Base sys T1	Base sys T2	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	233	223	116	96	125
PE Chiller [MWh]	40	40	14	8	0
Total PE [MWh]	273	262	131	103	125
PE reduction		4%	50%	61%	52%

Table 71 Case 1 construction systems optimization primary energy results

Case 2 and 3

Almost the same results have been achieved for cases 2 and 3, where the highest energy saving is related to the use of electric water-source heat pump. In fact, it generate a decrease of 62% of the energy consumption of case 2 and 61% in case 3.

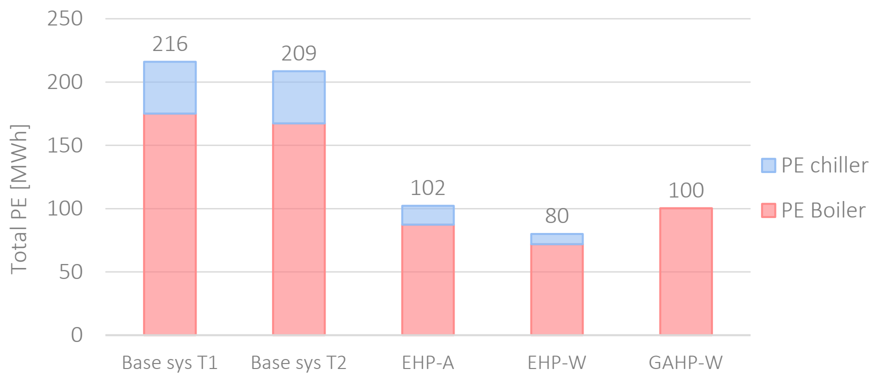


Chart 52 Baseline construction system optimization primary energy result

Case 2	Base sys T1	Base sys T2	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	175	167	87	72	100
PE Chiller [MWh]	41	41	15	8	0
Total PE [MWh]	216	209	102	80	100
PE reduction		3%	51%	62%	52%

Table 72 Case 2 construction systems optimization primary energy results

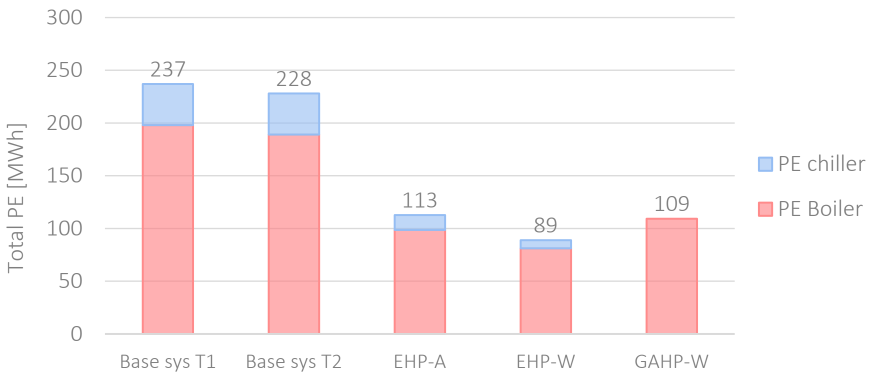


Chart 53 Case 3 construction system optimization primary energy result

Case 3	Base sys T1	Base sys T2	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	198	189	99	81	109
PE Chiller [MWh]	39	39	14	8	0
Total PE [MWh]	237	228	113	89	109
PE reduction		4%	51%	61%	52%

Table 73 Case 3 construction systems optimization primary energy results

Cases 4-17

Since the percentage of energy saving and the trend registered in the first four envelope combination is almost the same, the charts of cases from 4 to 17 were not included in this section. Only tables with data results have been plotted in order to check the results of the previous analyses.

Case 4	Base sys T1	Base sys T2	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	195	187	97	80	111
PE Chiller [MWh]	45	45	16	9	0
Total PE [MWh]	240	231	114	89	111
PE reduction		4%	51%	62%	52%

Case 5		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	206	197	103	84	117
PE Chiller [MWh]	46	46	17	9	0
Total PE [MWh]	252	243	119	93	117
PE reduction		4%	51%	61%	52%

Case 6		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	203	194	101	83	111
PE Chiller [MWh]	38	38	14	8	0
Total PE [MWh]	241	232	115	91	111
PE reduction		4%	50%	61%	52%

Case 7		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	186	178	93	76	108
PE Chiller [MWh]	46	46	17	9	0
Total PE [MWh]	232	224	109	85	108
PE reduction		3%	51%	62%	52%

Case 8		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	195	186	97	80	111
PE Chiller [MWh]	44	44	16	9	0
Total PE [MWh]	239	230	113	89	111
PE reduction		4%	51%	61%	52%

Case 9		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	194	185	97	79	108
PE Chiller [MWh]	39	39	14	8	0
Total PE [MWh]	233	224	111	87	108
PE reduction		4%	51%	61%	52%

Case 10		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	198	190	99	81	109
PE Chiller [MWh]	38	38	14	7	0
Total PE [MWh]	236	227	112	89	109
PE reduction		4%	50%	61%	52%

Case 11		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	191	182	95	78	109
PE Chiller [MWh]	45	45	16	9	0
Total PE [MWh]	236	227	111	87	109
PE reduction		4%	51%	62%	52%

Case 12		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	329	315	164	135	159
PE Chiller [MWh]	24	24	9	5	0
Total PE [MWh]	353	338	173	140	159
PE reduction		4%	49%	59%	53%

Case 13		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	226	216	113	93	121
PE Chiller [MWh]	37	37	13	7	0

Total PE [MWh]	263	253	126	100	121
PE reduction		4%	50%	60%	52%

Case 14		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	322	308	160	132	159
PE Chiller [MWh]	29	29	11	6	0
Total PE [MWh]	351	337	171	138	159
PE reduction		4%	49%	59%	53%

Case 15		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	235	225	117	97	127
PE Chiller [MWh]	41	41	15	8	0
Total PE [MWh]	276	266	132	105	127
PE reduction		4%	50%	61%	52%

Case 16		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	351	335	175	144	168
PE Chiller [MWh]	23	23	8	4	0
Total PE [MWh]	373	358	183	148	168
PE reduction		4%	49%	59%	53%

Case 17		Base syst.	EHP-A	EHP-W	GAHP-W
PE Bolier [MWh]	249	238	124	102	129
PE Chiller [MWh]	34	34	12	7	0
Total PE [MWh]	282	272	136	109	129
PE reduction		4%	50%	60%	52%

Table 74 Case 4-17 construction systems optimization primary energy results

4.2.1. OBSERVATIONS OF SYSTEMS OPTIMIZATION

The analyses of the primary energy saved in each case according to the different type of systems underlined that the best achievement is related to the use of electric water source heat pump in every case. This result is reliable since the seasonal efficiency of water source heat pump is higher than the one of an air source heat pump. This effect is strictly connected to the lower temperature fluctuation of water respect to the one of air.

The use of ground water is regulated by regional standards in order to decrease the waste of water source, respect protected feuds and avoid water pollution. The procedure to get the licence to use ground water is regulated by the regional standard Regolamento Regionale n°2 del 24 Marzo 2006 - *Disciplina dell'uso delle acque superficiali e sotterranee, dell'utilizzo delle acque a uso domestico, del risparmio idrico e del riutilizzo dell'acqua in attuazione dell'articolo 52, comma 1 lettera c) della legge regionale 12 Dicembre 2003, n 26*. The standard describes the method to get the concession for the use of ground water and the perforation of the ground. The concession is assigned to the building if the evaluation committee consider the feasibility of the project according to the morphology of the territory. According to Rif.L792 *Comune di Melzo (Provincia di Milano) Studio geologico a supporto del piano di governo del territorio redatto ai sensi della L.R. 11 marzo 2005, n° 12 e s.m.i*. the unique protected underground water feuds are located in via Belgio and via Colombo where the construction of new wells is denied. Therefore, water-source heat pump can be installed in the building.

Due to the results of this chapter, it is decided to use the electric water-source heat pump in the simulations of the next chapter.

CHAPTER

5

System schedules optimization and comfort assessment

Schedule assessment process

After the evaluation of the best heat pump and the type of terminals, the optimization process continues with the definition of the heating, middle and cooling season since the previous analyses were set on the standard period showed in UNI 11300. In this way, the energy consumption is optimized to save fuel and achieve internal comfort.

The analysis of the operative temperature (not reported in this work) of classrooms with performant systems and standard schedule, underlined that air temperature was not in the comfort range for most of the occupied hours and as consequence, the internal comfort conditions were not achieved. This effect is caused by the presence of internal gains like people and light that contribute to heat up the spaces and increase the air temperature until and over the comfort temperature limit. Therefore, the it is necessary to define the correct period of heating and cooling according to internal gains of this specific building.

The first step considers a different period of systems activation (boiler and chiller) based on fixed schedule on-off according to a specific period of time. This method worked out good result in terms of internal comfort. These simulations have tested the influence of clothing insulation in order to understand how the clothes choice can determine comfort. Since most of secondary schools in Italy don’t require dress code, students are free to adapt their clothes to the environment conditions. Basically, for each season (thus, for each representative month) three type of clothing insulation have been tested; the three values have been calculated according to the standard UNI EN ISO 7730 Annex C - *Estimation of thermal insulation of clothing ensembles* and according to the experience. The results of this first step are acceptable, but further optimization is still possible. Moreover, the air velocity has been set equal to 0.15 m/s except of the cooling season where it increased until 0.5 m/s.

The second step consist in the use of parametric schedule, based on the same period of heating and cooling used at the first step. As already shown in the previous chapters, comfort depends by operative temperature of the thermal zone., which connect the air temperature and the mean radiant temperature. Thus, parametric schedules define the set point of both the two temperatures to activate the systems.

The optimization of system schedule is based on classroom S1 and N1, since they represent the two worst cases among the thermal zones analysed. Moreover, to have a slender calculation, the assessment of each season is based on a representative month, the one in with the highest number of occupied hours and the following verification is done on the whole season.

5.1. CASE 1

The building renovation related to the case 1 considers the improvement of the envelope according to the minimum standard requirement.

Case 3 Envelope construction	Window	Roof	Ground	External wall	Blinds	Louvers
U base	base	base	base	base		
U standard	1.4	0.24	0.29	0.24	yes	yes
U intermediate	1	0.15	0.24	0.21	yes	yes
U Best	0.8	0.1	0.17	0.16	yes	yes

Table 75 Case 1 thermal transmittance of envelope

5.1.1. FIXED SCHEDULE DEFINITION

The application of standard schedule on the heating and cooling systems have provided a big fluctuation of internal operative temperature of thermal zones that generates discomfort for occupants. Therefore, the calculation of free-floating operative temperature, reported in the following chart it is useful to define the real period of system operations. In order to have a slender evaluation, the following analyses have been set on classroom S1 and N1 since they are the most significant.

In addition, the evaluation of comfort has been done according to the type of uses' clothing. In fact, unlike other European secondary school, in Italy there is no dress code and students are free to choose their type of clothes. Thus, according to standard UNI EN ISO 7730, the evaluation of comfort for the definition of the fixed system schedules has been set on three type of clothing insulation: 1.0, 0.9 and 0.8 clo for the heating and middle season; 0.6, 0.5 and 0.4 clo for the cooling season. These values represent a reliable average of the type of clothes worn by students during the occupied hours.

Clothing insulation [clo] according to standard UNI EN ISO 7730	
1.0	Trousers or long-sleeved shirt with T-shirt and sweater
0.9	Trousers or long-sleeved shirt with T-shirt and light sweater or suit jacket
0.8	Trousers or long-sleeved shirt with T-shirt and cotton suit jacket
0.6	Light long trousers or medium-sleeved with T-shirt or shirt
0.5	Short trousers or skirt and T-shirt
0.4	Short trousers or short skirt and light T-shirt

Table 76 Clothing insulation

Classroom S1

The chart of the operative temperature that explain the relation between air temperature and mean radiant temperature, of classroom S1 has been reported in order to understand when the internal temperature is in the acceptable range (20-26°C).

The chart shows that operative temperature in March, April and October-November is almost in the comfort range of the UNI EN ISO 7730, even if they are interested by high and low peaks. May, June and September are subjected by an increment of temperature that would generate high level of discomfort.

Thanks to this little analysis, the heating, middle and cooling season for this building have been defined and used for further analyses. Moreover, the representative month of the season has been decided to set the schedule assessment on it and then, verify the validity of this schedule on the whole season.

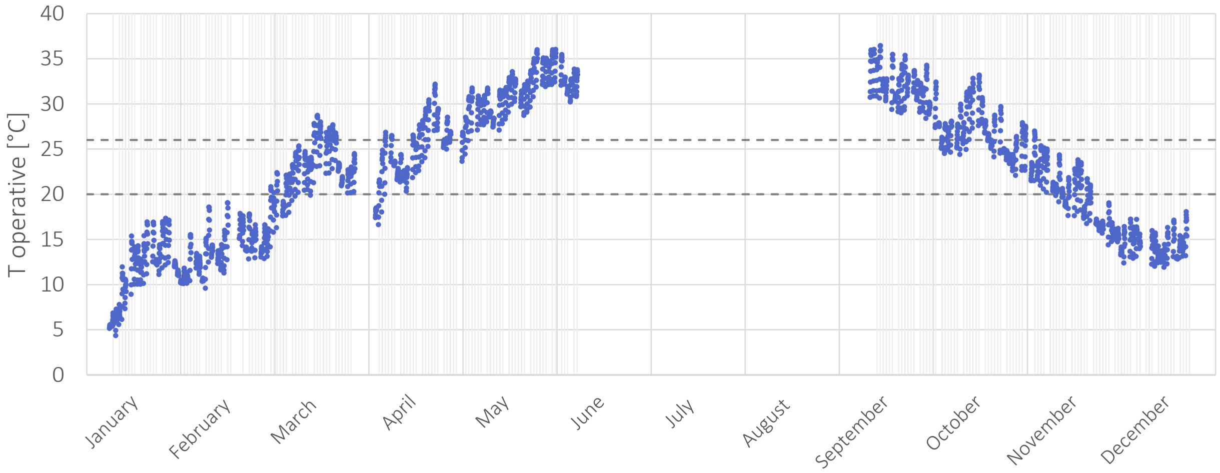


Chart 54 Case 1 S1 free-floating operative temperature

Seasons	From - to	Representative month
Heating season	from 1st November to 28th February	February
Middle season	from 1st March to 30th April and 1st October to 31st October	March
Cooling season	form 1st May to 8th June and 12nd September to 30th September	May

Table 77 Case 1 seasons assessment

Heating season

In the heating season systems are activated from 6.00 in the morning to 16.30 in the afternoon, according to the occupancy schedule. The air temperature set point is set at 20°C like the previous analyses.

The calculation of the operative temperature in February shows that values are close the line of 20°C with some peaks in which values increase and reach 23.55°C in the 16th of February. Other peaks of high temperature are registered on the 9th and 15th of February. The presence of these huge variation may cause discomfort for uses that feel too hot. This means that systems are activated when their work is not necessary, causing discomfort and loss of energy.

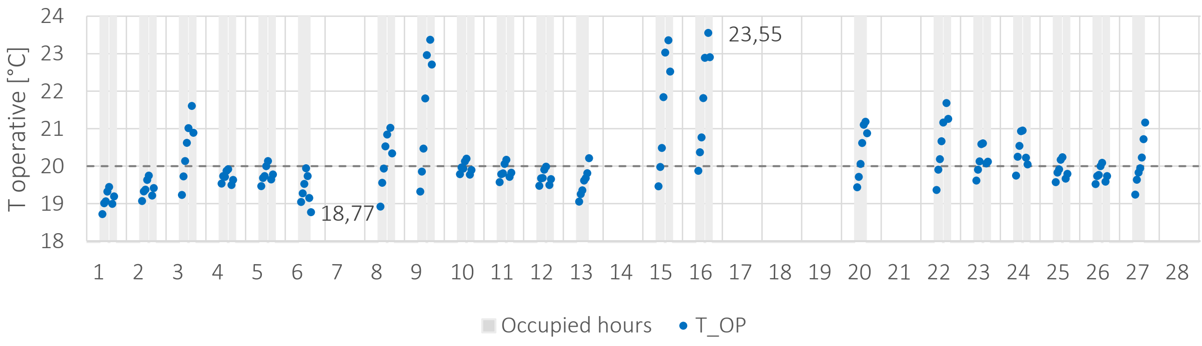


Chart 55 Case 1 Hourly operative temperature in February according to the fixed schedule

In order to check the internal comfort of students, the analyses of the predict mean vote and the predict percentage of discomfort have been provided. The evaluation of comfort considers the insulation effect of clothing and air velocity. Therefore, three analyses were run, according to different kind of clothes for the heating season.

The analyses with 1.0, 0.9 and 0.8 clo shows that the trend of PMVs is alleged to the one of operative temperature. In fact, the same peak days in which operative temperature is too high also PMVs are too high.

Despite the presence of peaks, these three type of clothing guarantee that all the occupied hours are in the comfort range A, B or C described by standards. The best values for PMV is reached with clothing insulation equal to 0.8 clo, but the corresponding predict percentage of discomfort is not the best value registered among the simulations. The most reliable value of clothing insulation in winter season according to the type of users is 0.9 clo.

The results in terms of comfort are good and acceptable but, better system schedule optimization is still possible.

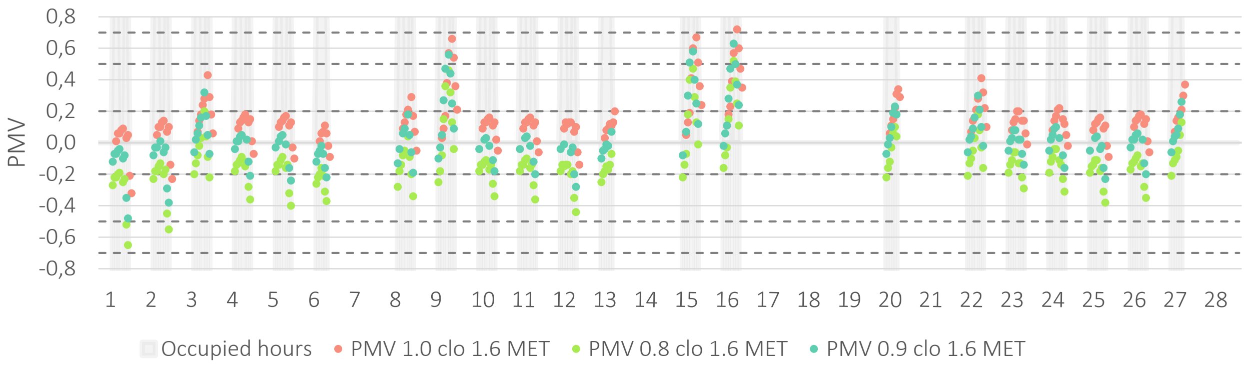


Chart 56 PMV in February the occupied hours according to users' clothing

The following charts and tables shows the frequency of comfort hours relate to the occupied hours for each category of comfort and type of clothing insulation.

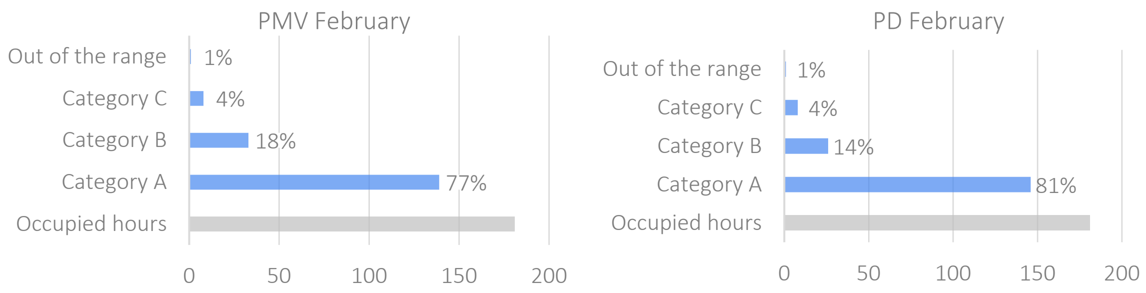


Chart 57 PMV and PD frequency case 1 S1 February 1.0 clo

February 1.0 clo	PMV		PD	
Occupied hours	181			
Category A	139	77%	146	81%
Category B	33	18%	26	14%

Category C	8	4%	8	4%
Out of the range	1	1%	1	1%

Table 78 PMV and PD case 1 S1 February 1.0 clo

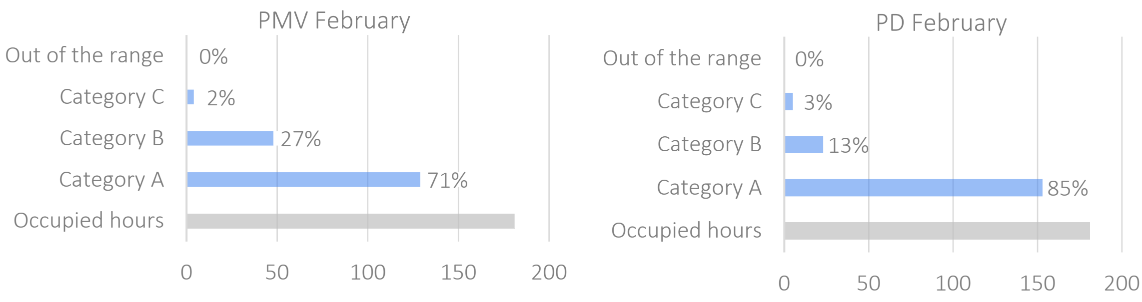


Chart 58 PMV and PD frequency case 1 S1 February 0.9 clo

February 0.9 clo	PMV		PD	
Occupied hours	181			
Category A	151	83%	153	85%
Category B	26	14%	23	13%
Category C	4	2%	5	3%
Out of the range	0	0%	0	0%

Table 79 PMV and PD case 1 S1 February 0.9 clo

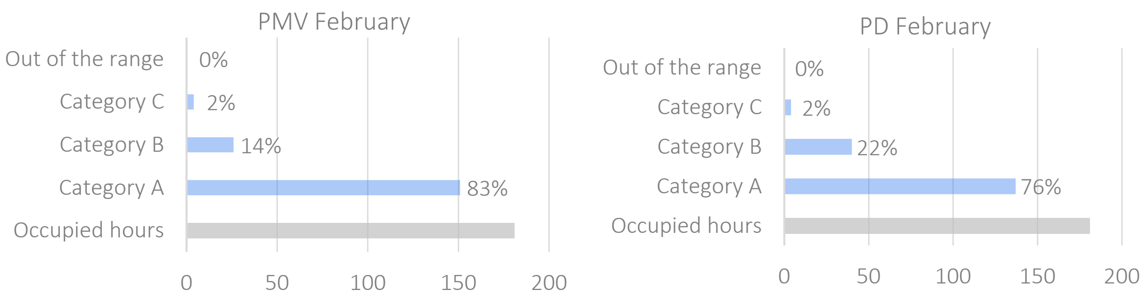


Chart 59 PMV and PD frequency case 1 S1 February 0.9 clo

February 0.8 clo	PMV		PD	
Occupied hours	181			
Category A	129	71%	137	76%
Category B	48	27%	40	22%
Category C	4	2%	4	2%
Out of the range	0	0%	0	0%

Table 80 PMV and PD case 1 S1 February 0.8 clo

Middle season

The system schedule assessment for the middle season is the most difficult one due to several variations of weather conditions that generates a fluctuation of external dry bulb temperature and mean radiant temperature of the thermal zone. Due to this effect, the operative temperature of the classroom S1 in March is very variable.

The activation of the system in this month is split in two parts: the first form the 1st to the 13rd in which the heating system starts at 6.00 until 10.00; the secondo from the 13th to the end of the month in which generators operate from 6.00 to 8.00 to preheat the room before students' entrance. Also, the set point is set equal to 21°C. Further analyses (not reported here) demonstrates that the variation of the set point for air temperature doesn't produce any significant effect on the internal comfort.

The activation of the cooling system is not taken into account for the middle season since there are openable window that can be opened by users to mitigate the internal environment, when the temperature is not in the comfort range. Thus, the simulation takes into account the presence of natural ventilation through windows.

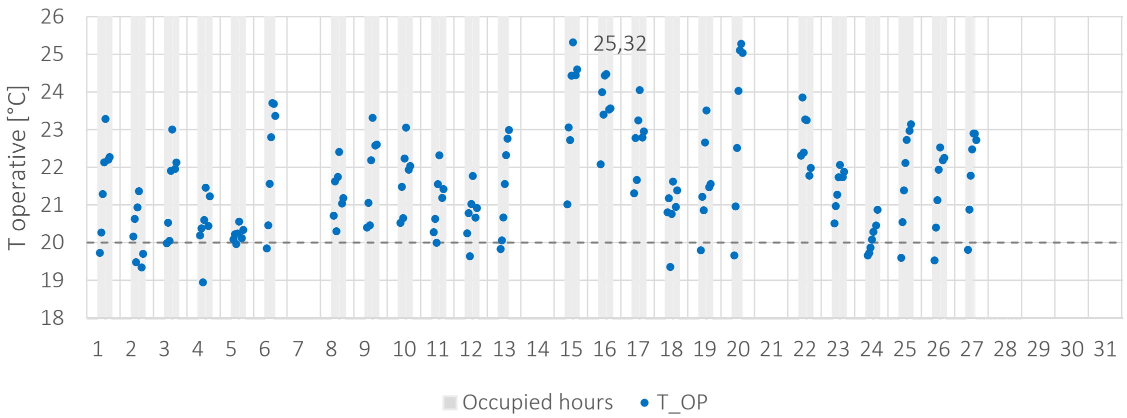


Chart 60 Case 1 hourly operative temperature in March according to the fixed schedule

The verification of internal comfort is done on PMV and PD according to the clothing insulation equal to 1.0, 0.9 and 0.8 like in the previous case. The results show that there is a big fluctuation of daily values during the occupied hours. The best condition is reached according to 0.8 clo even if there are hour in which this kind of clothes are not sufficient and cases in which it is too much. In fact, the values registered demonstrated that the percentage of hours in category A is no higher than 57%; the rest of the hours belong to category B and C and some points out of the range.

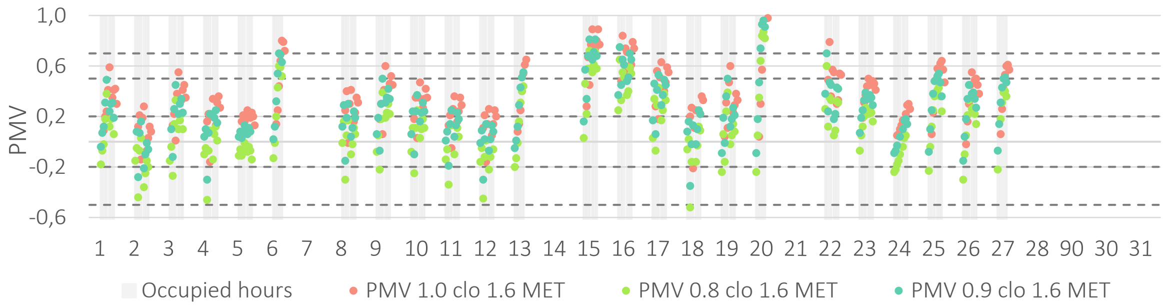


Chart 61 PMV in March the occupied hours according to users' clothing

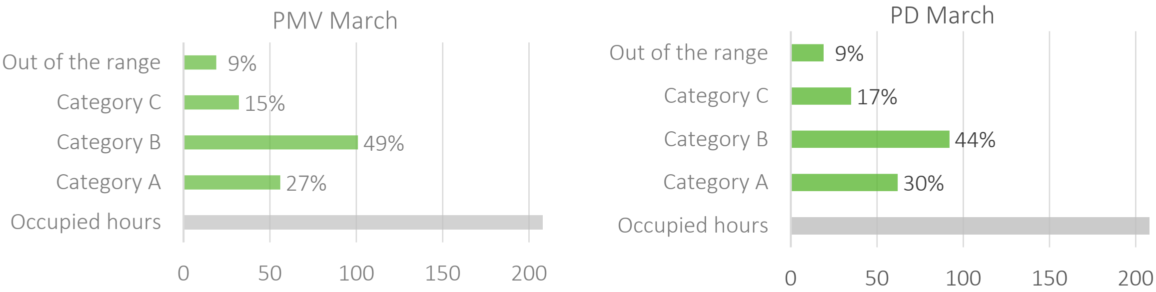


Chart 62 PMV and PD frequency case 1 S1 March 1.0 clo

March 1.0 clo	PMV		PD	
Occupied hours	208			
Category A	56	27%	62	30%
Category B	101	49%	92	44%
Category C	32	15%	35	17%
Out of the range	19	9%	19	9%

Table 81 PMV and PD case 1 S1 March 1.0 clo

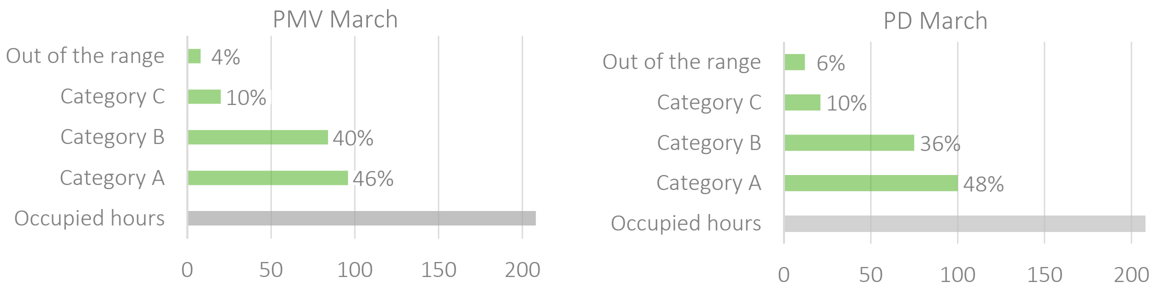


Chart 63 PMV and PD frequency case 1 S1 March 0.9 clo

March 0.9 clo	PMV		PD	
Occupied hours	208			
Category A	96	46%	100	48%
Category B	84	40%	75	36%
Category C	20	10%	21	10%
Out of the range	8	4%	12	6%

Table 82 PMV and PD case 1 S1 March 0.9 clo

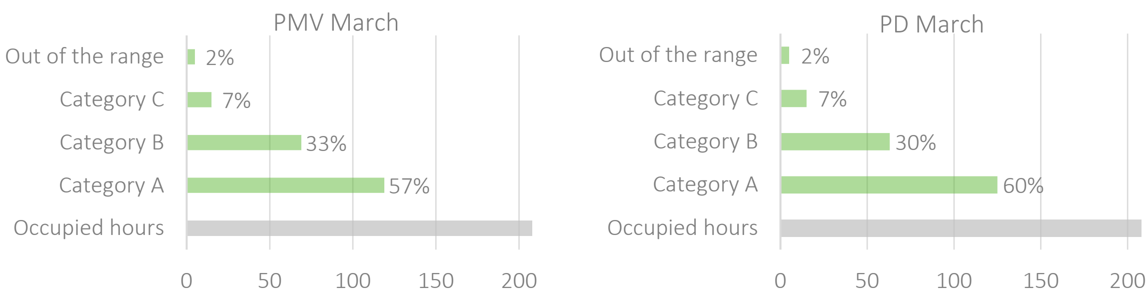


Chart 64 PMV and PD frequency case 1 S1 March 0.8 clo

March 0.8 clo	PMV		PD	
Occupied hours	208			
Category A	119	57%	125	60%
Category B	69	33%	63	30%

Category C	15	7%	15	7%
Out of the range	5	2%	5	2%

Table 83 PMV and PD case 1 S1 March 0.8 clo

Cooling season

In the cooling season, represented by May, the activation of chillers has been set from 8.00 to 16.30 during the week days and from 8.00 to 13.00 for Saturday, according to the occupancy. The set point has been lowered to 25°C to achieve a good level of internal comfort, since the set point at 26°C was not able to guarantee comfort; moreover, the air velocity has been set at to 0.5 m/s thanks to the presence of ventilators on the ceiling.

The operative temperature chart shows that the values are between 24°C and 26 °C for most of the occupied hour, even if there are some hours out for this range in which temperature reaches 26.56°C in the highest peak in the middle of the month and 23.68 °C for the lower peak at the beginning of May.

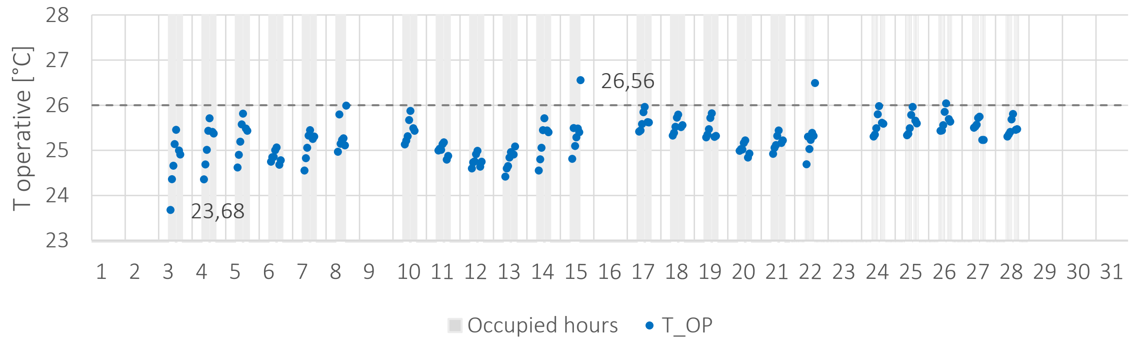


Chart 65 Case 1 hourly operative temperature in May according to the fixed schedule

The verification of internal comfort condition has been set on three type of clothing insulation equal to 0.6, 0.5 and 0.4 clo with air velocity of 0.5 m/s always.

The following chart shows that in all three cases, there is a huge daily variation of the PMV. In fact, with 0.6 clo there is no comfort in category A; with 0.5 clo the results are quite better, but few points in this category. Nevertheless, setting the clothing insulation equal to 0.4 clo (which is the most reliable value among the values considered), most of the occupied hours are in category A, 69%. This clothing value has been chosen to asses comfort of the cooling season in further analyses.

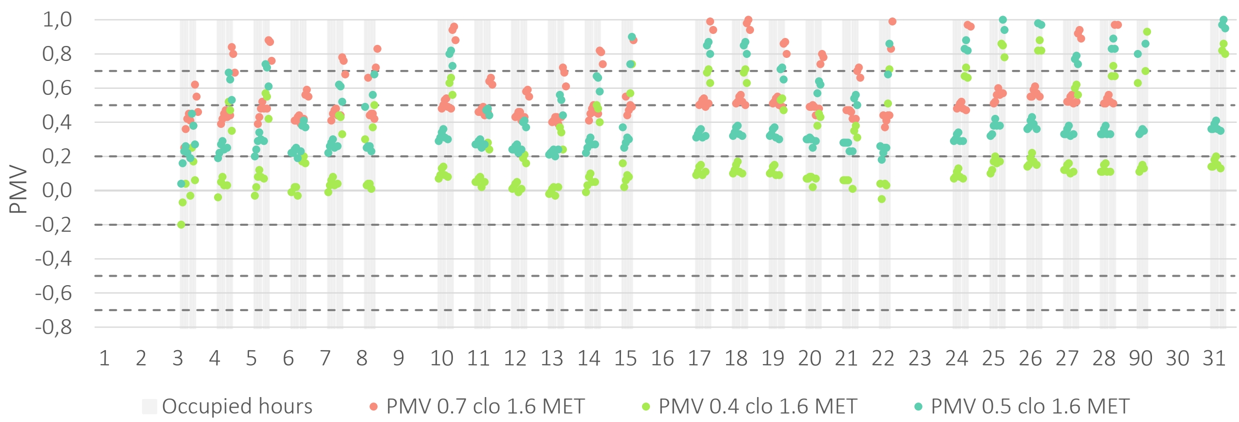


Chart 66 PMV in May the occupied hours according to users' clothing

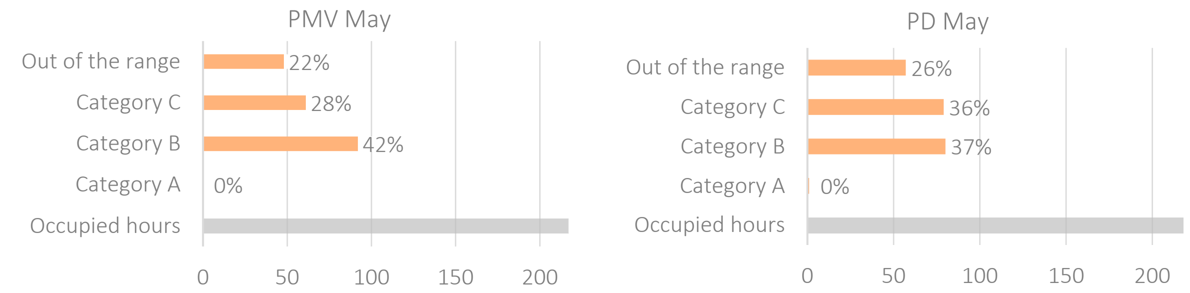


Chart 67 PMV and PD frequency case 1 S1 May 0.6 clo

May 0.6 clo	PMV		PD	
Occupied hours	217			
Category A	0	0%	1	0%
Category B	92	42%	80	37%
Category C	61	28%	79	36%
Out of the range	48	22%	57	26%

Table 84 PMV and PD case 1 S1 May 0.6 clo

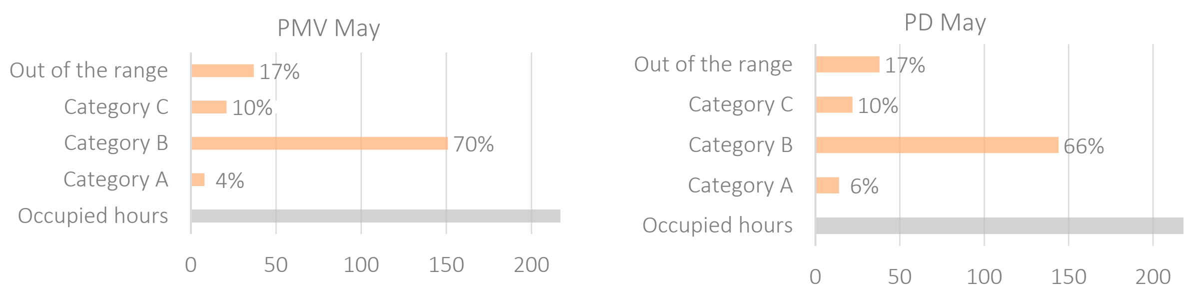


Chart 68 PMV and PD frequency case 1 S1 May 0.5 clo

May 0.5 clo	PMV		PD	
Occupied hours	217			
Category A	8	4%	14	6%
Category B	151	70%	144	66%
Category C	21	10%	22	10%
Out of the range	37	17%	38	17%

Table 85 PMV and PD case 1 S1 May 0.5 clo

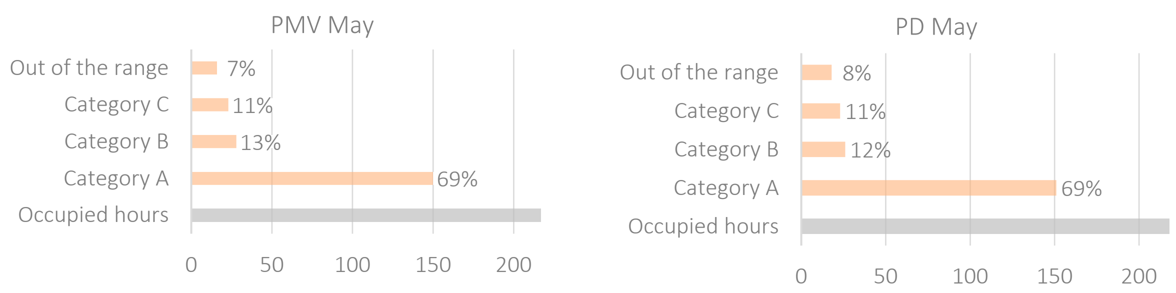


Chart 69 PMV and PD frequency case 1 S1 May 0.4 clo

May 0.4 clo	PMV		PD	
Occupied hours	217			
Category A	150	69%	151	69%
Category B	28	13%	26	12%
Category C	23	11%	23	11%
Out of the range	16	7%	18	8%

Table 86 PMV and PD case 1 S1 May 0.4 clo

Classroom N1

The trend of operative temperature of classroom N1 is lower respect to the one calculated in classroom S1 due to the north orientation that minimize solar gain. The definition of the seasons period is the same for the other classroom. The chart underlines some peaks in in March and April where the temperature is subjected to a big variation.

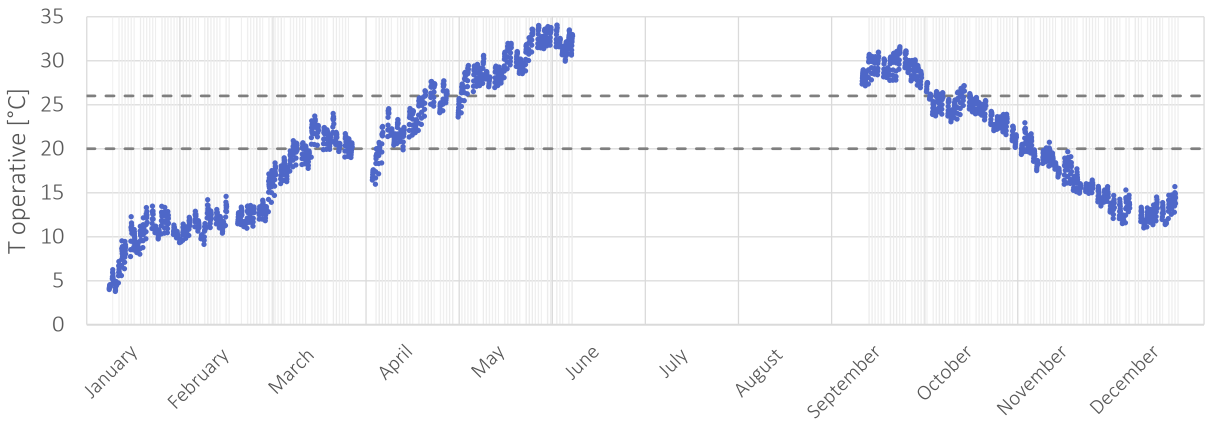


Chart 70 Case 1 N1 free-floating operative temperature

Heating season

The same schedule of classroom S1 has been kept for this evaluation. The calculation of the operative temperature in February shows that most of the values are under the 20°C line and the daily variation is significant. The lowest peak is registered at the 6th of February when the temperature falls at 18°C at the end of the day. This fluctuation depends on the variation of the mean radiant temperature since the air temperature is set constant at 20°C during the occupied hours.

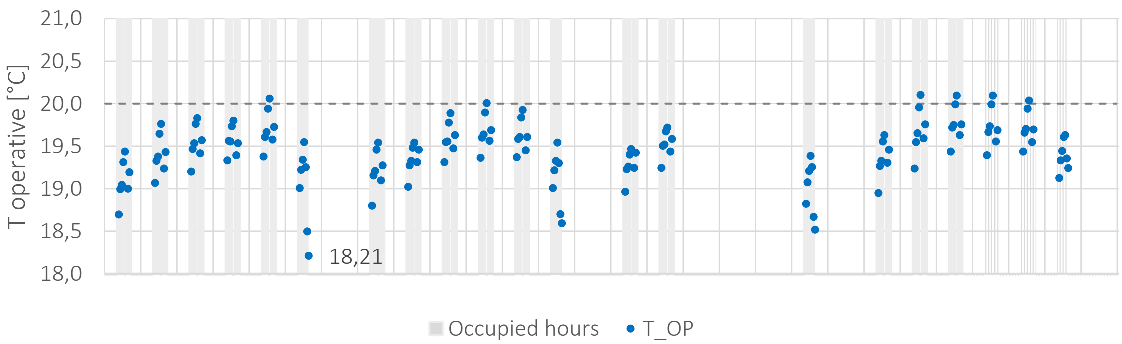


Chart 71 Case 1 hourly operative temperature in February according to the fixed schedule

The verification of internal comfort by PMV and PD according to the clothing insulation 1.0, 0.9 and 0.8 shows that the best result has been achieved with the heaviest clothing insulation, but this this value is not reliable for students of the secondary school. Therefore, as for classroom S1, clothing insulation preferred is 0.9 clo for which the 85% of the occupied hours is in the category A of comfort range.

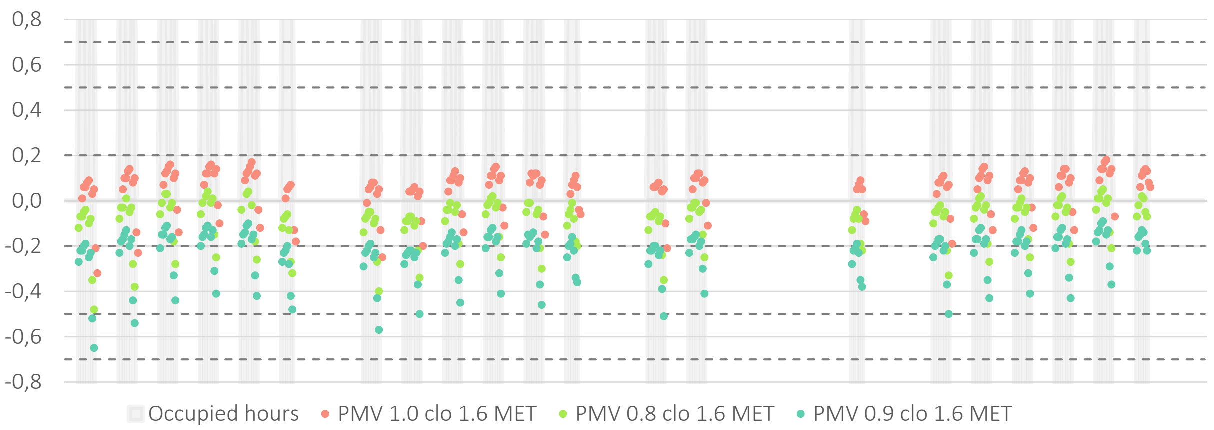


Chart 72 PMV in February the occupied hours according to users' clothing

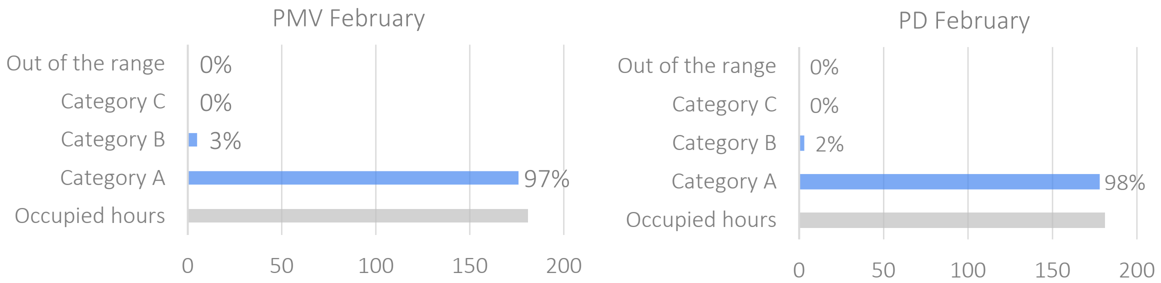


Chart 73 PMV and PD frequency case 1 N1 February 1.0 clo

February 1.0 clo	PMV		PD	
Occupied hours	181			
Category A	176	97%	178	98%
Category B	5	3%	3	2%
Category C	0	0%	0	0%
Out of the range	0	0%	0	0%

Table 87 PMV and PD case 1 N1 February 1.0 clo

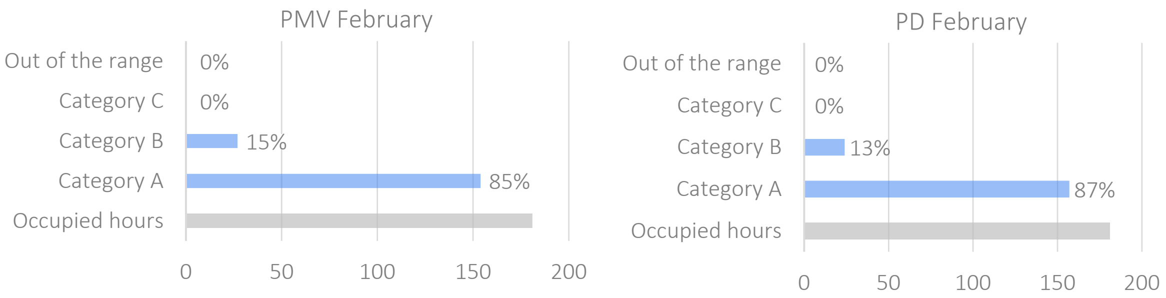


Chart 74 PMV and PD frequency case 1 N1 February 0.9 clo

February 0.9 clo	PMV		PD	
Occupied hours	181			
Category A	154	85%	157	87%
Category B	27	15%	24	13%
Category C	0	0%	0	0%
Out of the range	0	0%	0	0%

Table 88 PMV and PD case 1 N1 February 0.9 clo

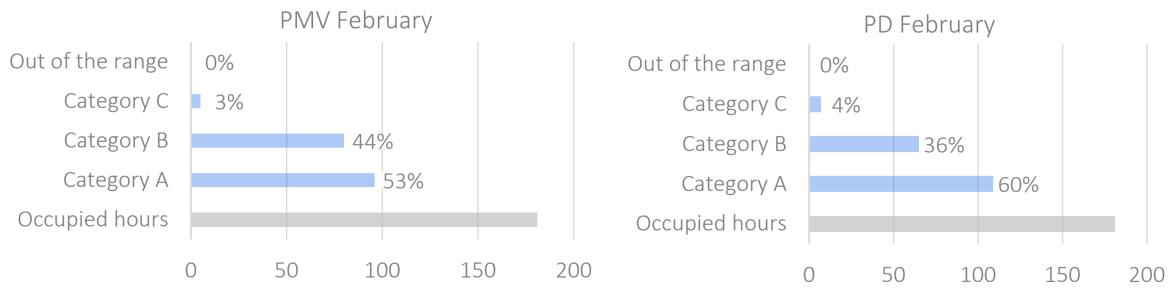


Chart 75 PMV and PD frequency case 1 N1 February 0.8 clo

February 0.8 clo	PMV		PD	
Occupied hours	181			
Category A	96	53%	109	60%
Category B	80	44%	65	36%
Category C	5	3%	7	4%
Out of the range	0	0%	0	0%

Table 89 PMV and PD case 1 N1 February 0.8 clo

Middle season

In the middle season the operative temperature varies according to the variation of external temperature and external weather conditions. Therefore, there are many peaks from 17°C to 23°C even if the natural ventilation and heating systems are operating. The fluctuation of values is significant as in classroom S1 and may causes problems of general discomfort and local discomfort.

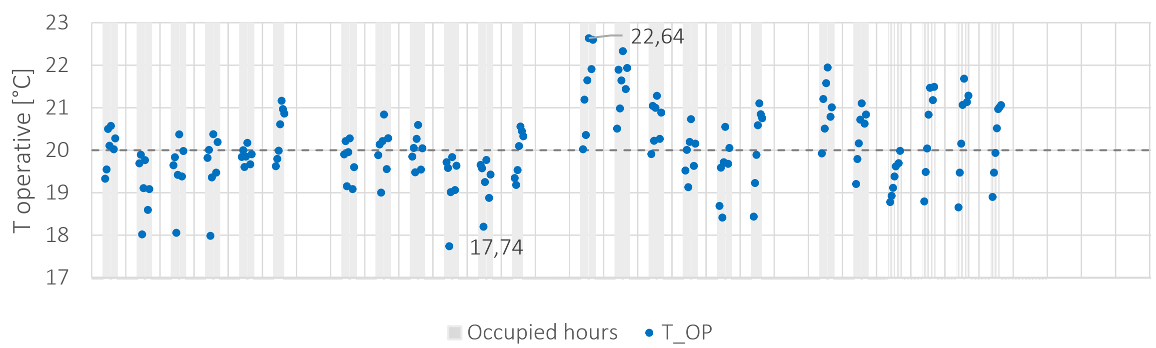


Chart 76 Case 1 hourly operative temperature in March according to the fixed schedule

The evaluation of the predict mean vote according to the clothing insulation showed by the following charts and tables, demonstrate that comfort condition is achieved and its related to the category A in most cases. The best result is obtained with 0.9 clo where the percentage of comfort hours in category A is equal to 75%. Despite this good result, the type of clothes worn by students must be almost equal for everyone. Therefore, the evaluation of comfort for this month is set on 0.8 clo like the analyses of classroom S1.

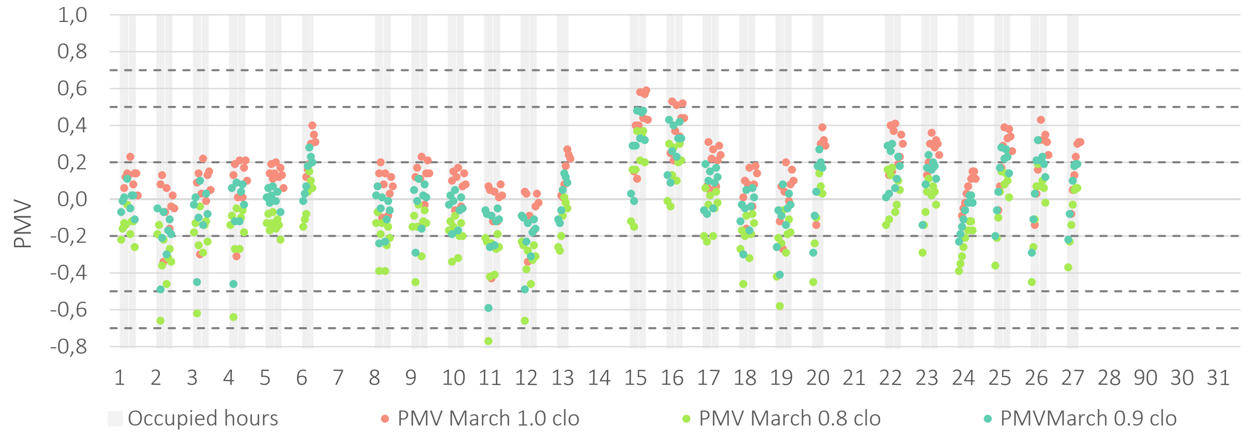


Chart 77 PMV in March the occupied hours according to users' clothing

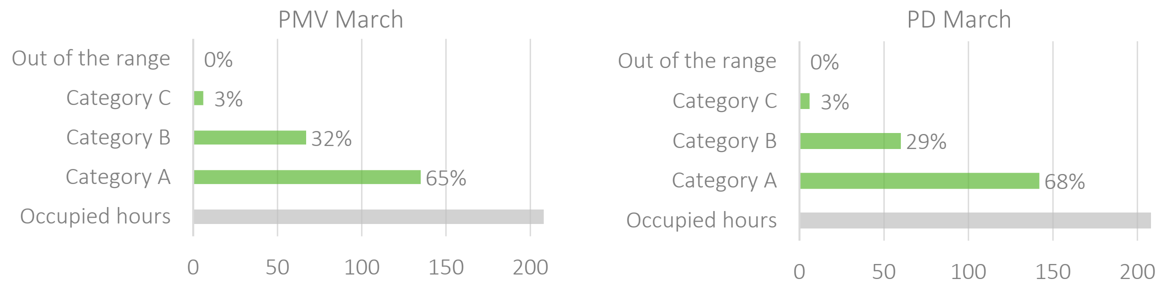


Chart 78 PMV and PD frequency case 1 N1 March 1.0 clo

March 1.0 clo	PMV		PD	
Occupied hours	208			
Category A	157	75%	142	68%
Category B	50	24%	60	29%
Category C	1	0%	6	3%
Out of the range	0	0%	0	0%

Table 90 PMV and PD case 1 N1 March 1.0 clo

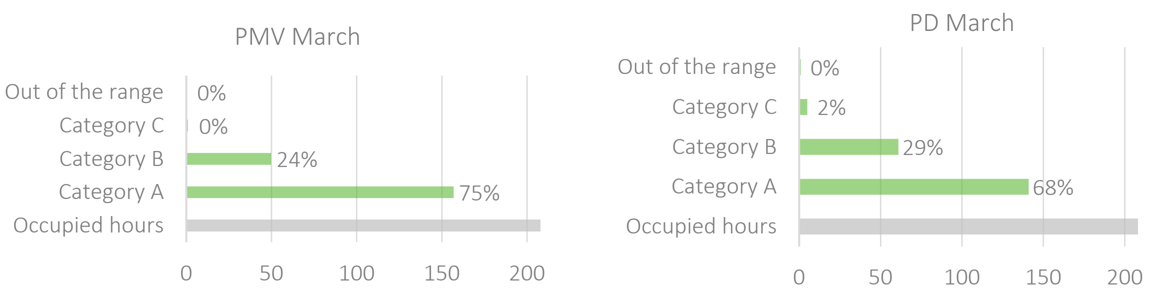


Chart 79 PMV and PD frequency case 1 N1 March 0.9 clo

March 0.9 clo	PMV		PD	
Occupied hours	181			
Category A	154	85%	141	68%
Category B	27	15%	61	29%
Category C	0	0%	5	2%
Out of the range	0	0%	1	0%

Table 91 PMV and PD case 1 N1 March 0.9 clo

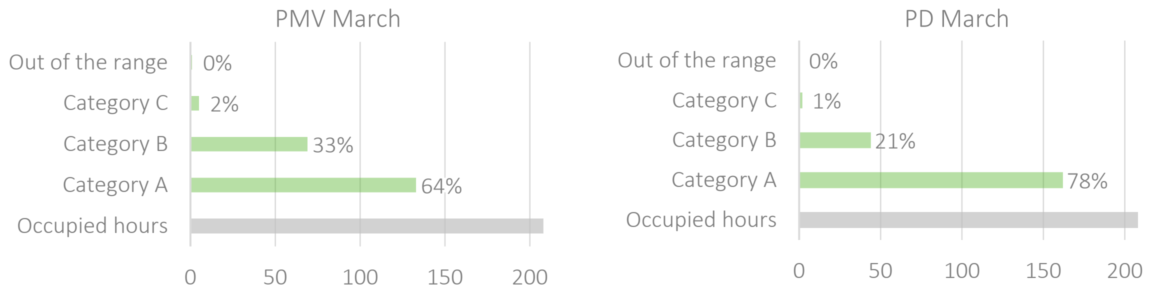


Chart 80 PMV and PD frequency case 1 N1 March 0.8 clo

March 0.8 clo	PMV		PD	
Occupied hours	208			
Category A	133	64%	162	78%
Category B	69	33%	44	21%
Category C	5	2%	2	1%
Out of the range	1	0%	0	0%

Table 92 PMV and PD case 1 N1 March 0.8 clo

Cooling season

The operative temperature calculated in the cooling period according to the chiller operation demonstrate that values concentrate on the line of 26°C with some peaks of low values at the beginning of the month and some high peak at the end. The absence of big daily fluctuation can have a positive effect in the assessment of thermal comfort

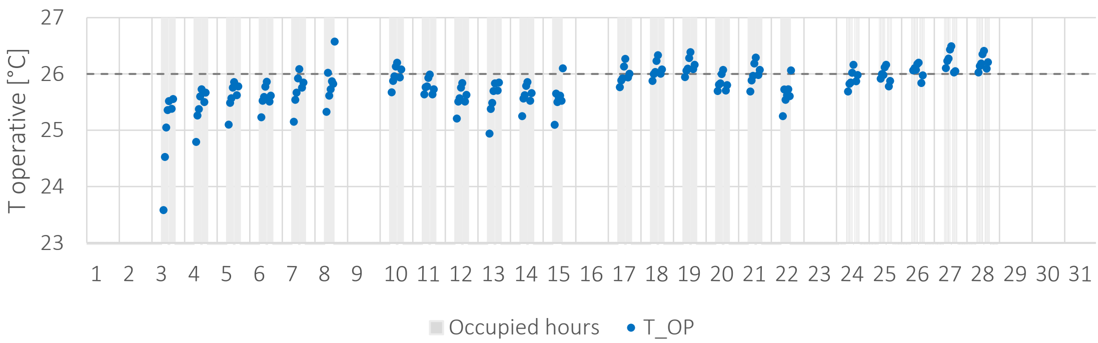


Chart 81 Case 1 hourly operative temperature in May according to the fixed schedule

The evaluation of thermal comfort on this classroom demonstrate that the greatest part of the occupied hours is in comfort condition of category A and B. The highest value is reached according to 0.4 clo as already defined for classroom S1.

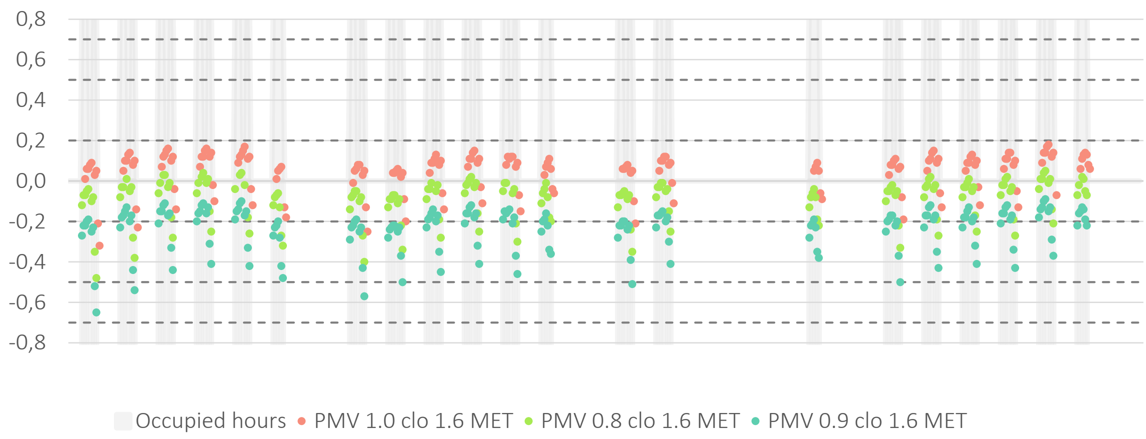


Chart 82 PMV in May the occupied hours according to users' clothing

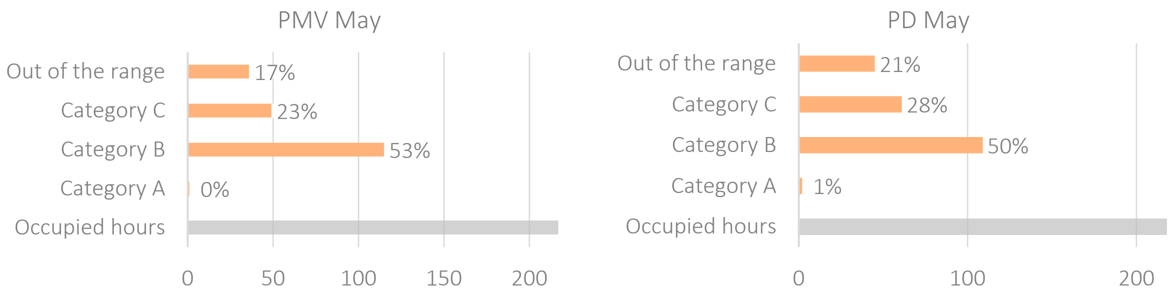


Chart 83 PMV and PD frequency case 1 N1 May 0.6 clo

May 0.6 clo	PMV		PD	
Occupied hours	217			
Category A	1	0%	2	1%
Category B	115	53%	109	50%
Category C	49	23%	61	28%
Out of the range	36	17%	45	21%

Table 93 PMV and PD case 1 N1 May 0.6 clo

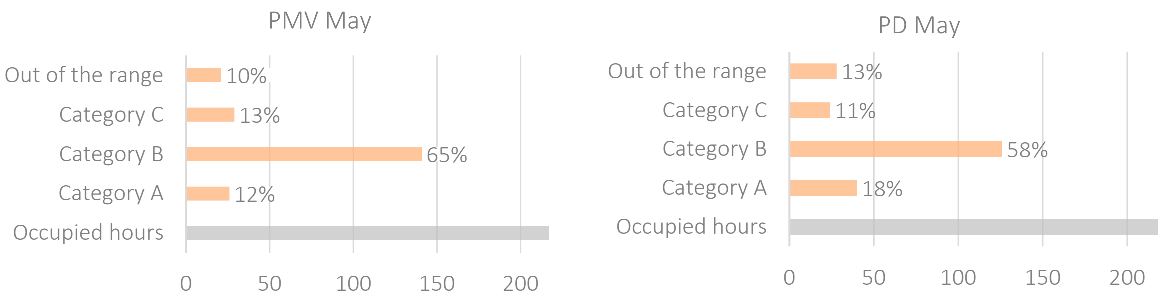


Chart 84 PMV and PD frequency case 1 N1 May 0.5 clo

May 0.5 clo	PMV		PD	
Occupied hours	217			
Category A	26	12%	40	18%
Category B	141	65%	126	58%
Category C	29	13%	24	11%
Out of the range	21	10%	28	13%

Table 94 PMV and PD case 1 N1 May 0.5 clo

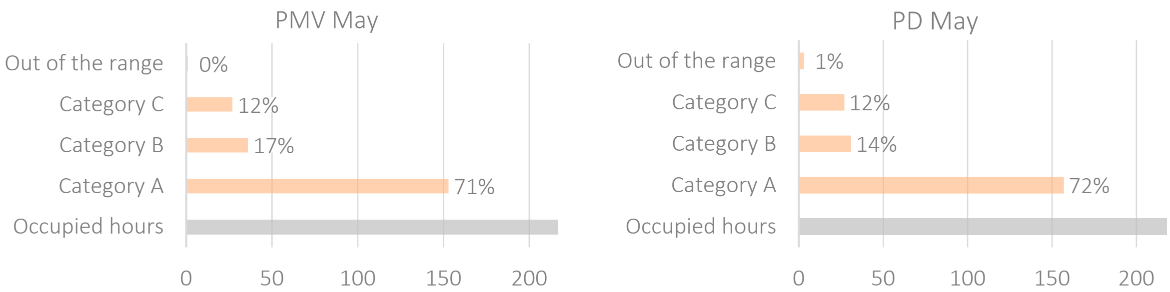


Chart 85 PMV and PD frequency case 1 N1 May 0.4 clo

May 0.4 clo	PMV		PD	
Occupied hours	217			
Category A	153	71%	157	72%
Category B	36	17%	31	14%
Category C	27	12%	27	12%
Out of the range	1	0%	3	1%

Table 95 PMV and PD case 1 N1 May 0.4 clo

5.1.2. PARAMETRIC SCHEDULE ASSESSMENT

The results of the previous section are quite good, but the improvement of the comfort condition is still possible. In fact, there is a big fluctuation of values in the middle and cooling season and this means that the building needs further optimization process. In order to do this, Classroom S1 was chosen to continue the optimization, since it is the worst case, whose results are the most variable. Then, the optimized schedule has ben applied on classroom N1 to check its functioning and continue the optimization for this part of the building.

The optimization of the fixed schedule use in the previous section starts on the analysis of the peak day (in terms of operative temperature) and its hourly variation during the occupied hours; therefore, the parameters used for the schedule optimization are based on this day. Then the optimized parametric schedule has been applied on the representative month and its functioning tested by the calculation of internal comfort. Moreover, these results have been compared with the one of the fixed schedule.

The same schedule is applied on the whole season and verified its validity by the calculation of comfort hours on the other months of the season.

Classroom S1

Optimization of the Heating season schedule

Starting from the peak day highlighted by the application of the fixed schedule, the 16th of February, the hourly operative temperature has been plotted and analysed. In fact, its fluctuation during the occupied hours is quite big. Therefore, passing form the use of fixed schedule to the application of parametric schedule, the variation of internal temperature has decreased. The peak in the middle of the day is related to the presence of people and light that generate heat and by passive solar gain. During these hours, the boiler doesn't operate because internal and passive gains are enough to achieve comfort.

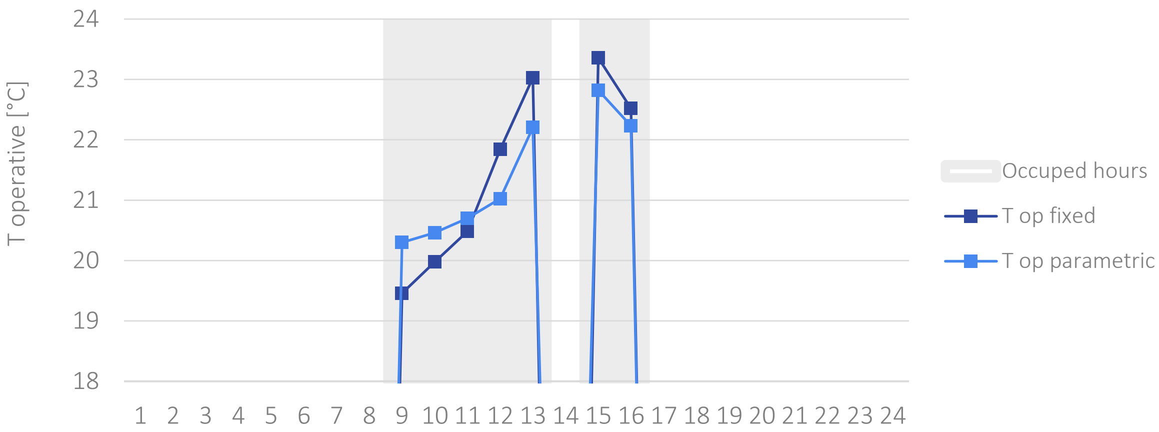


Chart 86 S1 Hourly operative temperature in the peak day 16th of February

The analysis of internals comfort is done on the representative month, February and then verified for the other months of the heating season using the clothing insulation value equal to 0.9 clo since the previous analyses have demonstrate that it is the best and the most reliable according to the experience. The heating schedule is bases on the following parameters.

Parametric schedule – Heating season		
Heating on	6.00-17.00	if Tmr≤ 19°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	-	-

Table 96 Case 1 S1 heating season parametric schedule data

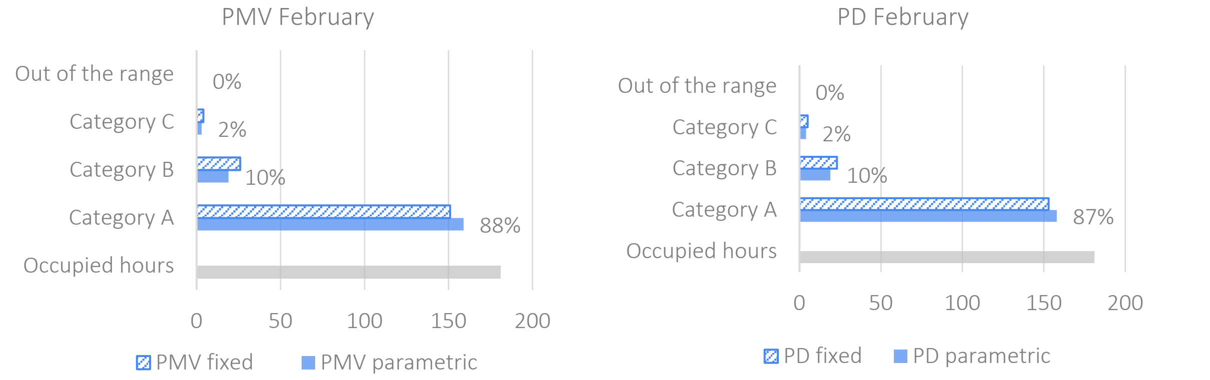


Chart 87 PMV and PD case 1 S1 frequency comparison of the parametric schedule with the fixed one, February 0.9 clo

The application of this schedule on the whole season has provided good results. In fact, the calculation of comfort hours respect to the occupied hours in January and December demonstrate that comfort is reached, and it belongs to category A for the 90% and only 10% to category B.

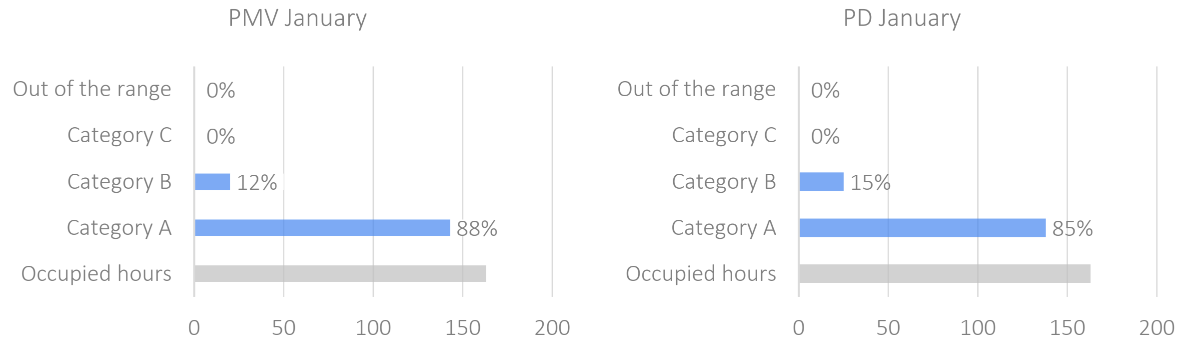


Chart 88 PMV and PD frequency case 1 S1 parametric schedule January 0.9 clo

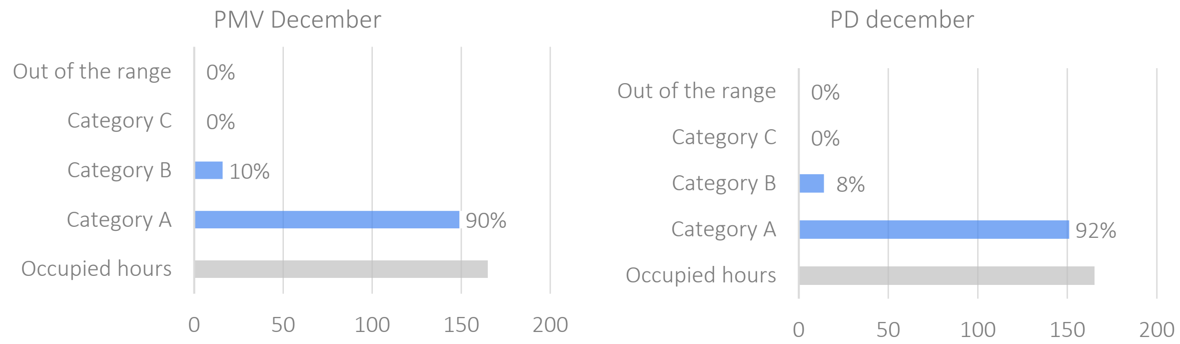


Chart 89 PMV and PD frequency case 1 S1 parametric schedule December 0.9 clo

Optimization of the Middle season schedule and ventilation

The assessment of the parametric schedule for the middle season start by the analysis of the hourly operative temperature of the peak day of classroom S1 which is the 15th of March. The operative temperature in the middle season rises until 25.5 °C causing thermal discomfort for occupants.

The application of parametric schedule for the heating and natural ventilation contribute to decrease the operative temperature during the occupied hours and decrease the temperature fluctuation on the same period.

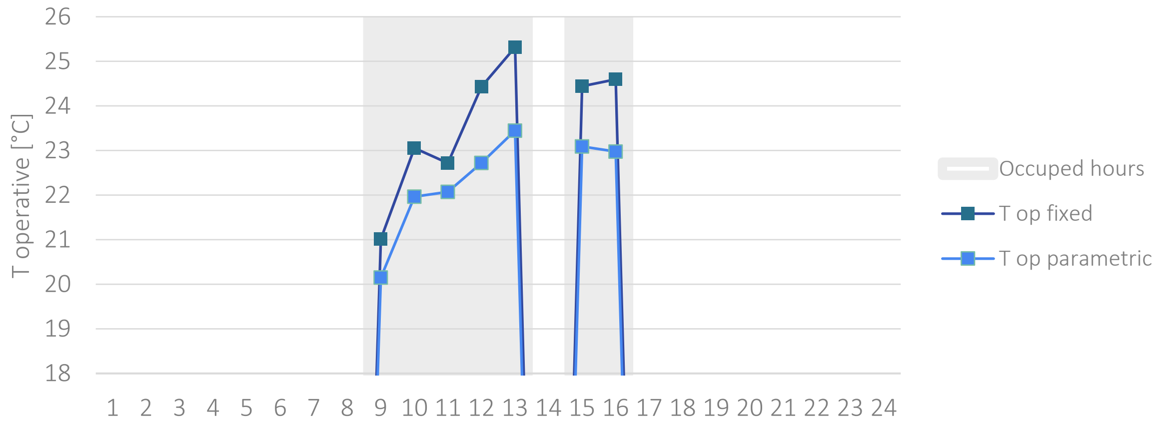


Chart 90 Operative temperature registered into classroom S1 during the peak day 15th of March

The fixed schedule for heating and ventilation have been modified in order to assess the parametric schedule that control the systems. In particular, knowing that the middle season is subjected to weather variation, schedule of heating and natural ventilation (window openings) are set according to the variation of internal mean radiant temperature and air temperature. Analyses of the previous section have been set on fixed schedules.

Parametric schedule – Middle season South		
Heating on	6.00 - 8.00	if Tmr≤ 17°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	8.00 – 17.00	If Ta≥ 23°C

Table 97 Case 1 S1 middle season parametric schedule data

In this way, results show an improvement of internal comfort in the months of the middle season such as March April, and October. Comfort evaluation is done on PMV and PD as the previous analyses.

The use of a variable schedule provides some good effect for the month analysed (march). First, the operative temperature of the thermal zone is more constant and close to the 20°C line respect to the result of the previous analyses (chapter 5.1.1) with some variation according to the climate condition of the external environment. The peak is shifted now on the 24th of march where the operative temperature reaches 23.75°C.

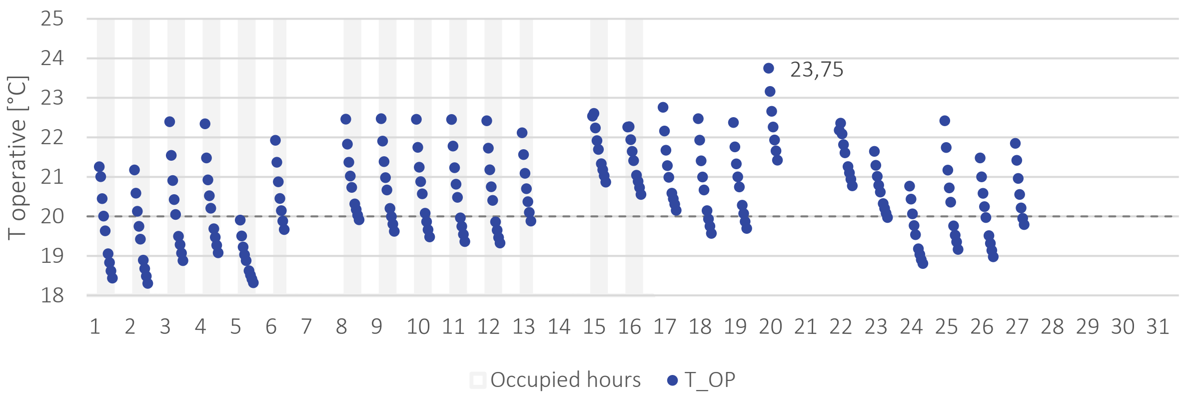


Chart 91 Case 1 S1 parametric schedule hourly operative temperature in March

The charts of the PMV and PD show that there is a little improvement of internal comfort conditions, considering a clothing insulation equal to 0.8 clo for March. Results shows an increment of comfort hours in category A in terms of predict mean vote and equal values for the percentage of discomfort. Category B has a little increment in PMV and PD that corresponds to a decrease of percentage in category C and out of the range.

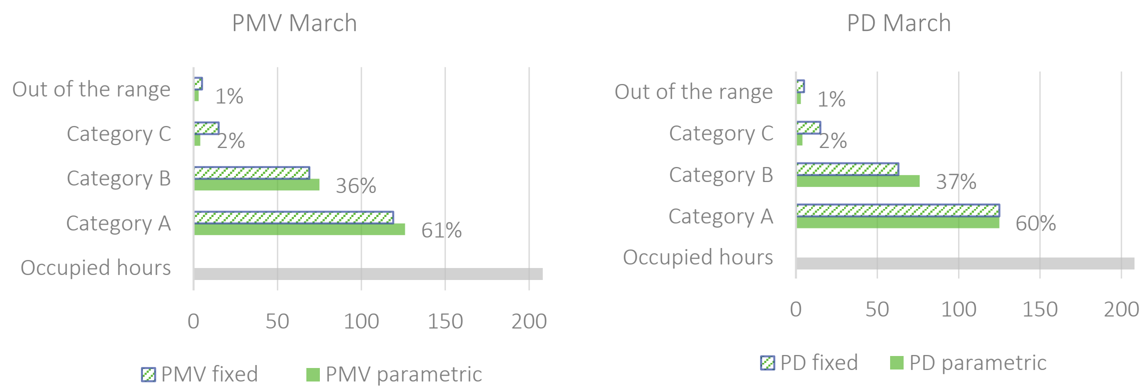
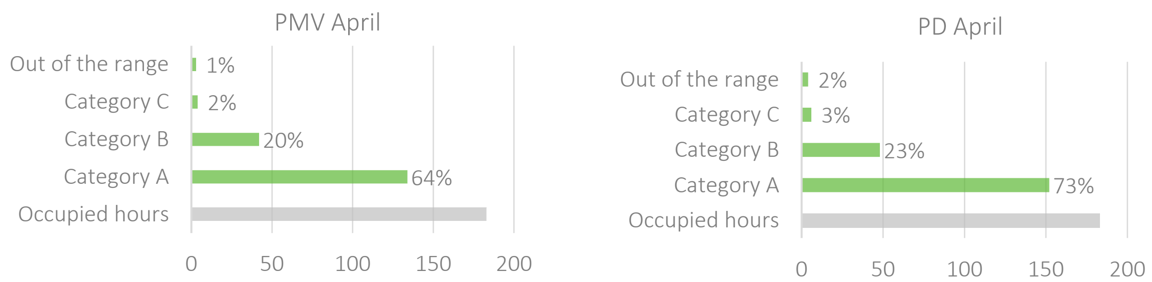


Chart 92 PMV and PD frequency case 1 S1 comparison of the parametric schedule with the fixed one, March 0.8 clo

Since these changes have provides good results, the schedules have been extended to the months of the middle season, April and October. Therefore, the same charts for PMV and PD have been reported for these months according to the type of clothing mainly used, 0.65 clo in April and 0.6 clo in October.

The flowing charts shows that most of the valued belong to category A, a little percentage close to 20% belong to category B and only some points are in category C or out of the comfort ranges.



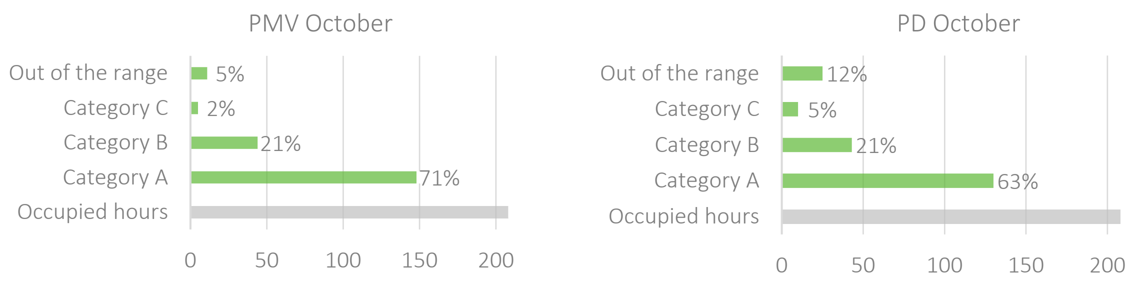


Chart 93 PMV and PD frequency case 1 S1 parametric schedule April 0.65 clo, October 0.6 clo

Optimization of the cooling season schedule and ventilation

The evaluation of the hourly operative temperature in the peak day for the summer month is on the 15th of May. The operative temperature is low when the cooling system operates according to the fixed schedule. The optimization of system schedule is done improve internal comfort and, at the same time, to increase the operative temperature in order to consume less energy.

The application of parametric schedule contributes to increase a bit the operative temperature, even if the improvement is not significant.

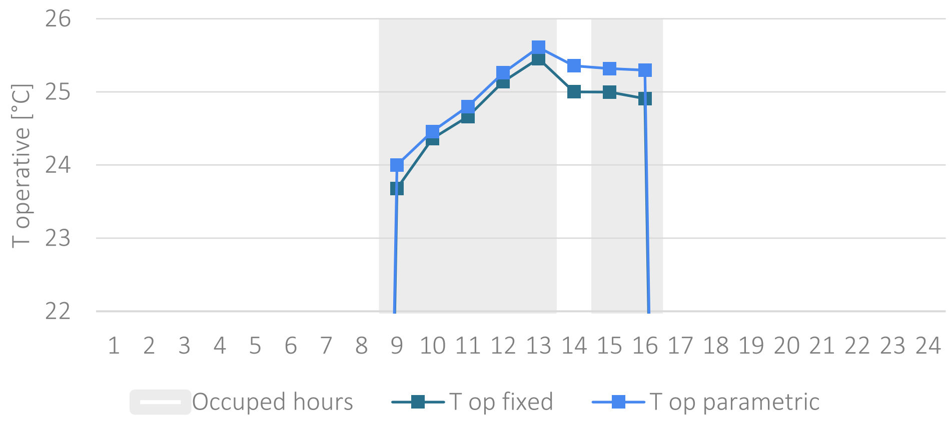


Chart 94 Operative temperature registered into classroom S1 during the peak day 15th of May

In the cooling season, the operation of the chiller is reduced by the use of natural ventilation in the first hours of the day in which external temperature is not too high and is able to mitigate internal air temperature to achieve a good level of internal comfort. Moreover, the internal air velocity is set equal to 0.5 m/s instead of 0.15 m/s as in all previous simulations.

Parametric schedule – Cooling season		
Heating on	-	-
Cooling on	11.00 – 16.00	If Tmr> 25°C, Ta>27°C
Natural ventilation on	8.00 – 11.00	If Ta≥ 25°C

Table 98 Case 1 S1 cooling season parametric schedule data

The schedule is checked by the analysis of internal comfort in May and the other months of the cooling season, June and September. The clothing insulation is set on 0.4 clo and air velocity on 0.5 m/s like in the cooling season for fixed schedule. The results in May, showed by the charts, demonstrate that there is an improvement of thermal comfort for category A and, as consequence, a reduction of hours in the other categories.

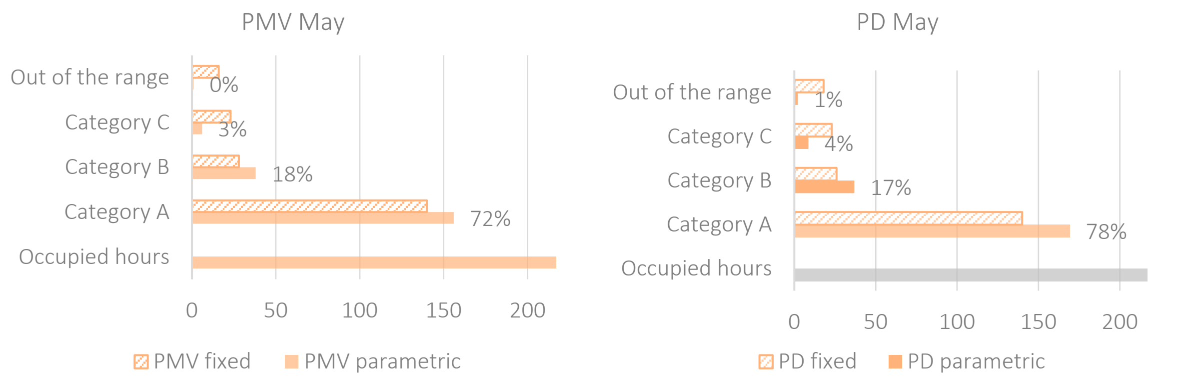


Chart 95 PMV and PD frequency case 1 S1 comparison of the parametric schedule with the fixed one, May 0.4 clo

Almost the same results have been obtained for other months of the season, in particular June and September, where there are only few points on category C of comfort. The great part of hours is included in category A and a little percentage in category B.

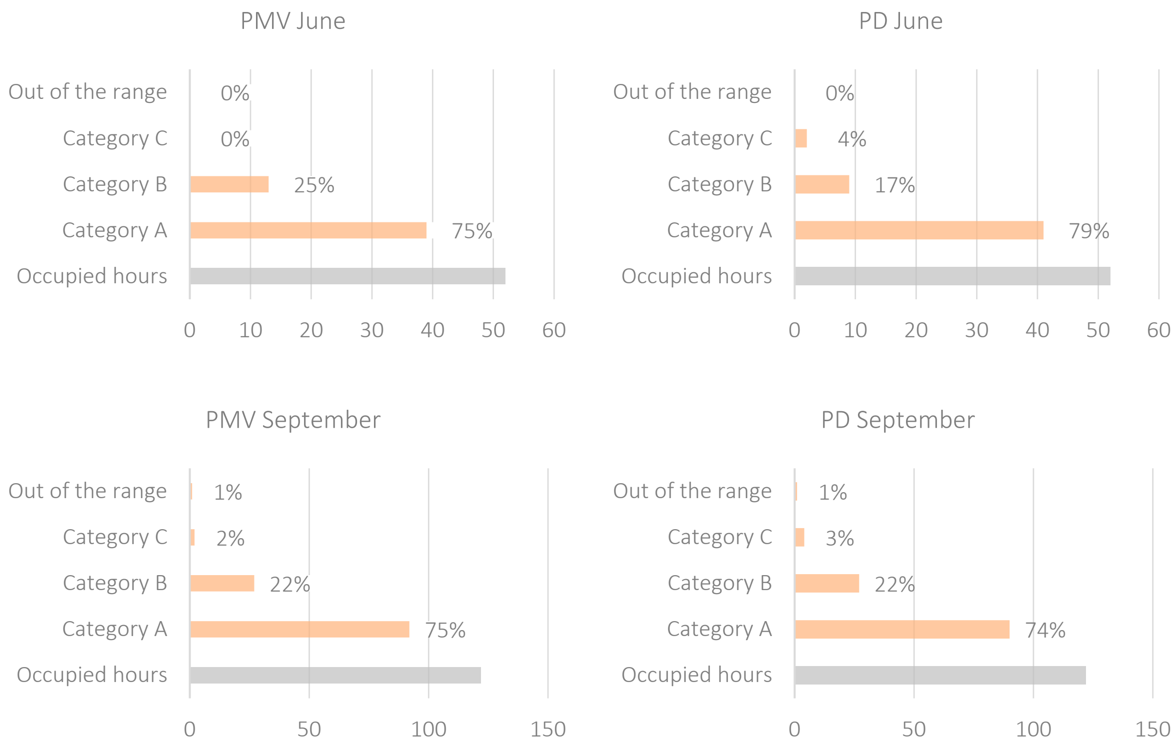


Chart 96 PMV and PD frequency case 1 S1 parametric schedule June, September 0.4 clo

Classroom N1

The same parametric schedules used in classroom S1 have been applied in classroom N1. Again, the evaluation of its validity is done by the analysis of internal comfort reached in this thermal zone. In particular, the results of the representative month of each season has been compared to the ones from the simulation with fixed schedules.

Optimization of the Heating season schedule

The parametric schedule of the heating season is the same used in the classroom S1. The analysis of internal comfort in February, demonstrate that there is an improvement of comfort hours in category A and a significant reduction of them in category B. No hours are included in category C or out of the range, therefore the comfort level of this thermal zone is quite high.

Moreover, good results are obtained in the other months of the heating season, where all the occupied hours are included in category A and B, for 90% and 10%.

Parametric schedule – Heating season		
Heating on	6.00-17.00	if Tmr≤ 19°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	-	-

Table 99 Case 1 N1 Heating season parametric schedule data

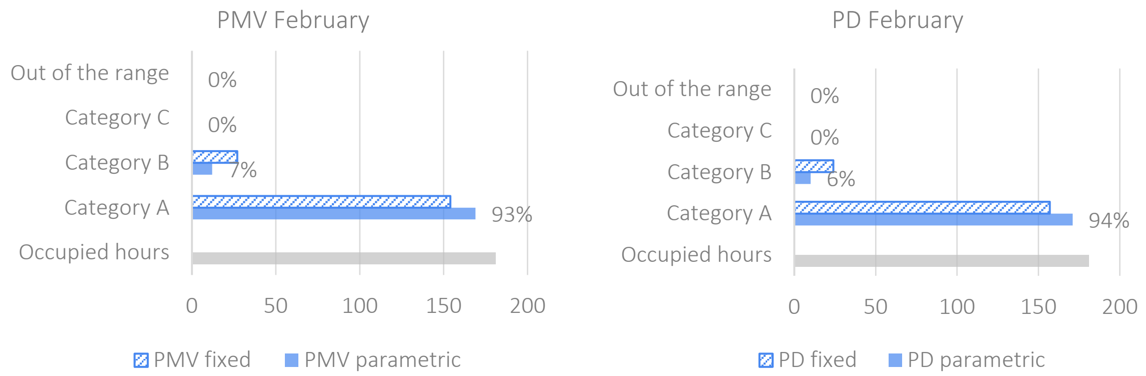
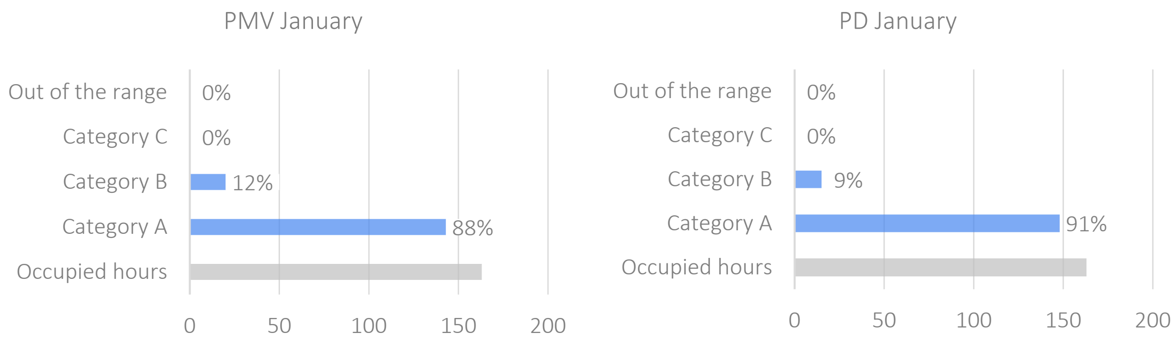
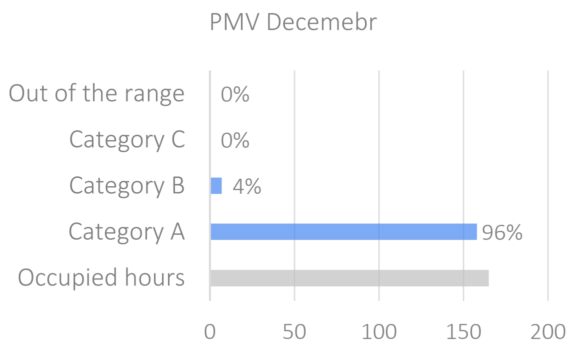


Chart 97 PMV and PD frequency case 1 N1 comparison of the parametric schedule with the fixed one, February 0.9 clo





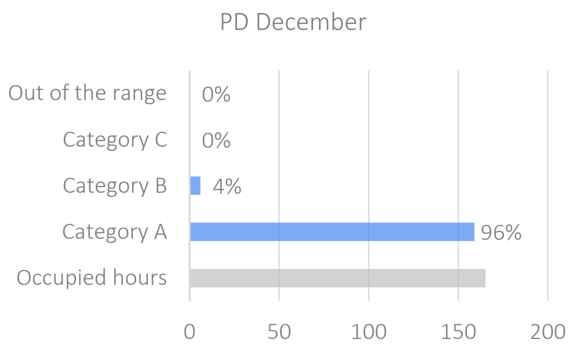


Chart 98 PMV and PD frequency case 1 N1 parametric schedule January and December 0.9 clo

Optimization of the Middle season schedule and ventilation

The application on classroom N1 of the parametric schedule used to assess comfort in S1 has not provided good result since in the middle season, solar gain in the North side is very low and the diffuse radiation alone is not able to heat up the thermal zone. Therefore, the parametric schedule is changed according to the energy needs of classroom N1.

The following table shows the values used in the assessment of the schedule for north oriented classrooms that are the result of many attempts.

Parametric schedule – Middle season North		
Heating on	6.00 - 10.00	if Tmr≤ 20°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	10.00 – 17.00	If Ta≥ 23°C

Table 100 Case 1 N1 middle season parametric schedule data

The evaluation of internal comfort has been done on the representative month, March considering a clothing insulation equal to 0.8 clo. The charts of PMV and PD show that there is a significant improvement of comfort in category A.

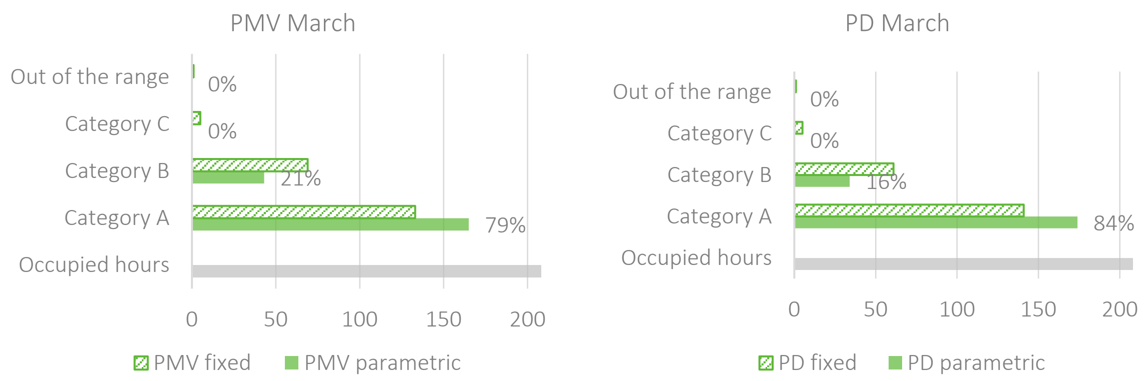
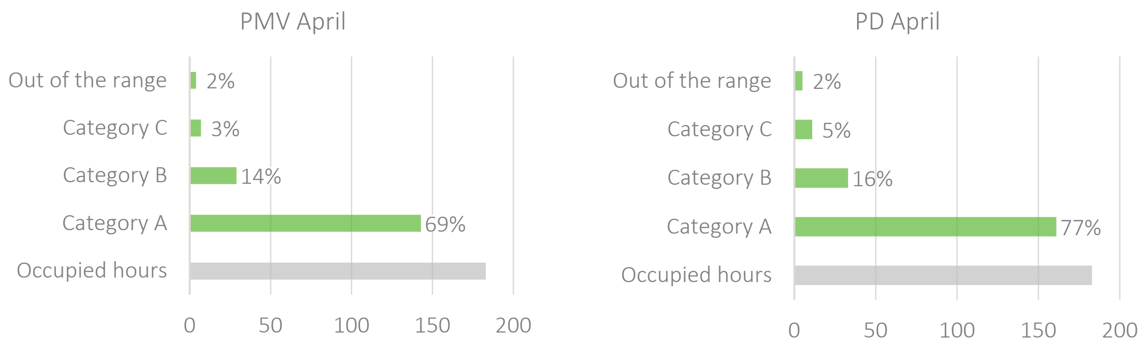
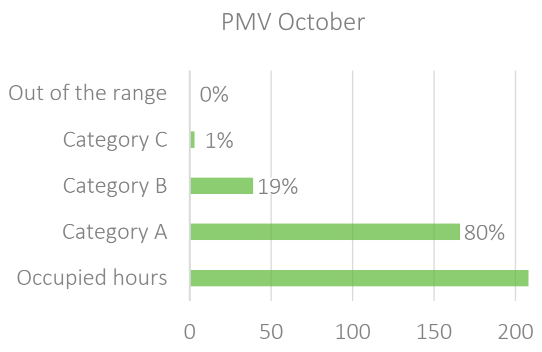


Chart 99 PMV and PD frequency case 1 N1 comparison of the parametric schedule with the fixed one, March 0.8 clo

The verification on the season, consider the frequency of comfort hours calculated in April and October for which the average clothing insulation is set equal to 0.65 and 0.6 clo. The results show that the greatest part of the occupied horus, 69-80% are included in category A, only 14-25% in category B and less than 5% in category C. There are few points out of the range that are connected to the variation of internal conditions according to the seasons variation of weather.





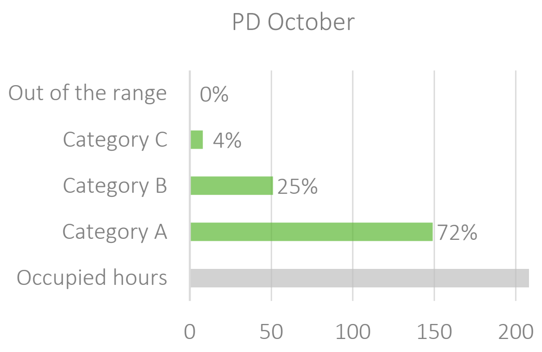


Chart 100 PMV and PD frequency case 1 N1 parametric schedule April 0.65 clo, October 0.6 clo

Optimization of the cooling season schedule and ventilation

For the cooling season, the values already used to assess thermal comfort in classroom S1 generates good result also for classroom N1 in May, June and September.

Parametric schedule – Cooling season		
Heating on	-	-
Cooling on	11.00 – 16.00	If Tmr> 25°C, Ta>27°C
Natural ventilation on	8.00 – 11.00	If Ta≥ 25°C

Table 101 Case 1 N1 cooling season parametric schedule data

Comfort conditions are reached during all the months of the cooling season. In particular, comfort hours are almost in category A with a little percentage in category B and few points in category C.

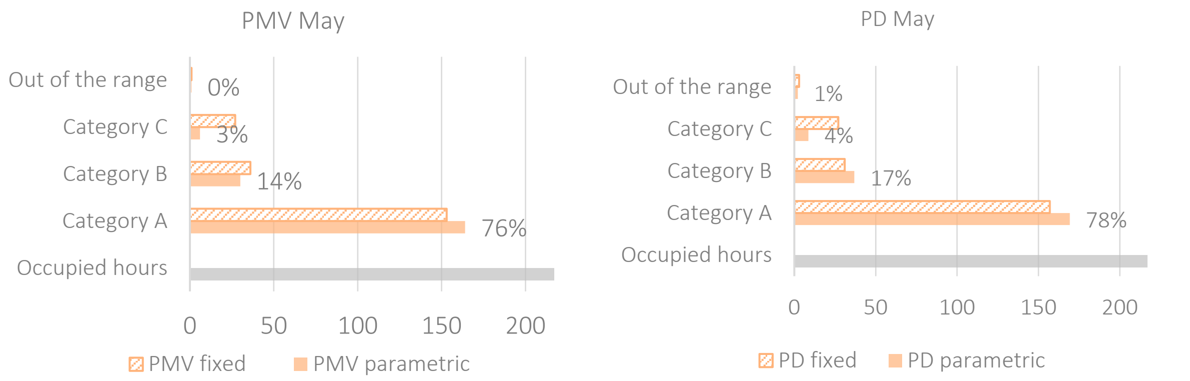


Chart 101 PMV and PD frequency case 1 N1 comparison of the parametric schedule with the fixed one, May 0.4 clo

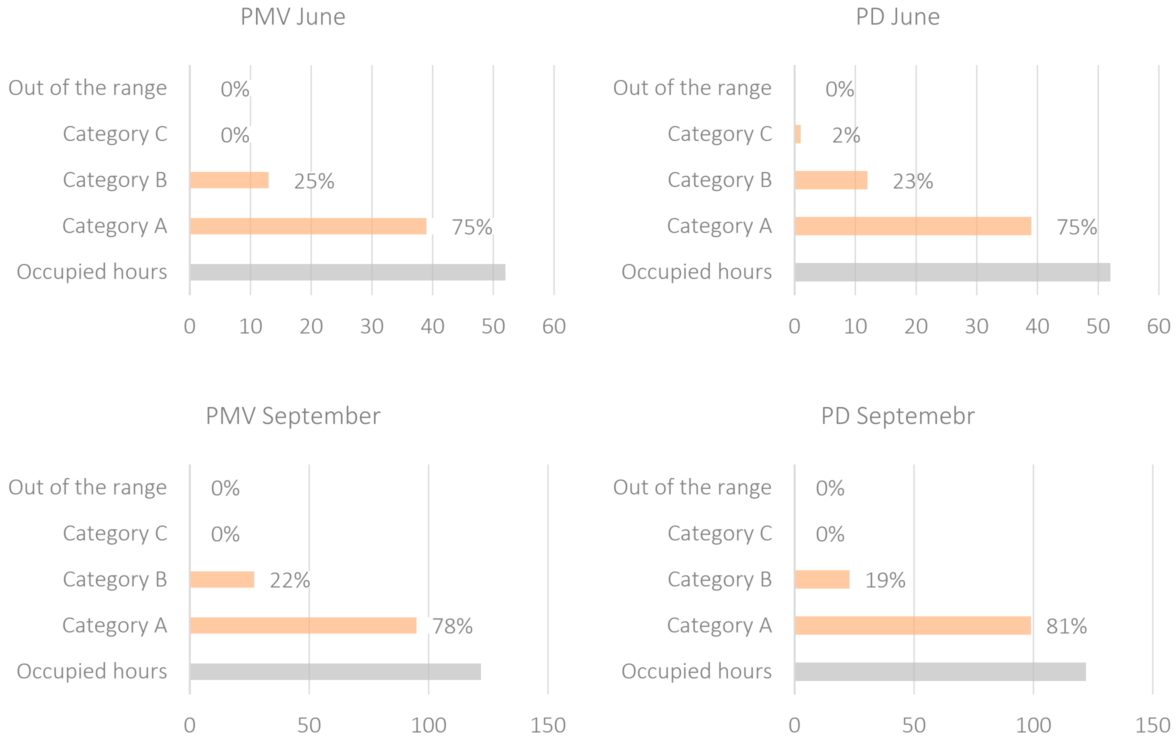


Chart 102 PMV and PD frequency case 1 N1 parametric schedule June, September 0.4 clo

5.1.3. PRIMARY ENERGY

The assessment of the primary energy has been done in order to understand the energy consumption of the building optimized according to the envelope characteristic Case 1 and three different schedules for systems and ventilation.

The results of the calculation of the total primary energy with standard, fixed and parametric schedules the show that the maximum energy cost is related to the use of the heating and cooling period imposed by the standard. Moreover, simulations demonstrate that the more the schedule is optimized, the less it the energy consumption. This means that the improvement of internal comfort doesn't generate an increase of energy consumption as wrongly thought.

This positive effect is related to the fact that the parametric schedules are set according to the specific needs of the building and its internal load. The use of a generic schedule, that *can be applied* to a generic building, generate discomfort for occupants and the operation of systems when it is not necessary generates energy waste.

Case 1	EHP-W	EHP-W	EHP-W
	Standard schedule	Fixed schedule	Parametric schedule
PE Bolier [MWh]	96	87	76
PE Chiller [MWh]	8	14	11
Total PE [MWh]	103	101	87
Energy saving		2%	16%

Table 102 Primary energy consumption and comparison between the three schedules

The peak analysis made on the 26th of May, underline that, respect to the free-floating, there is a little increase of gains since the internal temperature of the room is higher than the one in free-floating; therefore, the thermal flux from inside to outside increases.

On the other hand, losses through the envelope are severely reduced due to the optimization of the building envelope. In fact, the presence of external insulation on the façade contribute to decrease a lot the energy consumed during the heating season since it reflects heat back into the room. But in summer it has the same behaviour and heat generated by the presence of people, light and equipment is not able to go out because it is blocked by the envelope. Therefore, thermal losses are reduced.

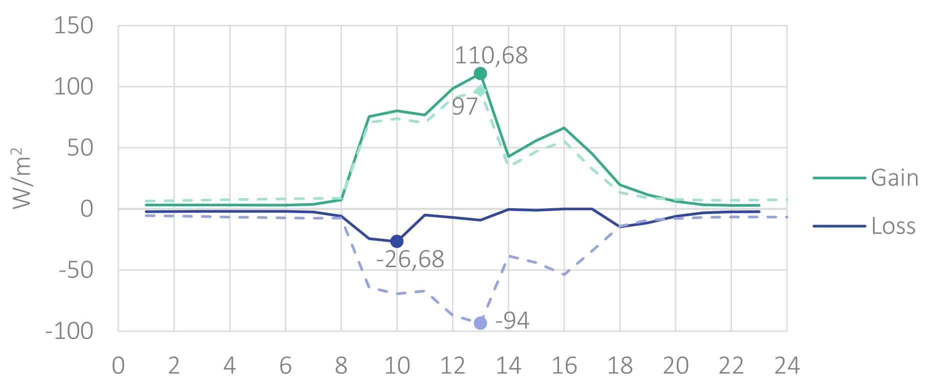


Chart 103 Hourly power on the peak day on the 26th of May of the parametric schedule simulation, compared with the free-floating one

5.1.4. ADAPTIVE COMFORT

The evaluation of the adaptive comfort has been done using the optimized schedule, the parametric one, for the heating season, avoiding the use of chiller during the summer season. In this case the chiller function has been substituted by natural ventilation through windows. They open when the mean radiant temperature of the thermal zone is higher than 25°C. In this way, there is a refresh of internal air with the external that mitigate internal climate.

The evaluation has been done with IES tool for adaptive comfort. This tool generates a report (reported in the annex D), which describes the evaluation criteria and writes a list of thermal zones that satisfy these criteria and the ones failed. The software has been set on adaptive comfort-category III for existing buildings, but good results have been achieved for category II (new buildings). Therefore, further evaluations has been set on considering the adaptive comfort of category II.

According to the category II of the standard EN ISO 15251, the six thermal zones analysed in this work has passed the verification, during the occupied hours. Failed rooms are offices and external functions that were not considered in the optimization process. The following table reports a synthesis of the amount of room passed and failed according to the geometry of the IES model.

Parametric schedule – Adaptive summer season		
Heating on	-	-
Cooling on	-	-
Natural ventilation on	8.00 – 17.00	If Ta≥ 25°C

Table 103 Case 1 S1 adaptive approach data

Adaptive comfort report results			
Total rooms	Passed	Failed	Unoccupied
65	56	9	0

Table 104 Case 1 Summary of the adaptive comfort IES report

In addition, internal comfort conditions have been evaluated considering the operative temperature and the relative humidity of classroom S1 and N1, as already done in the assessment of strategies. This analytical evaluation of data according to the adaptive comfort ranges, is useful to verify the report generated by the software and to focus the attention on single a thermal zone, in some specific months.

The results showed by the charts are aligned to the report extracted by the software. In fact, operative temperature and relative humidity of the two thermal zones are in the comfort range for most of the occupied hours. Better adaptive comfort conditions are reached in classroom N1 since it is not hit directly by solar radiation; only diffuse radiation can pass through the windows and its contribution of overheating is very low.

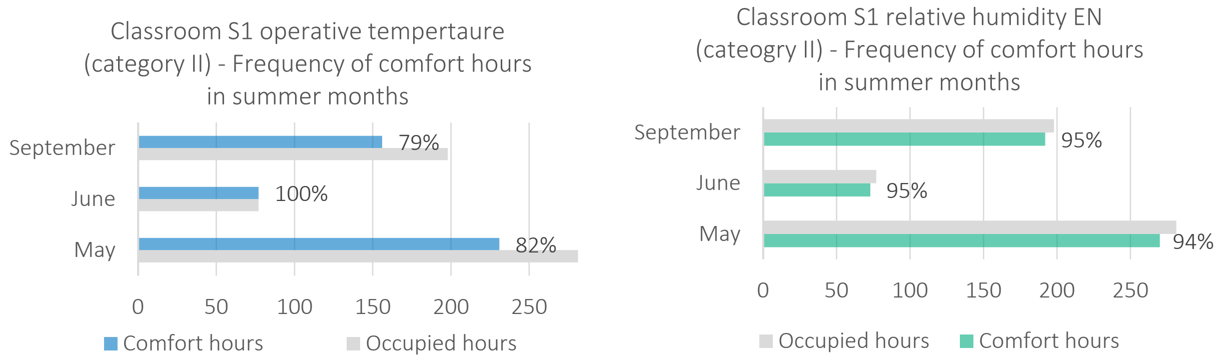


Chart 104 Case 1 Operative temperature and relative humidity of classroom S1 according to the adaptive approach

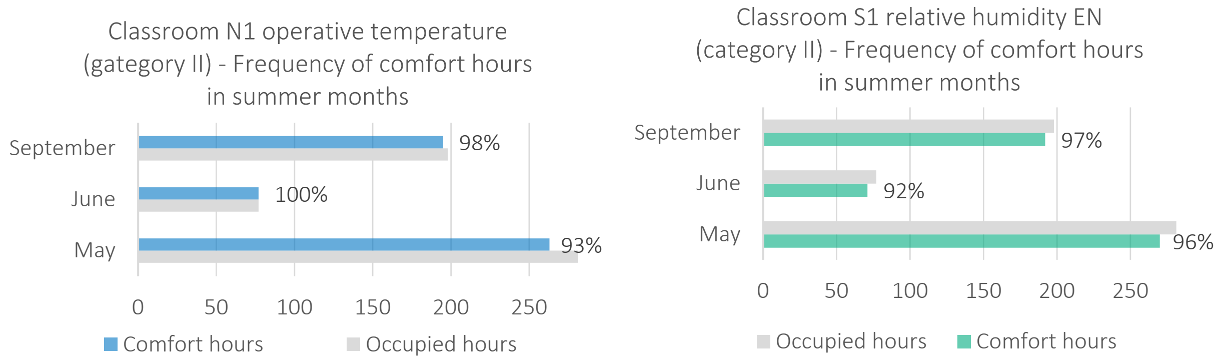


Chart 105 Case 1 Operative temperature and relative humidity of classroom N1 according to the adaptive approach

Non-adaptive comfort analysis and further verifications

From the results on the adaptive comfort, conditions set for the summer months guarantee internal comfort. The same simulation has been analysed with the non-adaptive approach. The verification of internal comfort conditions of classroom is referred only for classrooms S1 and N1 for which the PMV was analysed for summer months. This analysis uses the simulation of the adaptive approach (without summer conditioning, only openable window) and calculate the PMV categories according to the standard UNI EN ISO 7730. In this way it is possible to see the different results of the adaptive approach and the non-adaptive one.

PMV calculation for May, June and September considers as the previous analyses, a clothing insulation equal to 0.4 clo and air velocity equal to 0.5 m/s both for classroom S1 and N1.

Comparing the PMV calculated for the adaptive approach with the one of the simulation that uses chillers in summer, there are some important differences. As expected, avoiding the use of conditioning systems in summer generates a decrease of comfort conditions in particular in classroom S1 since it faces South. The gap between adaptive comfort simulation and simulations with systems is more relevant in S1 respect to the one in classroom N1.

In general, there is a decrease of comfort hours in category A almost equal to 10-20%,

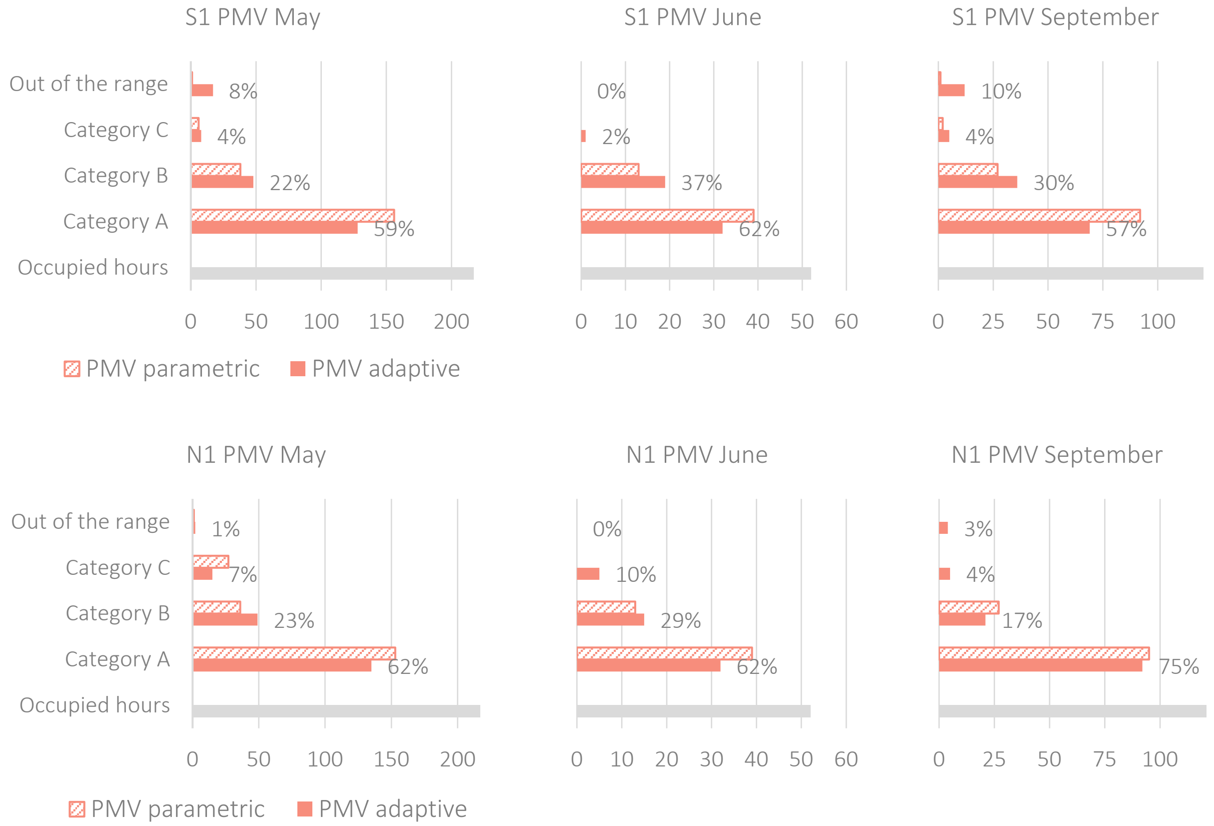


Chart 106 PMV case 1 comparison for summer months for classroom S1, N1

5.1.5. OBSERVATION ON CASE 1 COMFORT ASSESSMENT

The construction technologies used in the combination Case 1, considers the improvement the envelope of the existing building to achieve the standard thermal performance, according to the DM 26 6 2015. This choice guarantees to increase the quality of building envelope and permit to save energy to heat and cool internal spaces during the occupied hours. Moreover, the substitution of the old conditioning system with a new and more efficient plant, contributes to decrease the energy consumption for the heating season. The installation of chillers to cool down spaces during summer months is considered during the simulations even if the system of the existing building is composed only by boiler to heat water for terminals and for sanitary use.

According to this type of building envelope, the best results are obtained with the application of parametric schedule for systems operation. The systems of all classrooms are based on the same type of parametric schedule except for the middle season. In fact, in this period thermal zones have different behaviour in terms of internal operative temperature with different needs. In particular, two schedules for the middle season has been set, one for the south oriented classrooms and one for rooms that face north.

The improvement of building system has generated positive effect on the internal comfort during the occupied hours. In fact, the analyses of predict mean vote and percentage of discomfort people demonstrate that thermal conditions in most of the occupied hours is able to guarantee comfort in the range of category A and B.

Moreover, the adaptive comfort for the months of May, June and September is achieved, thanks to the improvement of the envelope.

5.2. CASE 2

This chapter consider the optimization of system and ventilation schedule according to the energy needs of the building with the envelope technology of Case 2, the most insulated combination.

Case 3 Envelope construction	Window	Roof	Ground	External wall	Blinds	Louvers
U base	base	base	base	base		
U standard	1.4	0.24	0.29	0.24	yes	yes
U intermediate	1	0.15	0.24	0.21	yes	yes
U Best	0.8	0.1	0.17	0.16	yes	yes

Table 105 Case 2 thermal transmittance of envelope

5.2.1. PARAMETRIC SYSTEMS SCHEDULE DEFINITION

The previous analyses on the schedule application demonstrate that the use of fixed schedule doesn't improve internal comfort conditions or decrease the energy consumption. Better results in terms of comfort and energy needs have been obtained with the application of parametric schedule.

Therefore, all the simulations and the evaluations on building envelope case 2 have been done by setting the system operation based on parametric schedules.

Classroom S1

The simulation in free-floating have been run in order to determine the period of heating, cooling and ventilation. In fact, applying the schedule used for the Case 1 the results in terms of comfort were not appropriate. Therefore, a new scheduling has been written specifically for this case.

Form the chart of the operative temperature in free-floating, there is a new definition of the heating, middle and cooling system. In particular, the main difference from the case 1 scheduling consists in the extension of the cooling season and the reduction of the heating season. The higher request of summer conditioning is aligned to the increase of the thermal performance of the building envelope. Since technologies used in case 2 is the most insulated among the cases taken into account the presence of internal gains contributes to increase the internal temperature in winter, but also in middle/summer. This means boiler loads decreases, while chiller loads increases.

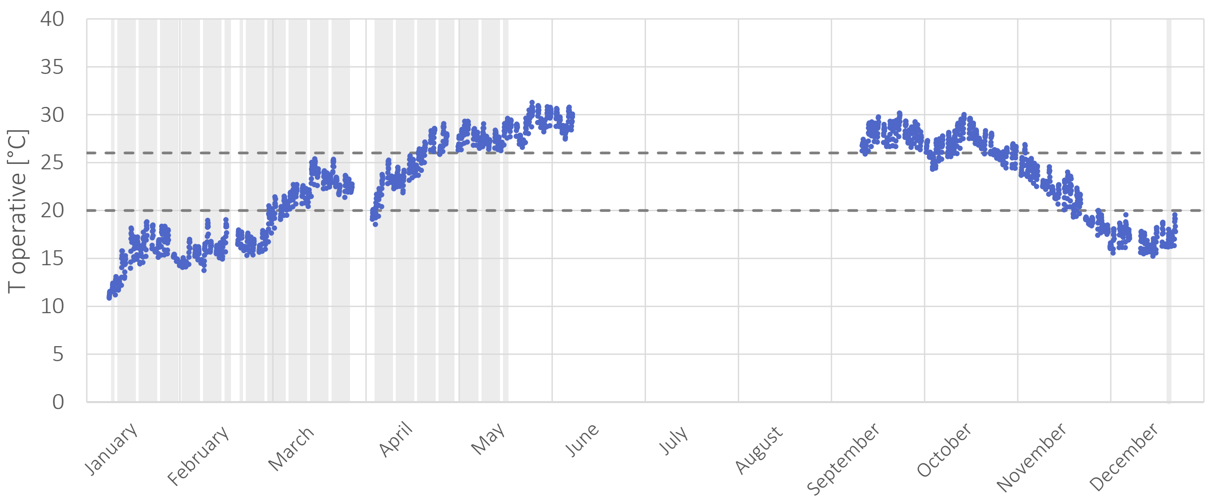


Chart 107 Case 2 S1 free-floating operative temperature

Seasons	From - to	Representative month
Heating season	from 15th November to 28th February	February
Middle season	from 1st March to 30th April and 1st November to 15th November	March
Cooling season	form 1st May to 8th June and 12nd September to 31th October	May

Table 106 Case 2 seasons assessment

Optimization of the Heating season schedule

The operation of the heating system during the heating season is based on the parametric schedule that activate the system when the mean radiant temperature is lower than 19°C. Basically the heating schedule is set on the same parameters of case 1 since their need in the winter season is almost the same.

The verification of internal comfort is done on the calculation of the predict mean vote in January, February and December. The following charts demonstrate that comfort is achieved for the great part of the occupied hours.

Parametric schedule – Heating season		
Heating on	6.00-17.00	if Tmr≤ 19°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	-	-

Table 107 Case 2 S1 heating season parametric schedule data

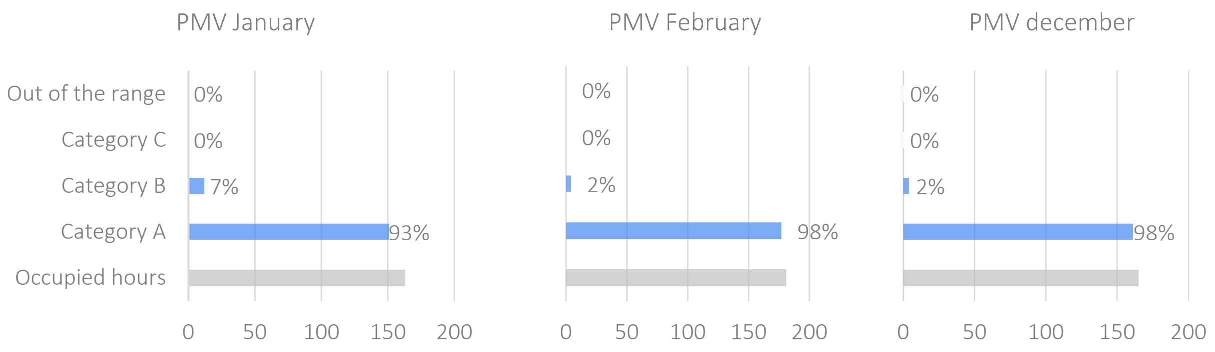


Chart 108 PMV frequency of January, February, December 0.9 clo

	PMV January 0.9 clo		PMV February 0.9 clo		PMV December0.9 clo	
Occupied hours	181		163		165	
Category A	177	98%	151	93%	161	98%
Category B	4	2%	12	7%	4	2%
Category C	0	0%	0	0%	0	0%
Out of the range	0	0%	0	0%	0	0%

Table 108 PMV case 2 February, December 0.9 clo

Optimization of the Middle season schedule and ventilation

The middle season is formed by three months March, April and November. Considering that in the middle season the type of clothing of occupants vary in function of the internal conditions. Due to this fact, the middle season is always the most critical period of the year for the system assessment.

Therefore, the following charts on PMV related to the months of the season, consider different type of clothing insulation according to the experience.

After many attempts, the best result in terms of internal comfort are obtained by the use of the following schedule.

Parametric schedule – Middle season South		
Heating on	6.00 - 8.00	if Tmr≤ 17°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	10.00 – 17.00	If Ta≥ 23°C

Table 109 Case 2 S1 Middle season parametric schedule data

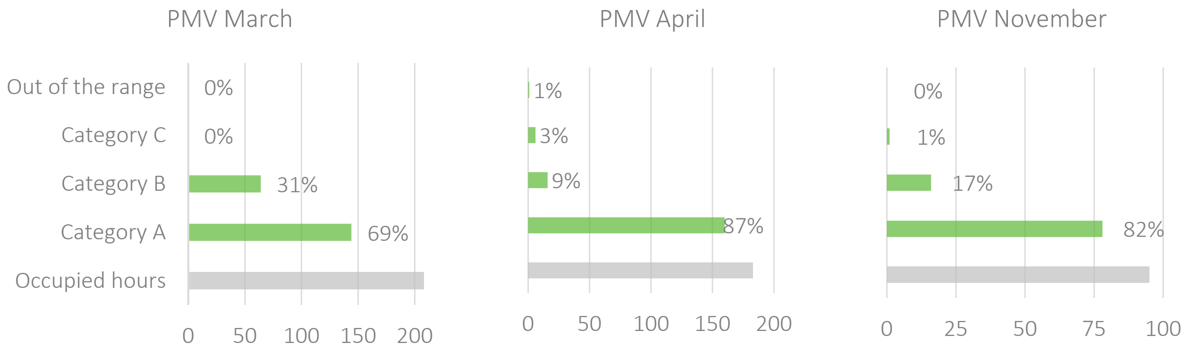


Chart 109 PMV frequency of March, 0.8 clo, April 0.65 clo, November 0.7 clo

	PMV March 0.8 clo	
Occupied hours	208	
Category A	144	69%
Category B	64	31%
Category C	0	0%
Out of the range	0	0%

PMV April 0.65 clo	
183	
160	87%
16	9%
6	3%
1	1%

PMV November 0.7 clo	
95.00	
78.00	82%
16.00	17%
1.00	1%
0.00	0%

Table 110 PMV case 2 March, April, November 0.8, 0.65,0.7 clo

Optimization of the cooling season schedule and ventilation

The cooling season schedule used in this case is the same of case 1 since the results achieved are good and acceptable. The unique difference from the previous case is related to the operation period. In fact, since case 2 consider a very performant envelope, the request of cooling is higher respect to the case 1 that uses a standard envelope. Therefore, the cooling season is extended from May to October.

The following charts demonstrate that the application of schedule for case 1 provide good internal comfort conditions for occupants that can be related to category A, for most of the occupied hours, and B for the rest part.

Parametric schedule – Cooling season		
Heating on	-	-
Cooling on	11.00 – 16.00	If Tmr> 25°C
Natural ventilation on	8.00 – 11.00	If Ta≥ 25°C

Table 111 Case 2 S1 cooling season parametric schedule data

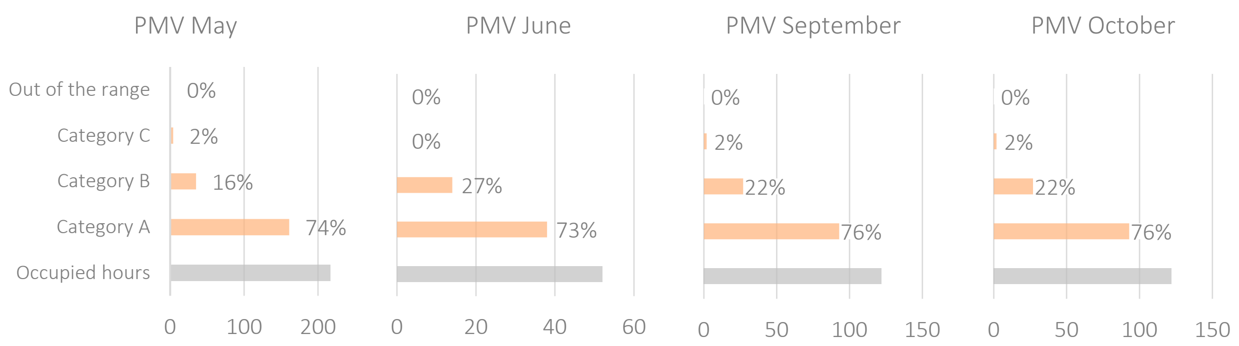


Chart 110 PMV frequency of May, June, September 0.4 clo, October 0.45 clo

	PMV May 0.4 clo	
Occupied hours	217	
Category A	161	74%
Category B	35	16%
Category C	4	2%
Out of the range	1	0%

PMV June 0.4 clo	
52	
38	73%
14	27%
0	0%
0	0%

PMV September 0.4 clo	
122	
93	76%
27	22%
2	2%
0	0%

PMV October 0.45 clo	
224	
164	73%
47	21%
9	4%
4	2%

Table 112 PMV case 2 May, June, September 0.4 clo, October 0.45 clo

Classroom N1

Heating, middle and cooling period defined for classroom S1 have been used also for classroom N1 since the results obtained are acceptable.

Heating and cooling season for the two thermal zones are based on the same parametric schedule; on the other hand, in middle season the needs of the two spaces are different due to the orientation and passive gains. Therefore, the set points for heating and ventilation and their activation in the middle season are different to each other.

Optimization of the Heating season schedule

The verification of internal comfort in terms of PMV for the months of the heating season (January, February and December, 15-30 November is not reported but its validity was checked on the software) provide good results. In fact, the occupied hours in winter are almost in category A which means that internal comfort is achieved for almost all occupants.

Parametric schedule – Heating season		
Heating on	6.00-17.00	if Tmr≤ 19°C
Cooling on	-	-
Natural ventilation on	-	-

Table 113 Case 2 N1 heating season parametric schedule data

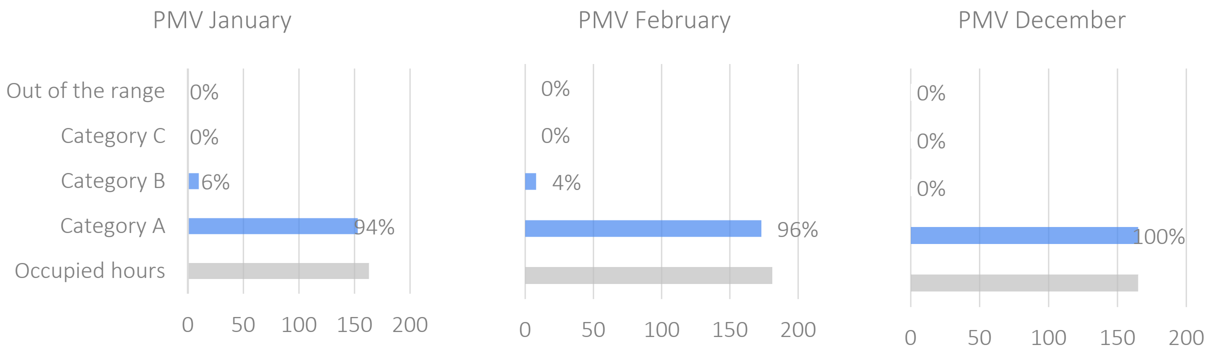


Chart 111 PMV frequency of January, February, December 0.9 clo

	PMV January 0.9 clo	
Occupied hours	163	
Category A	153	94%
Category B	10	6%
Category C	0	0%
Out of the range	0	0%

PMV February 0.9 clo	
181	
173	96%
8	4%
0	0%
0	0%

PMV December0.9 clo	
165	
165	100%
0	0%
0	0%
0	0%

Table 114 PMV case 2 January, February, December 0.9 clo

Optimization of the Middle season schedule and ventilation

Internal comfort in classroom N1 during the middle season is reached for most of the occupied hours. The heating systems are activated early in the morning before lessons in order to pre-heat the room for students. Then, the presence of internal gains contributes to increase the temperature and keep it in the comfort range; thus, the operation of heating system is not required.

If the operative temperature rises too much and generate discomfort, the air temperature mitigation can be provided by opening the windows according to a specific schedule.

Comparing these results with the ones of classroom S1, there is a little increase of comfort in category A for north oriented classroom. In particular, this increment has been registered in March and November. The reason can be connected to the different contribution of solar radiation that is higher in S1.

Parametric schedule – Middle season North		
Heating on	6.00 - 10.00	if Tmr≤ 19°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	10.00 – 17.00	If Ta≥ 23.5°C

Table 115 Case 2 N1 middle season parametric schedule data

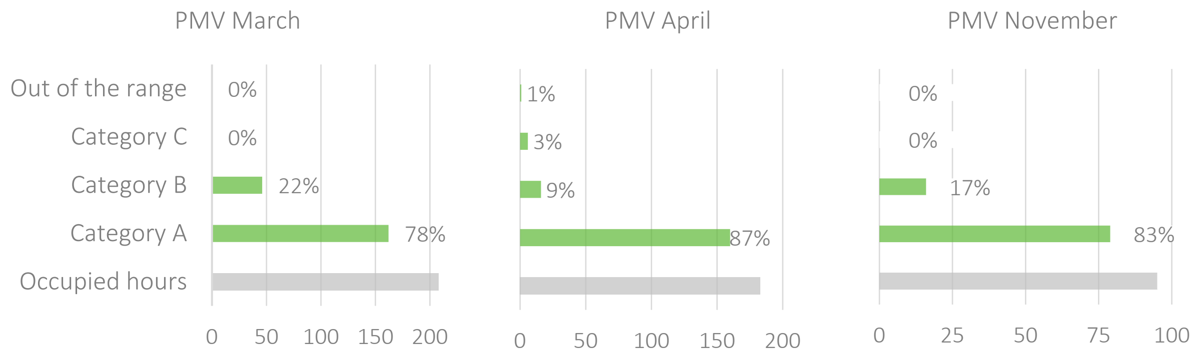


Chart 112 PMV frequency of March 0.8 clo, April 0.65 clo, November 0.7 clo

	PMV March 0.8 clo		PMV April 0.65 clo		PMV Novemberl 0.7 clo	
Occupied hours	208		183		95	
Category A	162	78%	160	87%	79	83%
Category B	46	22%	16	9%	16	17%
Category C	0	0%	6	3%	0	0%
Out of the range	0	0%	1	1%	0	0%

Table 116 PMV case 2 March, April, November 0.8, 0.65, 0.7 clo

Optimization of the cooling season schedule and ventilation

Also for classroom N1, the cooling season is extended from May to October.

The results of PMV analyses demonstrate that comfort conditions are reached. As in the previous case the great part of the occupied hours is in category A and a little in category B. Moreover, there are some hours in category C and out of the comfort range, but their contribution can be considered negligible.

Parametric schedule – Cooling season		
Heating on	-	-
Cooling on	11.00 – 16.00	If Tmr> 25°C
Natural ventilation on	8.00 – 11.00	If Ta≥ 25°C

Table 117 Case 2 N1 cooling season parametric schedule data

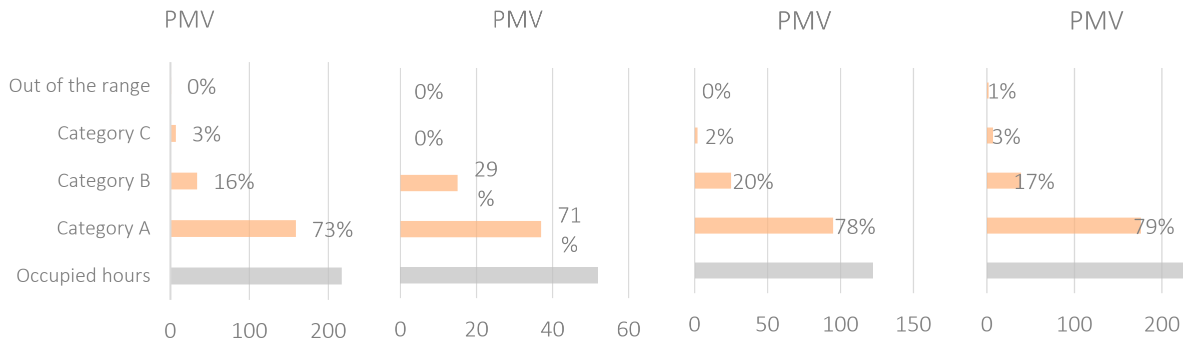


Chart 113 PMV frequency of May, June, September 0.4 clo, October 0.45 clo

	PMV May 0.4 clo	
Occupied hours	217	
Category A	159	73%
Category B	34	16%
Category C	7	3%
Out of the range	1	0%

PMV June 0.4 clo	
52	
37	71%
15	29%
0	0%
0	0%

PMV September 0.4 clo	
122	
95	78%
25	20%
2	2%
0	0%

PMV October 0.45 clo	
224	
176	79%
39	17%
7	3%
2	1%

Table 118 PMV case 2 May, June, September, October 0.4 clo

5.2.2. PRIMARY ENERGY

The energy consumption of the systems based on the parametric activation schedules is compared with the energy consumption with standard ones. The results underline that the total primary energy consumption has decreased of the 12%. Moreover, there is a big decrease of the energy consumed by the heating systems, that corresponds to an increment of energy used in the cooling season. This variation is related to the technologies used in the building envelope. In fact, the more the envelope is insulated the more is the energy required by the chiller to mitigate internal temperature.

Case 2	EHP-W	EHP-W
	Standard schedule	Parametric schedule
PE Bolier [MWh]	72	57
PE Chiller [MWh]	8	13
Total PE [MWh]	80	70
Energy saving		12 %

Table 119 Total primary energy for boiler and chiller for case 2

5.2.3. ADAPTIVE COMFORT

As in the case 1, the evaluation of the adaptive comfort is done using the adaptive comfort tool in IES. The report generated declared that 35 rooms have failed, and they are not in comfort conditions without the use of cooling system. In particular, the report underlined that these thermal zones are some laboratories and some classes placed at the ground and at the first floor. Classrooms S.1 and N.1 have failed. Moreover, among the failed spaces there are the external functions like gym and canteen that were not taken into account in the optimization process.

The reason of the failure of most of the classrooms and laboratories can be related to the variation of operative temperature that is influenced by the envelope technologies. The improvement of envelope insulation is a good strategy to achieve thermal comfort in winter, while reducing the energy consumption of the boiler because the presence on insulation block the heat generated by internal gains and passive gains keeping them inside the thermal zone. In summer there the same effect, increased by the higher contribution of solar gain; since heat can't pass through the envelop it is accumulated inside the room. Therefore, the operative temperature increases al lot and the comfort decrease.

In this case the presence of cooling system is required in order to provide a good level of acceptable comfort.

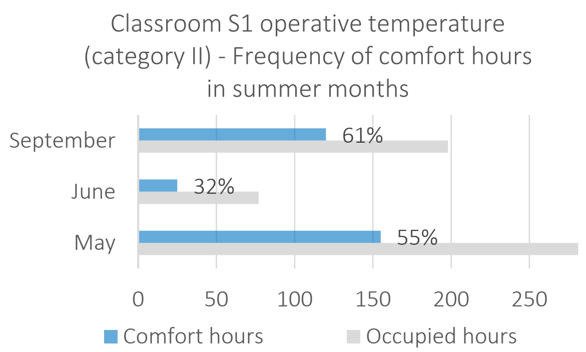
Parametric schedule – Adaptive summer season		
Heating on	-	-
Cooling on	-	-
Natural ventilation on	8.00 – 17.00	If Ta≥ 25°C

Table 120 Case 2 S1 adaptive approach data

Adaptive comfort report results			
Total rooms	Passed	Failed	Unoccupied
65	30	35	0

Table 121 Case 2 summary of the adaptive comfort IES report

In order to test IES report on the adaptive approach, the frequency of comfort hours related to the operative temperature and relative humidity have been plotted. They basically confirm what the report has written. The frequency of operative temperature is in the comfort range for less than 30% in June and around 50% in May and September. Higher values have been registered for the relative humidity, but always between 60% and 80%. Due to these relatively low values, adaptive comfort is not reached for these two thermal zones.



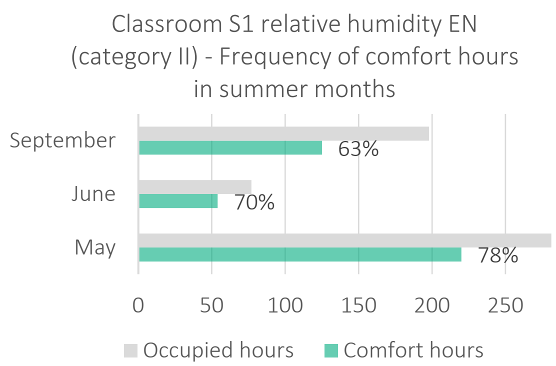
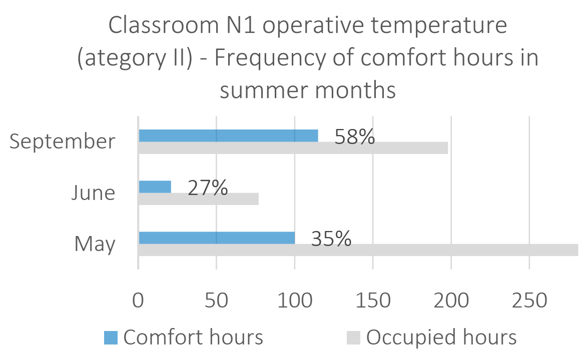


Chart 114 Case 2 Operative temperature and relative humidity of classroom S1 according to the adaptive approach



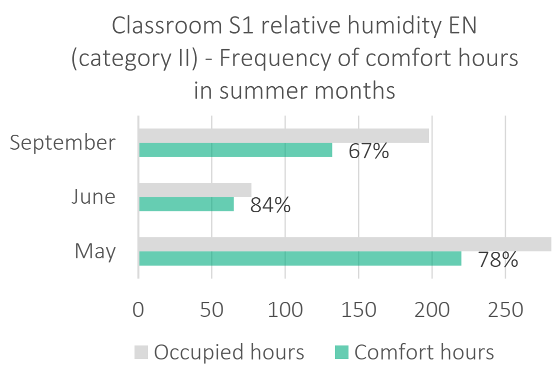


Chart 115 Case 2 Operative temperature and relative humidity of classroom N1 according to the adaptive approach

Comfort analysis and further verifications

The simulation of the adaptive approach has been evaluated according to the static approach. The classrooms analysed, S1 and N1 confirm that it is not possible to achieve internal comfort without mechanical cooling system according to the case 2 envelope technology.

The following charts report the comfort hours according to the category A, B and C of the standard UNI EN ISO 7730 considering the clothing insulation equal to 0.4 clo and air velocity equal to 0.5 m/s as in the previous simulation for the summer months. In fact, comfort conditions are not reached in any month.

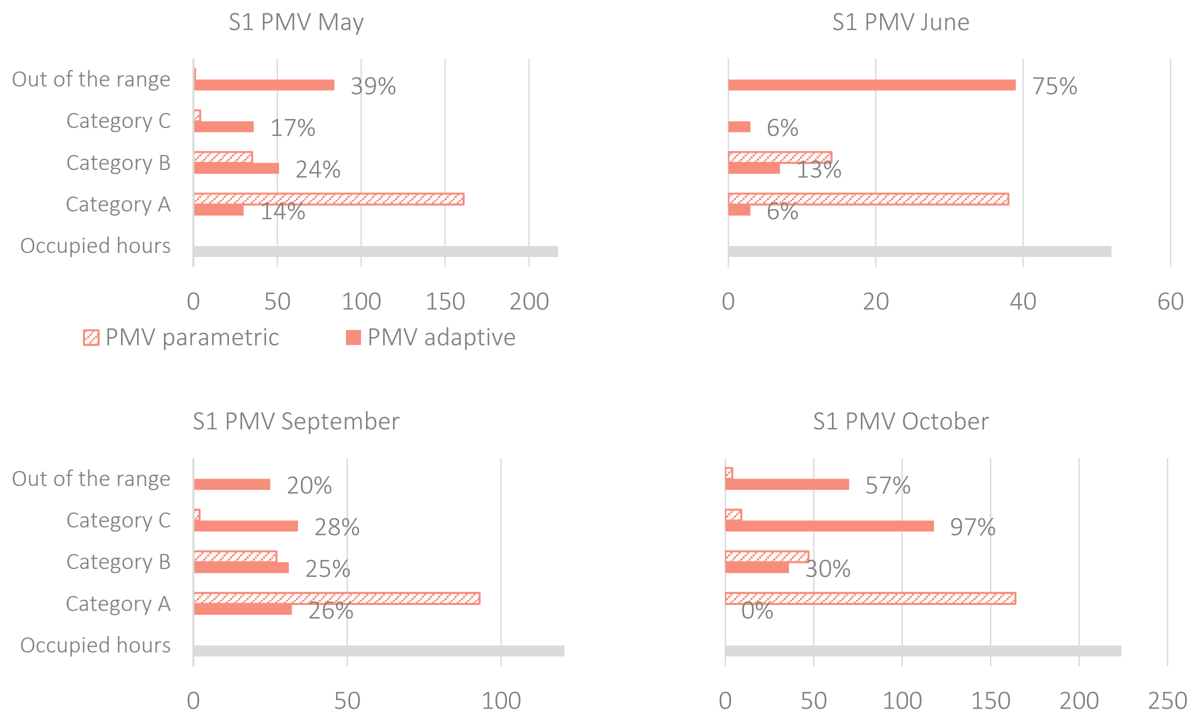


Chart 116 PMV case 2 comparison for summer months for classroom S1

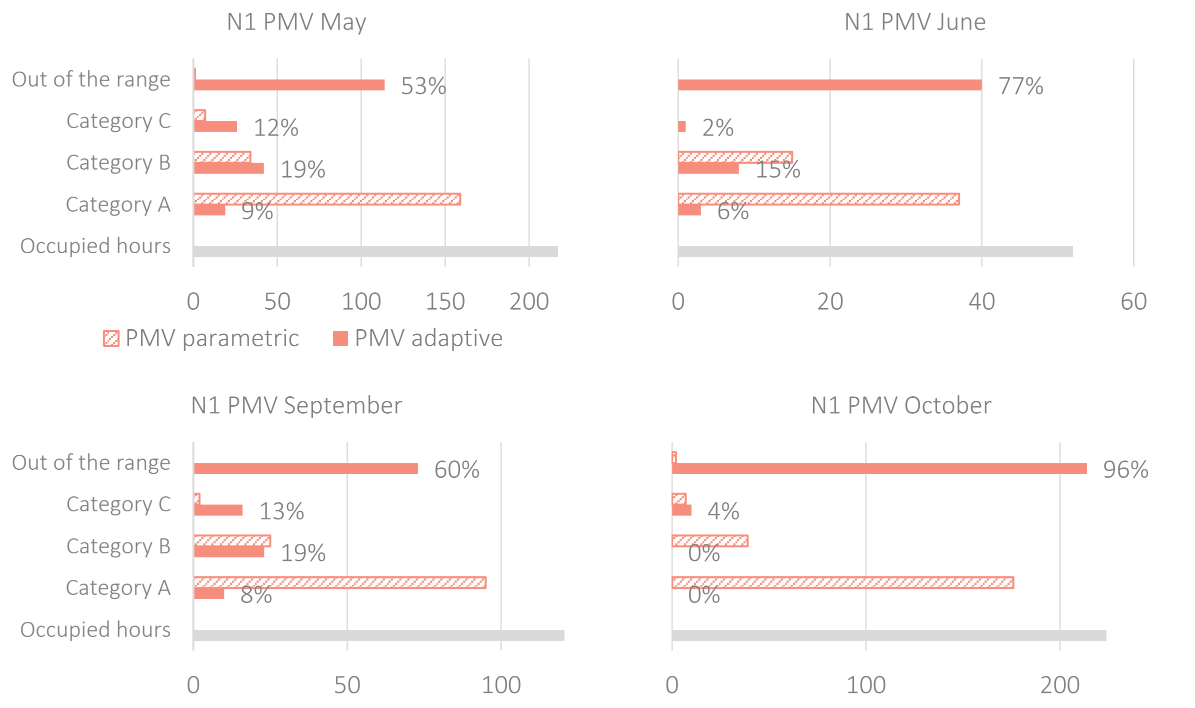


Chart 117 PMV case 2 comparison for summer months for classroom N1

5.2.4. OBSERVATIONS ON CASE 2

The renovation of the building in this section considers the application of construction technologies from case 2. This is the best combination in terms of thermal resistance and transmittance of building elements. Therefore, the use of a very performant envelope is able to decrease to decrease the energy consumption in winter season. In fact, all the energy generated by internal gains tends to go out due to a difference of temperature, but it is blocked by the envelope. Therefore, the great part of heat stored in the thermal zone and acquired by passive gains (solar radiation) is kept inside the space and contributes to guarantee comfort conditions for the winter season. In addition, thanks to the presence of internal and passive gains, the energy consumption in winter season is reduced.

Despite the positive effect during the winter season, in middle/summer the heat stored inside classroom is not able to go out and contribute to increase internal temperature. This means that the presence of cooling system is strictly required in all thermal zone used for activities. Since in this period the internal air temperature of the building in the best configuration (case2) is higher than the one of the same building in the standard setting (case 1), the energy expended by the cooling system to achieve comfort is much higher.

The best results in terms of internal comfort are achieve by the application of parametric schedules which are able to smooth the fluctuation of operative temperature during the occupied hours and guarantee that internal conditions are kept constant. As in case 1, the thermal load registered in the middle season are different according to the orientation of the classrooms, thus the energy given by the system must be set correctly to avoid discomfort. Therefore, the systems operation is different for the classroom on the South side of the building respect to the ones that faces North and they are based on two different type of schedules.

The application and the improvement of conditioning system have positive results in terms of internal comfort. In fact, all the classrooms have reached comfort conditions of category A and B according to the static approach showed by the standard UNI EN ISO 7730. Nevertheless, the best envelope configuration is not able to guarantee adaptive comfort in May, June and September, since its envelope is too insulated for this climate condition. Therefore, a cooling system is strictly necessary to guarantee internal comfort in middle/summer months.

5.3. CASE 3

The envelope of case 3 considers intermediate values of construction elements showed by the following table.

Case 3 Envelope construction	Window	Roof	Ground	External wall	Blinds	Louvers
U base	base	base	base	base		
U standard	1.4	0.24	0.29	0.24	yes	yes
U intermediate	1	0.15	0.24	0.21	yes	yes
U Best	0.8	0.1	0.17	0.16	yes	yes

Table 122 Case 3 thermal transmittance of envelope

5.3.1. PARAMETRIC SCHEDULE

Classroom S1

The assessment of the schedules systems on the building, whose envelope follows the construction elements of case 3, starts by the definition of the heating, middle and cooling season based on the yearly trend of the operative temperature registered in classroom S1 (the thermal zone in the worst position).

The chart of operative temperature demonstrates that in winter season, as expected, the heating system is necessary in order to guarantee comfort; thus, the heating season is set between 15th of November and the end of February.

In March and April, the operative temperature of classroom S1 is in the lower area of the comfort range 20-26°C, with some peaks in which operative temperature is some degrees below the range. In October the operative temperature is almost in the comfort range but is located in the upper part of it and there are some peaks over the comfort range. This behaviour is generated by the thermal mass of the envelope that shift the penetration of heat in March and April and slow down the heat dissipation in September-October. Therefore, in March and April heating system must be activate in the first hours of the day and in October windows must be opened in order to refresh and mitigate internal air.

In May, June and September the operative temperature is in the comfort range for half of the occupied hours and the other part is out of the comfort range.

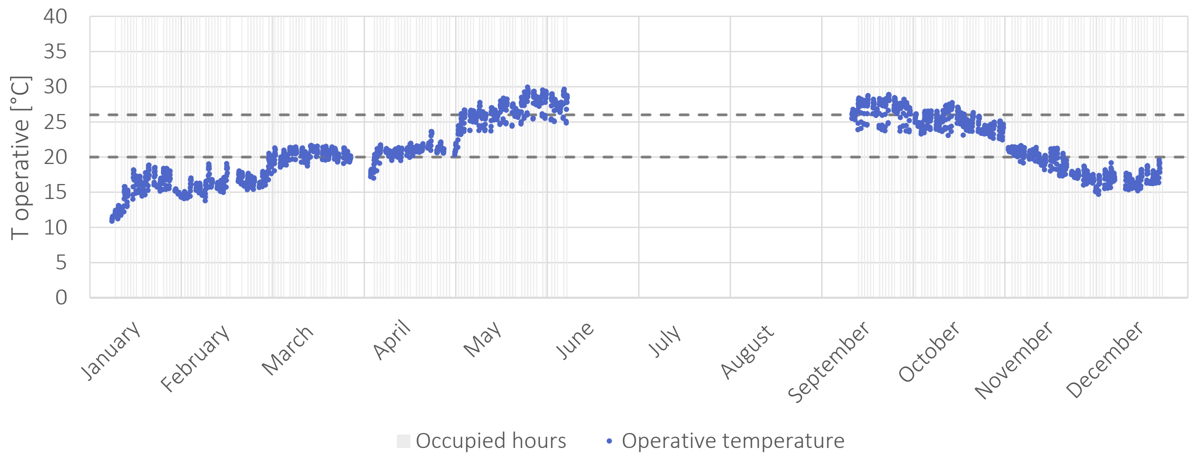


Chart 118 Case 3 S1 free-floating operative temperature

Seasons	From - to	Representative month
Heating season	from 15th November to 28th February	February
Middle season	from 1st March to 30th April and 1st October to 31st October	March
Cooling season	form 1st May to 8th June and 12nd September to 1th October	May

Table 123 Case 3 seasons assessment

The assessment of heating, cooling and ventilation schedule has been assessed after many attempts and they have been verified according to the predict mean vote as already done for case 1 and 2. The schedule parameter and the best results of PMV of classroom S1 and N1 for each season are reported in the following charts and tables. In all cases internal comfort is achieved and almost belong to category A in the heating season, in category A with about 10-15% of the occupied hours in comfort category B in the middle and the cooling season.

Also in case 3, the simulations consider the a different parametric schedule for heating and natural ventilation in the middle season for South and North classrooms, because their needs are different. Moreover, thermal loads of the same classrooms in the cooling season are quite different according to the building envelope construction. Therefore, the operation of chillers and natural ventilation has been spitted in order to achieve higher quality of internal comfort.

Optimization of the Heating season schedule

Parametric schedule – Heating season		
Heating on	6.00-17.00	if Tmr≤ 18.5°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	-	-

Table 124 Case 3 S1 heating season parametric schedule data

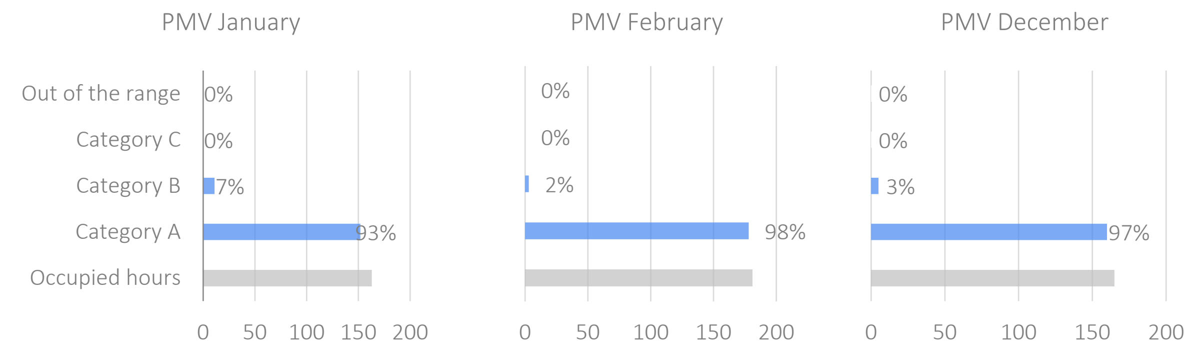


Chart 119 PMV frequency of January, February, December 0.9 clo

	PMV January 0.9 clo		PMV February 0.9 clo		PMV December0.9 clo	
Occupied hours	163		181		165	
Category A	152	93%	178	98%	160	97%
Category B	11	7%	3	2%	5	3%
Category C	0	0%	0	0%	0	0%
Out of the range	0	0%	0	0%	0	0%

Table 125 PMV case 3 January, February, December 0.9 clo

Optimization of the Middle season schedule and ventilation

Parametric schedule – Middle season South		
Heating on	6.00 - 8.00	if Tmr≤ 17.5°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	10.00 – 17.00	If Ta≥ 23°C

Table 126 Case 3 S1 middle season parametric schedule data

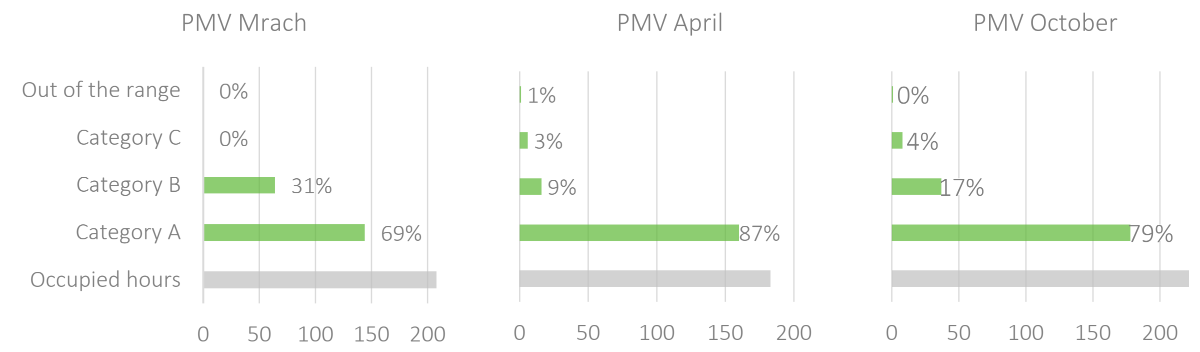


Chart 120 PMV frequency of March, 0.8 clo, April 0.65 clo, October 0.6 clo

	PMV March 0.8 clo		PMV April 0.65 clo		PMV October 0.6 clo	
Occupied hours	208		183		224	
Category A	144	69%	160	87%	178	79%
Category B	64	31%	16	9%	37	17%
Category C	0	0%	6	3%	8	4%
Out of the range	0	0%	1	1%	1	0%

Table 127 PMV case 3 March, April, October 0.8, 0.65, 0.6 clo

Optimization of the cooling season schedule and ventilation

Parametric schedule – Cooling season		
Heating on	-	-
Cooling on	11.00 – 16.00	If Tmr> 25.5°C, Ta<20°C
Natural ventilation on	8.00 – 11.00	If Ta≥ 24.5°C

Table 128 Case 3 S1 cooling season parametric schedule data

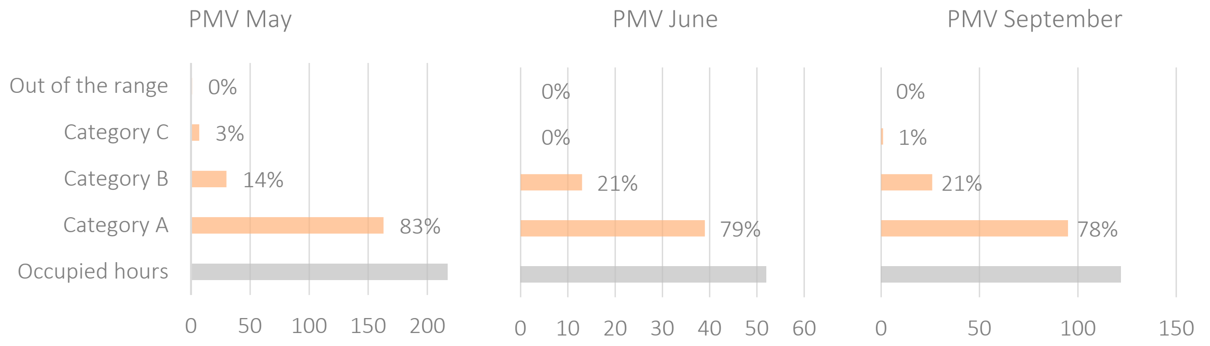


Chart 121 PMV frequency of May, June, September 0.4 clo

	PMV May 0.4 clo	
Occupied hours	217	
Category A	163	83%
Category B	30	14%
Category C	7	3%
Out of the range	1	0%

PMV June 0.4 clo	
52	
39	79%
13	21%
0	0%
0	0%

PMV September 0.4 clo	
122	
95	78%
26	21%
1	1%
0	0%

Table 129 PMV case 3 May, June, September 0.4 clo

Classroom N1

Optimization of the Heating season schedule

Parametric schedule – Heating season		
Heating on	6.00-17.00	if Tmr≤ 18.5°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	-	-

Table 130 Case 3 N1 heating season parametric schedule data

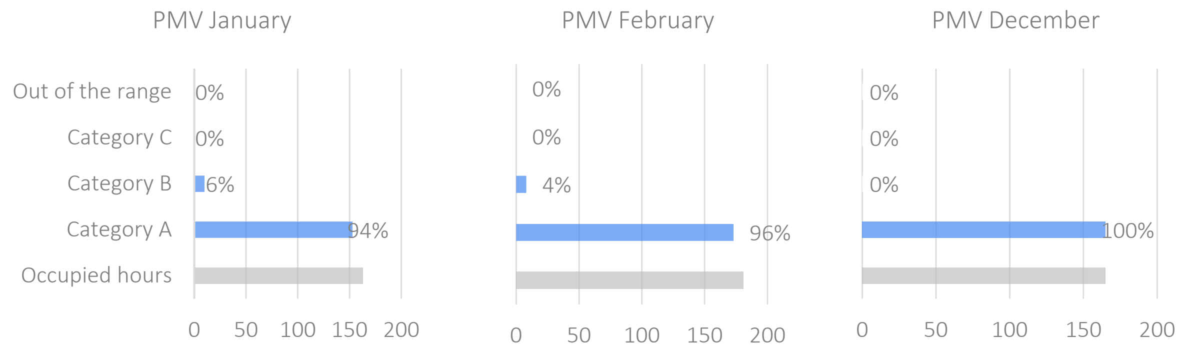


Chart 122 PMV frequency of January, February, December 0.9 clo

	PMV January 0.9 clo	
Occupied hours	163	
Category A	153	94%
Category B	10	6%
Category C	0	0%
Out of the range	0	0%

PMV February 0.9 clo	
181	
173	96%
8	4%
0	0%
0	0%

PMV December0.9 clo	
165	
165	100%
0	0%
0	0%
0	0%

Table 131 PMV case 3 January, February, December 0.9 clo

Optimization of the Middle season schedule and ventilation

Parametric schedule – Middle season North		
Heating on	6.00 - 8.00	if Tmr≤ 19.5°C, Ta<20°C
Cooling on	-	-
Natural ventilation on	10.00 – 17.00	If Ta≥ 23.5°C

Table 132 Case 3 N1 middle season parametric schedule data

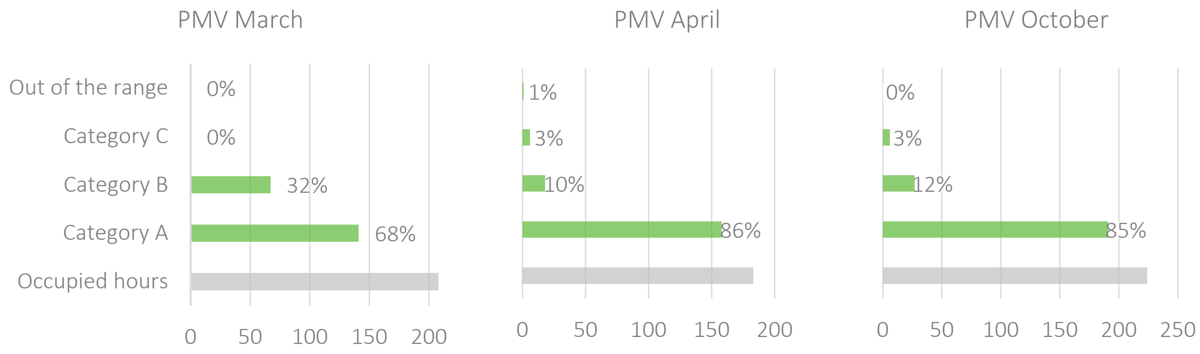


Chart 123 PMV frequency of March, 0.8 clo, April 0.65 clo, October 0.6 clo

	PMV March 0.8 clo	
Occupied hours	208	
Category A	141	68%
Category B	67	32%
Category C	0	0%
Out of the range	0	0%

PMV April 0.65 clo	
183	
158	86%
18	10%
6	3%
1	1%

PMV October 0.6 clo	
224	
191	85%
27	12%
6	3%
0	0%

Table 133 PMV case 3 March, April, October, 0.8, 0.65, 0.6 clo

Optimization of the cooling season schedule and ventilation

Parametric schedule – Cooling season		
Heating on	-	-
Cooling on	11.00 – 16.00	If Tmr> 26°C
Natural ventilation on	8.00 – 11.00	If Ta≥ 25.5°C

Table 134 Case 3 N1 cooling season parametric schedule data

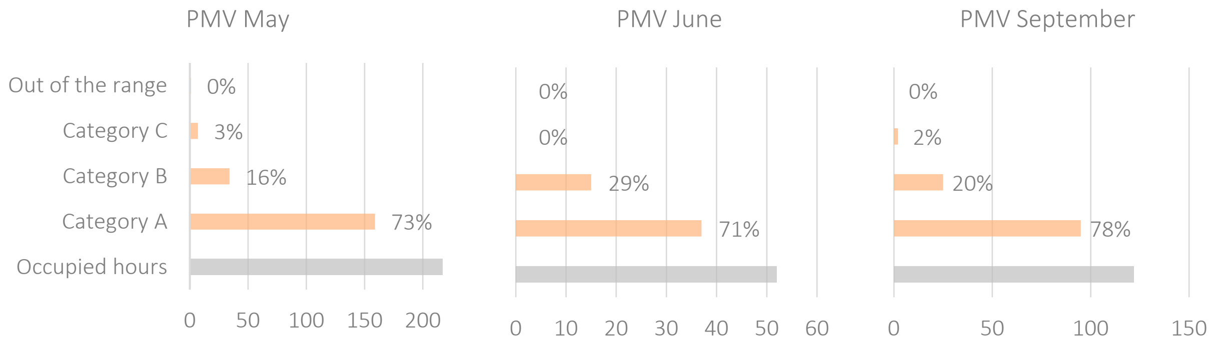


Chart 124 PMV frequency of May, June, September 0.4 clo

	PMV May 0.4 clo	
Occupied hours	217	
Category A	159	73%
Category B	34	16%
Category C	7	3%
Out of the range	1	0%

PMV June 0.4 clo	
52	
37	71%
15	29%
0	0%
0	0%

PMV September 0.4 clo	
122	
95	78%
25	20%
2	2%
0	0%

Table 135 PMV case 3 May, June, September 0.4 clo

5.3.2. PRIMARY ENERGY

The calculation of total primary energy consumed by the building of case 3 is compared with the one used if the systems operation was set on the standard schedule, whose functioning is based on unchangeable parameters. The results show that the improvement of internal comfort, according to the improvement of systems schedules, have provided a decrease of energy. The energy saving is equal to 23% of the energy that would be used by standard systems operation.

Case 3	EHP-W	EHP-W
	Standard schedule	Parametric schedule
PE Bolier [MWh]	81	57
PE Chiller [MWh]	8	11
Total PE [MWh]	89	68
Energy saving		-23%

Table 136 Total primary energy for boiler and chiller for case 3

5.3.3. ADAPTIVE COMFORT

The evaluation of the adaptive comfort has been done by the report generated by the software and by hand calculation in which data have been handled in order to verify the frequency of comfort hours respect to the occupied ones, according to the operative temperature and the relative humidity.

The internal air temperature in middle/summer months (May, June and September) is mitigated by the use of natural ventilation through window which is based on the parametric schedule showed in the table.

The report generated by the IES adaptive comfort tool, underline that natural ventilation is able to guarantee a good level of internal comfort even without chillers. In fact, the report shows that 53 thermal zones have passed the verification and 12 have failed, since they are spaces for offices, gym and canteen that were not taken into account during the optimization process.

Parametric schedule – Adaptive summer season		
Heating on	-	-
Cooling on	-	-
Natural ventilation on	8.00 – 17.00	If Ta≥ 25.5°C

Table 137 Case 3 S1 adaptive approach data

Adaptive comfort report results			
Total rooms	Passed	Failed	Unoccupied
65	53	12	0

Table 138 Case 3 summary of the adaptive comfort IES report

The report generated by the software has been checked by hand calculation of data, in particular focusing on the operative temperature and relative humidity registered in classroom S1 and N1. The charts of the frequency of comfort hours with respect to the occupied hours, related to the operative temperature show that adaptive comfort is achieved in summer months, but there is a significant part of occupied hours that is not able to guarantee comfort. In fact, in May, comfort hours are equal to 72% for the classroom S1 and 64% for N1. June has registered higher values equal to 87% for S1 and 85% for N1. In September the frequency of comfort hours decreases until 58% for both classrooms. Comparing the results of classroom S1 and N1, comfort hours are a bit higher in the South oriented thermal zone, probably due to the influence of solar gain that hit directly the façade during the morning and contribute to heat up the space. Instead, classroom N1 is not influenced by solar gain form the façade except for the diffuse radiation whose contribution is very low.

Instead, the charts of comfort relative humidity show this parameter is almost constant during the occupied hours of summer months. In fact, the percentage of comfort hours is always in the range of 70-89% except for June in S1 where this value is equal to 55%.

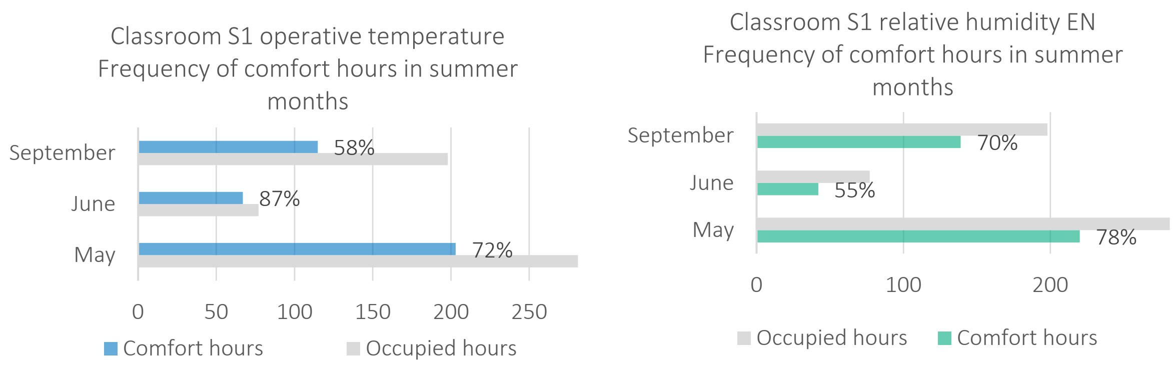


Chart 125 Case 3 Operative temperature and relative humidity of classroom S1 according to the adaptive approach

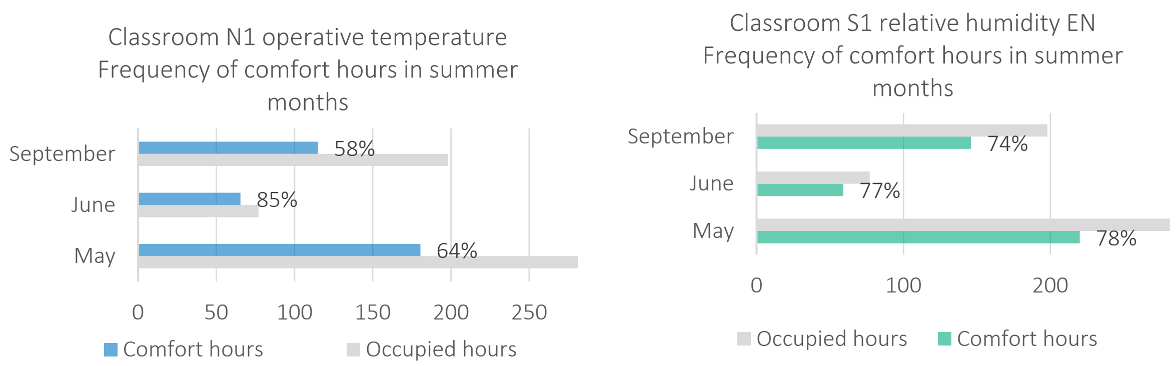


Chart 126 Case 3 Operative temperature and relative humidity of classroom N1 according to the adaptive approach

Comfort analysis and further verifications

As in the previous cases 1 and 2, the simulation without the use of chiller in summer has been tested according to the static approach fort comfort evaluation and compared with the results obtained with the simulation with middle/summer conditioning system in order to understand the difference between the two methods.

The following charts for classroom S1 and N1 show that there is a big reduction of internal comfort if the cooling system has been avoided. In May, the results of the two classrooms underline that half of the occupied hours are included in comfort category B and only ne third of them in category A. In June and September, about 62% of the occupied hours remain in category A (respect to the 80% of the simulation with cooling system) and about 35-40% in category B. In these months there is a reduction of comfort ours in category A and an increase of them in category B.

In both thermal zones, all months of the summer season have registered few points in category C and out of the range even if they have increased respect to the simulation with mechanical summer conditioning.

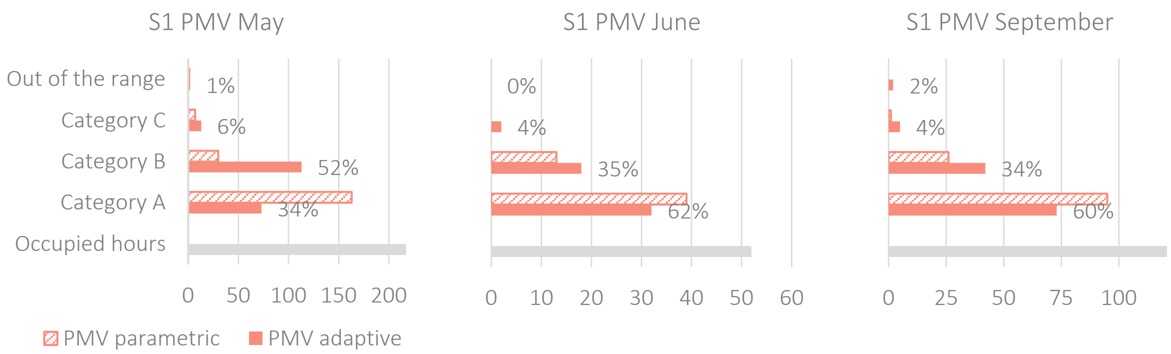


Chart 127 PMV case 3 comparison for summer months for classroom S1

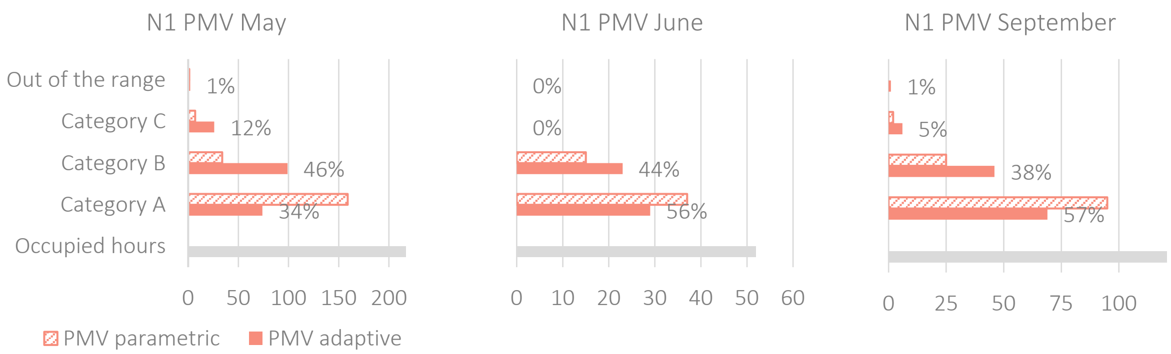


Chart 128 PMV case 3 comparison for summer months for classroom N1

5.3.4. OBSERVATIONS ON CASE 3

The envelope construction related to case 3 consider an intermediated value of thermal performance between the best and the standard values. The system schedule assessment and the comfort evaluation have been done in order to understand if parametric schedule of case 1 and 2 can be reused. In fact, the process to define the new schedule for case 3 starts form the schedule used in case 2, but results demonstrated that those values are not able to achieve the best result in terms of internal comfort. In fact, the parameters of the schedule have been changed in order to improve internal comfort. The best schedule parameters reported in chapter 5.3.1 are the results of many attempts (not reported in this work).

The presence of heating and cooling systems in the school building can guarantee a good level of internal comfort. In the middle and in middle/summer seasons, where external conditions are not too rigid, the use of natural ventilation though window can be a passive solution to cool down spaces and achieve internal comfort, without the activation of chillers. This strategy is a good solution to save energy and decrease the cost of building operation.

According to the construction technologies used in case 3, adaptive comfort (category II) is guaranteed in May, June and September, avoiding the used of chillers according to the report generated by the software. More detailed analysis has been done on this topic in order to understand the variation of the comfort hours during the occupied ones. In fact, the charts on the frequency of comfort hours according to the operative temperature and relative humidity have shown that adaptive comfort is achieved, but the percentage of comfort hours are not so close to the occupied hours. Therefore, the adaptive comfort result is acceptable but further optimization is still possible in this case.

CHAPTER

6

Economic evaluation of the project

6.1. COST ASSESSMENT

The economic evaluation of the optimization choices is useful to assess the real cost of interventions and to make an economic analysis of the results.

At the first stage each intervention has been evaluated from the economical point of view, taking into account the unit price[1] of the work. This evaluation is useful to understand which intervention is the most expensive, and the economical difference between the choices, among the group of the same intervention.

Since the building is placed in Melzo, in the province of Milano, the costs of interventions have been set on the price list of Milano actually used for public building projects [*Listino prezzi del Comune di Milano per l'esecuzione di opera pubbliche e manutenzione – edizione 2018*] which is based on the regional price list, in force since 2011. The unique exception is related to the evaluation of window costs, because the price list of Milano is not sufficiently detailed to achieve a reliable result according to the project choices. Therefore, the evaluation has been done by using real prices of windows and glazed door and their cost estimation has been done with ISS software. In addition, since the cost of window application is evaluated according to a real case, the evaluation of old window removal and application of new ones is done according to the price list of Milano, already used.

The table and the chart underline that the highest cost is related to the substitution of systems. In fact, their application requires the cost of the thermal machines, the distribution system, terminals according to the type of generator chosen, controller devices in each thermal zone and for the global building and further cost of excavation, placement and connection of the ground water pipeline to the building (only for water source heat pumps).

The second most expensive intervention is associated to the improvement of glazed surfaces. Since the external glazed surface covers the great part of the total external vertical surface, the cost of window and glazed doors substitution is very high. Comparing this cost with the one of the improvement of external walls (addition of thermal insulation on the external wall surface) the difference is very important because the area of opaque façade in much low respect to the transparent one.

The calculation has not taken into account the substitution of lighting system or equipment.

Optimized element	Thermal transmittance U	Cost €
Window	U_{window} 1.4	€ 457'247.78
	U_{window} 1.0	€ 474'456.03
	U_{window} 0.8	€ 491'664.28
Shading	Internal blinds	€ 34'289.13
	External louvers	€ 112'808.00
Roof	U_{roof} 0.24	€ 358'294.87
	U_{roof} 0.15	€ 381'094.87
	U_{roof} 0.10	€ 410'334.87
Ground	U_{ground} 0.29	€ 317'421.91
	U_{ground} 0.24	€ 364'501.91
	U_{ground} 0.17	€ 413'581.91

[1] Unit price (*prezzo unitatio della lavorazione*) is the cost of the single work specified by the description. This cost considers the real cost of the material and the work process done to install it on site; it also may include transportation costs or taxes.

External wall	U $_{external\ wall}$ 0.24	€ 73'180.80
	U $_{external\ wall}$ 0.21	€ 51'519.40
	U $_{external\ wall}$ 0.16	€ 99'091.20
Scaffolding	-	€ 17'704.80
Systems	EHP-A	€ 557'312.59
	EHP-W	€ 554'167.99
	GAHP-W	€ 754'479.65

Table 139 Cost calculation of optimization choices

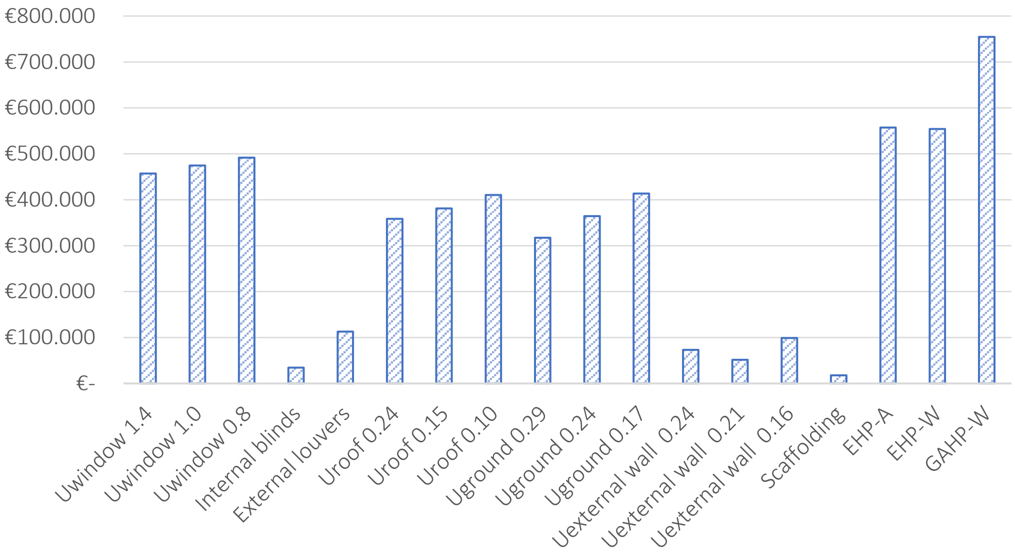


Chart 129 Cost of interventions

Cost of cases

The economical evaluation of intervention has been done as a sum of the single costs of interventions. In order to have a slender calculation the results are collected into a table that reports the total cost of intervention, according to the building characteristics, and the cost per meter square. The calculation of the cost per meter square takes into account the area is the useful floor area of the part of the school considered into the project.

The following table collect all cases.

N°	windows	blinds	louvers	roof	ground	external wall	System	€	€/m2
Case 1	w 1.4	b yes	l no	r 0.24	g 0.29	e 0.24	EHP-W	€ 1'812'307.28	€ 578.46
Case 2	w 0.8	b yes	l yes	r 0.1	g 0.17	e 0.16	EHP-W	€ 2'133'642.18	€ 681.02
Case 3	w 1	b yes	l yes	r 0.15	g 0.24	e 0.21	EHP-W	€ 1'990'542.13	€ 635.35
Case 4	w 0.8	b yes	l no	r 0.1	g 0.29	e 0.24	EHP-A	€ 1'901'908.38	€ 607.06
Case 5	w 1	b yes	l no	r 0.15	g 0.29	e 0.24	EHP-A	€ 1'855'460.13	€ 592.23
Case 6	w 1	b yes	l yes	r 0.1	g 0.29	e 0.24	EHP-A	€ 1'997'508.13	€ 637.57
Case 7	w 0.8	b yes	l no	r 0.1	g 0.29	e 0.16	EHP-A	€ 1'927'818.78	€ 615.33
Case 8	w 0.8	b yes	l no	r 0.15	g 0.29	e 0.21	GAHP-W	€ 2'048'174.04	€ 653.74
Case 9	w 1	b yes	l yes	r 0.1	g 0.29	e 0.16	EHP-A	€ 2'023'418.53	€ 645.84
Case 10	w 1.4	b yes	l yes	r 0.15	g 0.17	e 0.16	EHP-A	€ 2'073'130.28	€ 661.71
Case 11	w 0.8	b yes	l no	r 0.15	g 0.24	e 0.21	GAHP-W	€ 2'095'254.04	€ 668.77
Case 12	w 0.8	b yes	l yes	r 0.1	g base	e base	EHP-A	€ 1'624'113.67	€ 518.39
Case 13	w 0.8	b yes	l yes	r 0.1	g 0.17	e base	GAHP-W	€ 2'234'862.64	€ 713.33
Case 14	w 0.8	b yes	l no	r 0.1	g base	e base	EHP-W	€ 1'508'161.07	€ 481.38
Case 15	w 0.8	b yes	l no	r 0.1	g 0.29	e base	EHP-W	€ 1'825'582.98	€ 582.69
Case 16	w 1.4	b yes	l yes	r 0.15	g base	e base	EHP-A	€ 1'560'457.17	€ 498.07
Case 17	w 1.4	b yes	l yes	r 0.24	g 0.17	e base	EHP-A	€ 1'951'239.08	€ 622.80

Table 140 Cost calculation of optimized combinations

6.2. PAYBACK PERIOD CALCULATION

Payback period calculation is a method to determine the point in time at which the initial investment is paid off. The payback period method of financial appraisal is used to evaluate capital projects and to calculate the return per year from the beginning of the project until the accumulated returns are equal to the cost of the investment. When the cost of the investment is balanced by the payment results, the investment has been paid back and the time taken to achieve this payback is called payback period.

The payback method is used in this work to assess the payback time and evaluate if the investment on building renovation is useful or not from the financial point of view. In this section the calculation of the payback period has been done on the three cases analysed by handle calculation, making some hypothesis on the variation of some parameters like the discount rate and the value of inflation. These hypotheses consider the possible average value of their yearly variation, in order to have a slender calculation. Among the simplifications, the discount rate is considered equal to 5% and, as consequence, it is used to assess the yearly value of cumulative base inflation, base inflation and energetic inflation. The percentage of public subsidies has been calculated according to the D.g.r 17/01/18 - *Programma nazionale in materia di edilizia scolastica per il triennio 2018-2020 – Individuazione dei criteri per la raccolta del fabbisogno di interventi di edilizia*. The legislation describes the method used by the regional government to evaluate renovation project of public school buildings and assign the regional subsidies. The maximum percentage is equal to 80% of the cost of construction (distributed in 10 years) and a minimum initial cost no lower than € 100’000. The ranking list favours the seismic upgrade interventions and the ones that aim to the structure barely safe achievement and, at the third place, the evaluation of the sustainability of the project. Therefore, the public subsides rate has been hypnotized equal to 50%.

The result of the analysis determines the payback period and the calculation of the operative cash flow and the cumulative operative cash flow, that considers the initial cost of construction, public subsides, and the nominal energy saving generated by the improvement of the building efficiency respect to the baseline. The following tables collect the parameters used in the calculation; the spreadsheet of the cases are collected in annex F.

Parameters	
€/kWh, gas	0.06
€/kWh,ele	0.2
$f_{PE\ ng}$	1.05
$f_{PE,ele}$	2.42

Table 141 Data for the energy cost assessment

	Energy Boiler /year	Energy Chiller /year	€ gas/year	€ ele/year	€ tot/year	€ saved /year	Cost of constr.€	€m
Baseline	467	18	€ 28'021	€ 3'524	€ 31'545			
Case 1	40	3		€ 8'595	€ 8'595	€ 22'949	€ 1'812'307	€ 1.81
Case 2	30	3		€ 6'612	€ 6'612	€ 24'933	€ 2'133'642	€ 2.13
Case 3	33	3		€ 7'355	€ 7'355	€ 24'189	€ 1'990'542	€ 1.99

Table 142 Results matrix of the case 1-3

The three cases analysed in the calculation are very expensive since the intervention interests the whole building. In fact, considering the previous boundary conditions for the calculation, the payback period is very high, and it is equal to 35 years for the case 1, 39 years for the case 2 and 37 of the case 3. Case 1 consider the improvement of the building envelope of the legislation D.m. 26/06/15, while case 2 consider the best envelope combination among the choices considered in chapter 4 and case 3 uses an intermediate thermal performance of the building envelope. By the payback calculation, case 2 is the intervention with the higher payback period since it is the most expensive, while case 1 is the one with the lower payback period of the three cases. Keeping fixed the boundary conditions, the payback period is proportional to the cost of construction.

The following charts show the trend of operative cash flow, grey columns, that considers the single contributions according to the bank account reference system: positive gains and negative losses/money expended. This variable shows (independently) the initial cost of construction and, the nominal value of public contributions in ten years and gains due to energy saving, which increase over time. On the other side, the cumulative operative cash flow, considers the same parameters of the operative cash flow as a unique economic balance in which positive and negative contributions are summed. In fact, the initial negative peak is related to the cost of construction; then the slope rises thanks to the public contributions, but after 10 years when regional finances are suspended, the slope decrease because the unique positive gains are related to the energy saving.

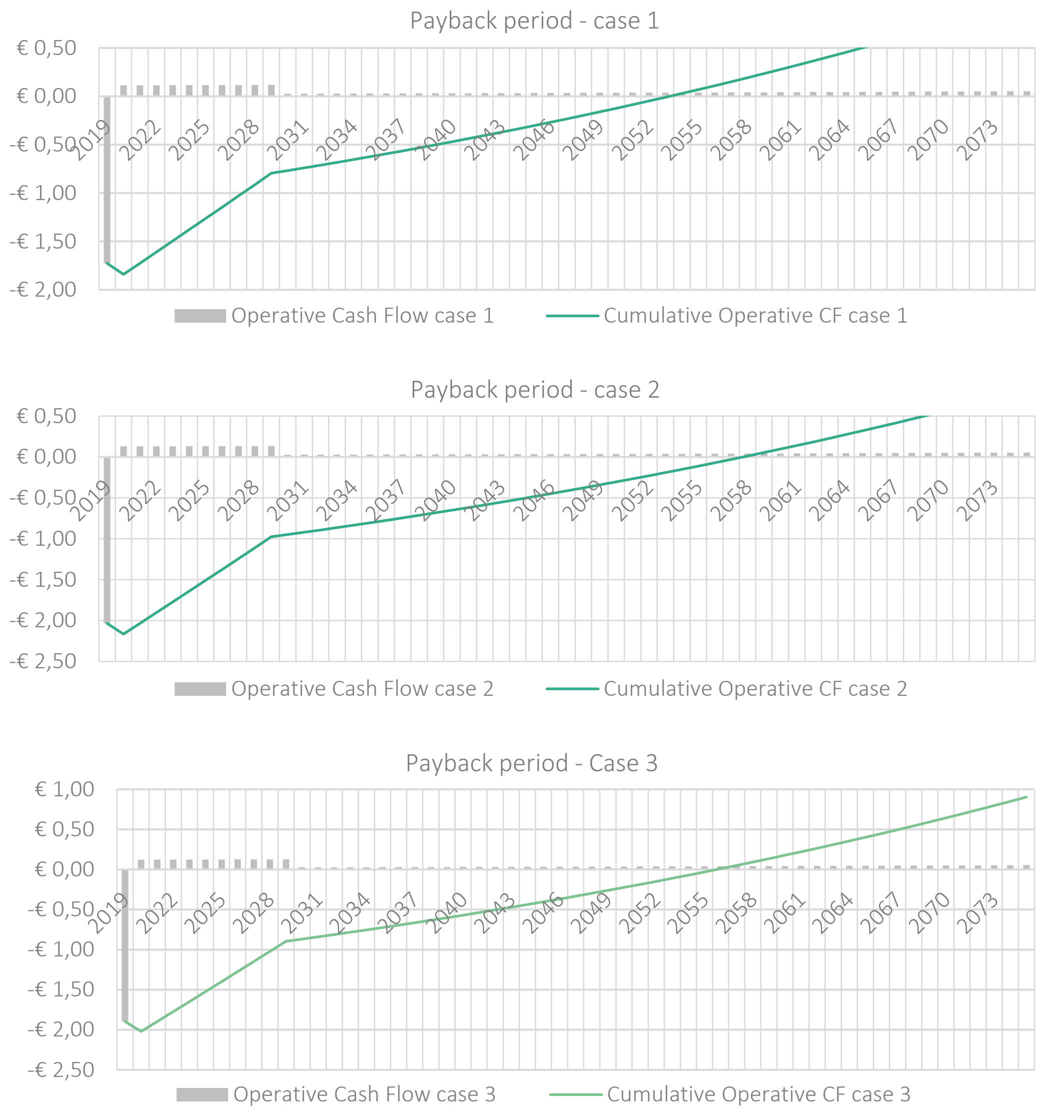


Chart 130 Payback period case 1, 2, 3

The payback period of the three cases considered in the analysis is very high and, from the financial point of view, it is probably more convenient to use the same amount of money in other type of investments. Therefore, the following analysis calculates the payback period of a different kind of intervention. The previous analyses [2] on the building underlined that the improvement of thermal performance of transparent surfaces can generate a big decrease of energy consumption. Therefore, the substitution of windows with more performant glazing has been analysed to understand if it provides better financial results respect to case 1, 2, and 3.

The result of the analysis demonstrate that the improvement of windows generates a payback period equal to 11 years, which is much shorter than the ones of case 1,2 and 3.

	Energy Boiler /year	Energy Chiller /year	€ gas/year	€ ele/year	€ tot/year	€ saved /year	Cost of constr.€	€m
Window substitution	419	10	€ 25'143	€ 1'901	€ 27'044	€ 4'501	€ 491'664	€ 0.49

Table 143 Results matrix of the windows substitution

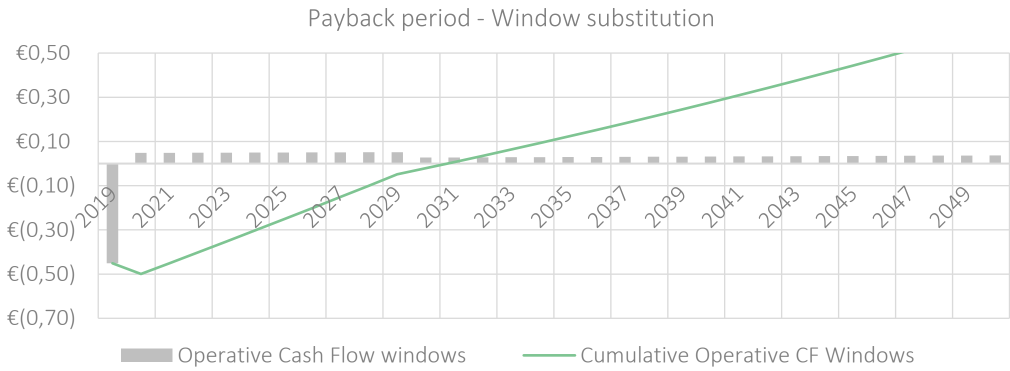


Chart 131 Payback period of windows substitution

6.2.1. Further comfort verification on window change

The substitution of windows can be a good strategy in terms of energy saving (as already shown in chapter 4.2) and from the financial point of view, since this intervention is not very expensive than the payback period is not so high. In order to evaluate if this intervention has positive effect for occupants, a new comfort analysis has been done by the calculation of PMV in classroom S1 and N1 in the representative months of the season, February, March and May as already used to check internal comfort condition in the previous chapters. Moreover, the type of clothing insulation is kept equal to the ones used in the previous verifications, 0.9 clo in February, 0.8 clo in March and 0.4 clo in May with an air velocity equal to 0.5 m/s.

The following charts compare the PMV of the simulation with baseline windows with PMV of the simulation with optimized windows (the best Uw). The results demonstrate that there is a reduction of the internal

[2] From the comparison of the envelope optimization strategies reported in chapter 3.2.3, all the three models considered in the analysis showed that the first intervention is related to the substitution of windows in order to decrease the energy consumption and improve local comfort.

discomfort, related in particular to the improvement of thermal transmittance of windows and the reduction of infiltration that may cause local discomfort. According to the charts, this intervention has a positive effect in the improvement of internal comfort in winter and middle season, while it has lower influence on summer comfort conditions.

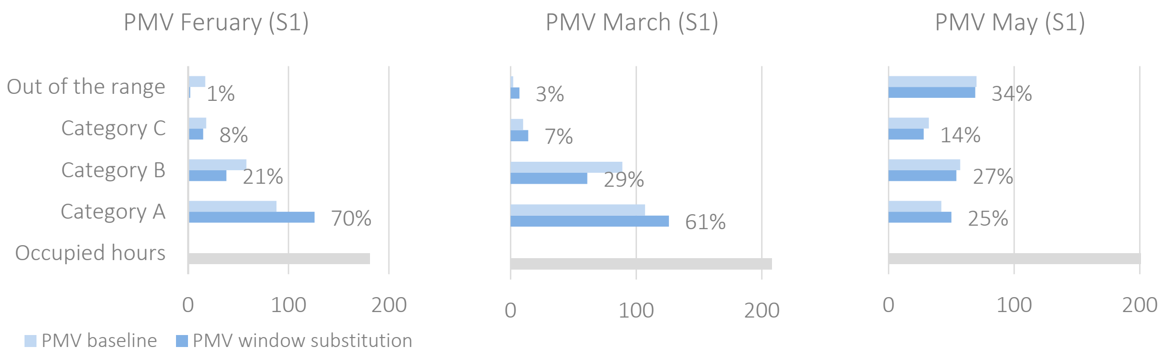


Chart 132 PMV in classroom S1 in the representative months of the three seasons

	PMV February 0.9 clo	
Occupied hours	181	
Category A	126	70%
Category B	38	21%
Category C	15	8%
Out of the range	2	1%

PMV March 0.8 clo	
208	
126	61%
61	29%
14	7%
7	3%

PMV May 0.4 clo	
201	
50	25%
54	27%
28	14%
69	34%

Table 144 PMV in S1 in the seasonal representative months, February, March, May

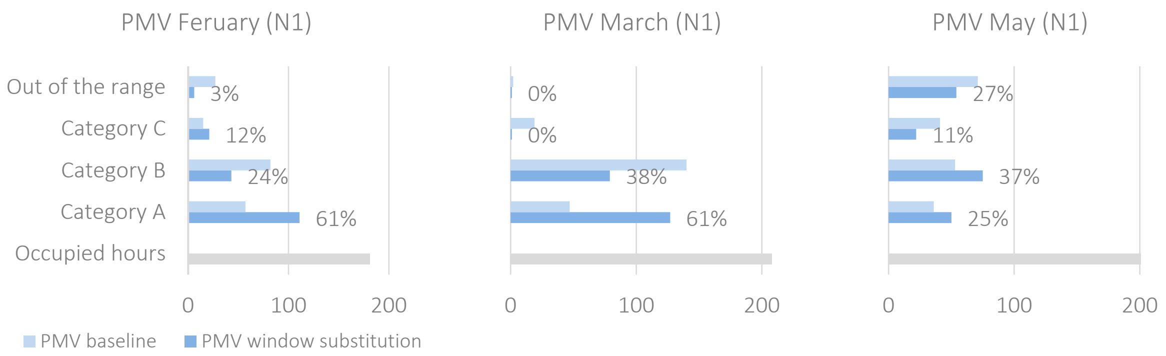


Chart 133 PMV in classroom N1 in the representative months of the three seasons

	PMV February 0.9 clo	
Occupied hours	181	
Category A	111	61%
Category B	43	24%
Category C	21	12%
Out of the range	6	3%

PMV March 0.8 clo	
208	
127	61%
79	38%
1	0%
1	0%

PMV May 0.4 clo	
201	
50	25%
75	37%
22	11%
54	27%

Table 145 PMV in N1 in the seasonal representative months, February, March, May

The following charts compare the PMV of classroom S1 in the three cases analysed, the baseline and the window substitution. The highest value in the heating (February) season is registered in case 3, in the middle (March) in case 2 and in cooling season (may) again in case 3. As expected, the PMV of the baseline construction reaches its highest value in the middle season, where a big part of the occupied hours in comfort category B.

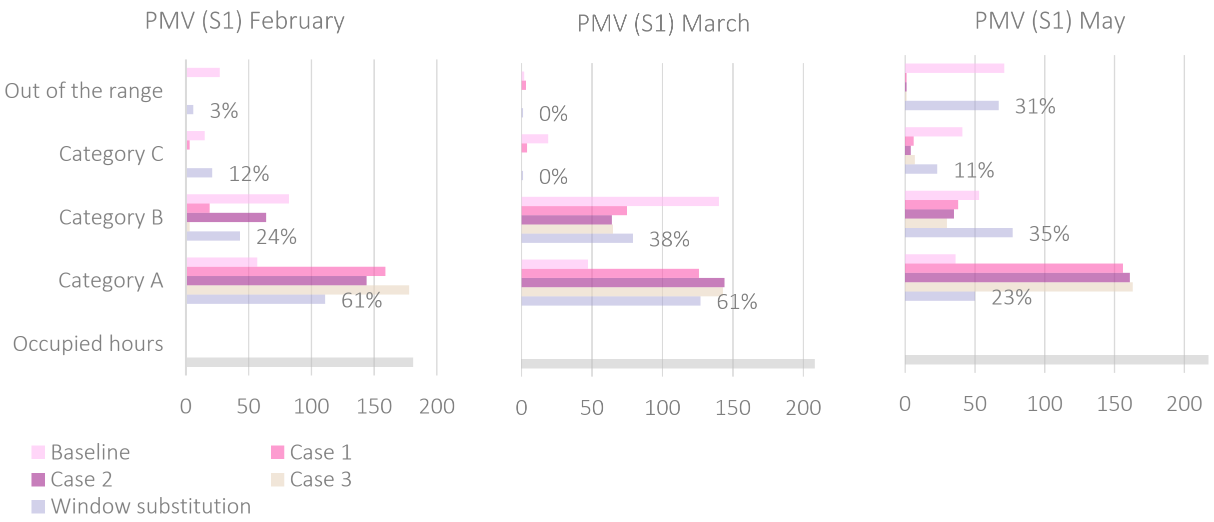


Chart 134 Seasonal PMV comparison of classroom S1

PMV february 0.9 clo	Baseline	Case 1	Case 2	Case 3	Win. Sub.	
Occupied hours	0				181	
Category A	57	159	144	178	111	61%
Category B	82	19	64	3	43	24%
Category C	15	3	0	0	21	12%
Out of the range	27	0	0	0	6	3%

PMV March 0.8 clo	Baseline	Case 1	Case 2	Case 3	Win. Sub.	
Occupied hours	0				208	
Category A	47	126	144	143	127	61%
Category B	140	75	64	65	79	38%
Category C	19	4	0	0	1	0%
Out of the range	2	3	0	0	1	0%

PMV May 0.4 clo	Baseline	Case 1	Case 2	Case 3	Win. Sub.	
Occupied hours	0				217	
Category A	36	156	161	163	50	23%
Category B	53	38	35	30	77	35%
Category C	41	6	4	7	23	11%
Out of the range	71	1	1	1	67	31%

Table 146 Seasonal PMV comparison of classroom S1

6.2.2. Observations

Comparing the three cases with the intervention of window substitution, the payback period is very different since case 1, 2 and 3 consider the renovation of the whole building and a high value of the construction cost, while window improvement requires less financial sources that generates a shorter payback period.

The evaluation of payback period is a useful instrument to have a prevision of the financial success of the investment. Many parameters can affect the reliability of the results such as discount rate, base and energy inflation and so on. In public buildings, in particular in school and healthcare, an investment can be considered fruitful even if the payback period is very high. This because in some context (e.g. public school buildings) the wellness and the health of occupants is more important than the financial earnings. Therefore, the calculation of the payback period is a technical data that should be added into the multicriteria analysis for the evaluation of the intervention.

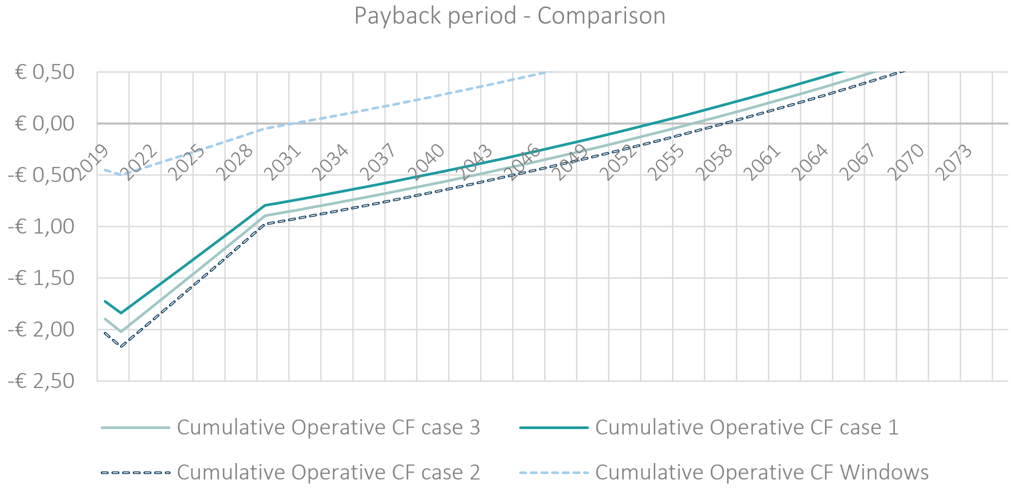


Chart 135 Payback cases comparison

	Case 1	Case 2	Case 3	Windows
Payback years	35	39	37	11

Table 147 Payback results

7.1. CONCLUSIONS: MULTICRITERIA COMPARISON

The secondary school building *Piero Mascagni* in Melzo, used as a case study, has been analysed according to the climate condition of Milano in order to understand how the environment affects the thermal behaviour of the building and what kind of passive strategies can be used to define a list of possible intervention for the building renovation. The analyses showed that the building is heating oriented since in summer months, June, July and August, the school is closed for students. Therefore, the interventions of building renewal aim to improve the thermal performance of the envelope in order to decrease the heat losses during the winter season and, at the same time, guarantee a good level of internal comfort during the year.

Firstly, the reduction of energy consumption has been done by the application of passive strategies that consider the improvement of the insulation layer of the envelope (external walls, roof, ground slab and windows) with different level of thermal transmittance and by the implementation of transparent surfaces with external and internal shading device to avoid glare and overheating in summer. The second step of the optimization process considers the substitution of the old systems with a new conditioning system for winter and summer season, more efficient than the original. Moreover, natural ventilation has been considered in the middle season and the cooling season, since it is a passive strategy that decrease the energy consumption of the chillers.

The assessment of internal comfort condition has been done according to the regulation of systems operation. In fact, the improvement of the building envelope generates a reduction of the heating season period and an increase of the cooling season. Therefore, standard schedules showed by the standard UNI EN ISO 11300-1 are no longer suitable for this type of building to guarantee internal comfort and low energy consumption at the same time. The new schedules have been set on different set point parameters that take into account not only the value of air temperature but also the variation of mean radiant temperature, that varies according to the position of the occupant respect to the wall-glazed surfaces and according to their internal surface temperature. In fact, thermal comfort is strictly connected by both temperature which are represented by the operative temperature.

The application of heating schedule for climate zone E suggested by the standard UNI TS 11300-1 have not provided good results in terms of comfort; therefore, heating and cooling schedules have been adjusted according to the building needs. This optimization has been done only on three cases which involve case 1, that aims to improve the thermal transmittance of the envelope until the minimum value imposed by the DM 26/06/15, case 2 that consider the best envelope combination among the possible optimization choices and case 3 as an intermediate combination between case 1 and 2.

After the assessment of building intervention and internal comfort, an economic evaluation has been provided in order to establish which is the most expensive/cheapest intervention and to calculate the payback period of the intervention.

The three cases analysed in the previous chapters worked out results in terms of primary energy consumption, non-adaptive internal comfort according to the standard UN EN ISO 7730, adaptive comfort of EN 15251, cost of construction and the payback period.

The choice of the best renovation case among the ones considered is not trivial and sometimes there isn't any *best* intervention, since the final decision depends on the main target of the public commission and contractors, and by the context of the project. Nevertheless, the results worked out from the analyses can be reorganized in order to set a ranking list and make a multi-criteria evaluation to support the final decision, like the structure of certification protocols LEED and WELL. The five variables used in this multicriteria analysis are connected to the cost of construction per meter square, the primary energy consumed by the system operation, the payback period of the investment and the achievement of adaptive and non-adaptive comfort. The calculation of the non-adaptive comfort has been done as a weighted average percentage of the comfort hours that are included in category A of PMV showed by the standard UNI EN ISO 7730.

Each variable, considered in the multi-criteria evaluation, can earn from 1 to 3 points considering 1 the worst case and 3 the most convenient (2 an intermediate value). Point assignment of adaptive comfort and payback period have been calculated in a different way. Adaptive comfort can be achieved or not, therefore 0 means that the intervention is not able to satisfy the adaptive comfort conditions, while 1 means that it is reached. The payback period can earn 3 points if the period is lower than 10 years, 2 points when the period is lower than 20 years and 1 point when it is higher than 20 years. In the end, points of each variable have been summed up in order to evaluate which is the intervention with the higher final score. The first table collect the data analysed into a matrix; the second table shows the score earned by each case according a specific variable and the final score that sums the earned points.

	€/m^2	tot PE	Comfort	Adaptive Comf.	PB period
Case 1 - standard U	578	87	76%	yes	35
Case 2 – best U	681	70	83%	no	39
Case 3 – intermediate U	635	68	85%	yes	37

Table 148 Data matrix of multicriterial analysis

	SCORE					FINAL SCORE
	€/m^2	tot PE	Comfort	Adaptive Comf.	PB period	
Case 1 - standard U	3	1	1	1	1	7
Case 2 – best U	1	2	2	0	1	6
Case 3 – intermediate U	2	3	3	1	1	10

Table 149 Result matrix of multicriteria analysis

According to the result table, the score related to the cost of intervention, primary energy and comfort are different for each case. On the other hand, scores of adaptive comfort and payback period are close to each other. Adaptive comfort is achieved only in case 1 and 3 (earning 1 point), while the score of the payback period is the same for every case. In fact, the payback period is higher than 30 years in every case and there isn't any significant difference among them (1 point for each case).

The calculation of the final score indicates that the best intervention is case 3. This case considers an improvement of the building envelope that overcome the minimum thermal transmittance of the construction elements but not so low like case 2. In fact, case 2 (the intervention with the best U values of building elements) is the worst combination according to these criteria, and even worse than the intervention of case 1. This result is reliable since is the most expensive intervention and the higher payback period, it doesn't generate a significant reduction of primary energy and it is not associated to the best internal comfort conditions. Moreover, adaptive comfort is not achieved in summer since, the presence of thicker insulation layer of the envelope doesn't work well in summer. In fact, it blocks the passage of heat stored inside the thermal zone, due to internal gains and solar gain, causing the overheating of the space.

Natural ventilation is not able to balance these thermal load, thus mechanical conditioning system is required to guarantee a good quality of internal comfort.

This thesis represents a possible design process of a public building renovation that aims to improve the quality of internal comfort and the school environment for students. The design of possible intervention of building renovation is bases on the optimization of passive and active design choices and on the dialog between internal comfort achievement and the reduction of energy consumption of system operation. The continuous check of energy and comfort targets requires many attempts, and, in a real application, it should be extended to all thermal zone of the school building.

Results of this work demonstrate that the targets of high quality of internal comfort and energy saving (thus, approaching to the *nearly zero energy* balance) can be reached if all the actors involved in the project have a correct awareness of the design choices and maintenance operation of the building. Designers must be able to give technical supports of the interventions and provide some evaluation criteria for the contractor and the public commission. In this way, they can choose the executive intervention according to the availability of resources and targets (e.g. the lowest energy consumption), knowing the effects provided by this choice on the other parameters (e.g. comfort level or construction costs). Moreover, user should be sensitized on the correct maintenance of thermal condition of internal spaces and on the adaptation strategies that should be applied to the building and on their own body, in order to maintain internal comfort and decrease the energy consumption.

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