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Energy performance assessment of the heating system refurbishment on a school building in Modena, Italy

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Abstract

The aim of this paper is the energy performance assessment of the school building Istituto Comprensivo "G. Marconi", located in Modena, Italy. This work describes the dynamic modeling of the building envelope and its heating system, carried out by means of the simulation software TRNSYS 17. According to the developed model, the school space heating loads, as well as the seasonal energy requirements, are evaluated by considering the actual heating system, which consists of gas-fired condensing boilers coupled to high temperature radiators. Then, the school heating system refurbishment is simulated: the paper evaluates the energy savings obtained by replacing boilers and radiators with an air-to-water multi-compressor heat pump, coupled to low temperature aluminum radiators, and by improving the system control strategy. Finally, the impact of the discussed energy saving measures on building energy performance and students thermal comfort is reported.

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Keywords: School building; Trnsys; Dynamic simulation; Air source heat pump; Energy saving.

1. Introduction

In order to limit the global climate change, the European Union (EU) has recently focused its policy on the improvement of energy efficiency. Since buildings sector accounts for about 40% of European primary energy consumption and around 36% of greenhouse gases emissions [1], European Commission has indicated a series of specific targets to improve buildings energy performance. By means of EPBD Directives [2-3], European Parliament has imposed on Member States the transition to Nearly Zero Energy Buildings (nZEB): from 2021 (2019 for public buildings), all new buildings have to comply nZEB requirements.

Within this background, the recent Energy Efficiency Directive [4] confirms these targets and indicates a series of proposals in order to accelerate existing building renovation: as an example, starting from January 2014, Public Administrations (PA) has to retrofit a share of 3% of owned or occupied buildings, each year.

A large part of PA building stock is composed by school buildings. Such buildings are particularly suitable for energy retrofitting, because of their high heating and cooling loads and high-required ventilation rates. Furthermore, the maintenance of high-level indoor air quality and thermal comfort, needed to ensure the health and the productivity of students, requires a huge

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amount of energy. Several works present in literature report that it is possible to achieve strong energy savings by means of educational building retrofit: in Italy, about 55% of existing school buildings was built before 1976 [5] and it is characterized by a very poor quality of building envelope. For this reason, many researchers have presented the analysis of energy saving measures performed on school buildings. For example, Genco et al. [6] studied the energy performance of two school buildings by means of a dynamic software, under different climatic conditions. Authors proposed the installation of a trigeneration plant in order to reduce schools energy consumptions and they showed the effectiveness of the evaluated retrofitting measure. The energetic and economic feasibility of a solar-assisted heating and cooling system, composed by evacuated solar collectors and an absorption chiller, and coupled to different types of school buildings, was performed by Calise [7]. In this study, the author demonstrated that the proposed system could ensure an important energy saving, but the investment cost could be affordable only with public funds. Ascione et al. [8] introduced a new method for energy audits of historical buildings: the developed procedure was applied to an Italian educational building, which was simulated by means of the dynamic software EnergyPlus; results pointed out that despite of historical constraints, remarkable energy savings can be achieved.

The aim of the present work is the assessment of the actual energy performance of a school building, performed by means of a dynamic model. The educational building was simulated by using the dynamic software TRNSYS 17 [9], which allows the modeling of the whole building components: building envelope, school users occupancy profile and HVAC system. Dynamic simulation allows to point out the influence of external and internal parameters, such as the climate, the envelope quality, the heating plant performance and the control system, on school energy consumption and the thermal comfort of occupants.

Finally, the refurbishment of the school heating system was proposed. More in detail, the paper reports the energy saving potential achievable by installing a multi-compressor air-to-water heat pump in place of condensing boilers actually installed. As reported before, the energy retrofit of the school building represents a suitable solution for the reduction of total energy consumption and the enhancement of building energy efficiency.

2. The case study: Istituto Comprensivo "G. Marconi", Modena (Italy)

The building considered in this paper is the primary and secondary school "Istituto Comprensivo G. Marconi". The educational building was built during 1950 and it is located in Castelfranco Emilia, a small town in the province of Modena, placed in the north of Italy (Lat. 44.55° N, Long. 11.02° E). According to Italian law, Castelfranco Emilia is collocated in climatic zone E (the city is characterized by 2269 Heating Degree Days) and the standard heating season ranges from October 15th to April 15th.

The school is located near the center of the town and it consists of a four-storey structure (see Figure 1), characterized by an irregular hollow shape.

a b

Fig. 1. Position (a) of the school in Castelfranco Emilia and the building envelope (b)

2.1. Building description and envelope characterization

The investigated school building is characterized by an elevation of 15.4 m above ground level (global height of 16.9 m due to basement level). The structure consists of four conditioned storeys, articulated in classrooms, corridors, toilets, a staff office zone and a gym. Above the second floor, an unconditioned attic zone is present. The building net conditioned volume is equal to about 18392 m^3, while the surface to volume ratio S/V is 0.32 m^{-1}. The geometrical characteristics of each storey, as net floor area, windows area and surface area, are reported in Table 1.

According to the school building construction period (1950), the overall energy performance of the envelope is very low. In Italy, the first specific law concerning building energy efficiency was enacted in 1976 (law n. 373/1976, [10]): for this reason, the school is not compliant with current Italian law requirements in terms of U-value of envelope component and heating system performance. In the present analysis, four different opaque envelope components were considered, whose main thermophysical characteristics are reported in Table 2.

Table 1. Geometric characteristics of the school building

Zone	Net floor area (m^2)	Surface area (m^2)	Windows area (m^2)	Net volume (m^3)
Basement	819.8	1628.5	51.3	2295.5
Ground Floor	772.7	985.7	191.8	3446.8
First Floor	1208.7	1266.1	277.6	4955.8
Second Floor	1208.7	2658.3	302.6	4942.1
Gym	436.0	904.5	46.1	2752.0
Total	4445.9	7443.1	869.4	18392.2

As pointed out by the comparison with current transmittance limits imposed by law (U_{lim}), building envelope elements are characterized by a very poor quality, that cause strong energy losses. School windows have been replaced during '80s and they currently present a low energy performance, too. Main data concerning installed windows are shown in Table 2: transparent elements consist of double glass glazing 4/6/4, characterized by no low-emissive treatment, with air as spacing gas. Windows g-value was assumed equal to 0.75.

Table 2. Thermophysical properties of building envelope components

Envelope component	s (m)	U-value (W/m^2K)	U_{lim} (W/m^2K)	Material
External wall	0.50	1.35	0.30	Brick
Internal wall	0.40	1.32	/	Brick
Windows	/	3.71	1.90	Double glass
Floor	0.36	1.76	0.31	Concrete
Roof	0.31	1.53	0.26	Concrete

Actually, the building HVAC system is composed by two condensing boilers fired by natural gas, which provide the space heating energy needs of the school. The rated heating capacity of installed boilers is 300 kW and they are characterized by a rated efficiency at full load of 99.2%. A climatic compensation, which modulates supply water temperature as a linear function of external air temperature, guarantees system modulation capability; no internal control appliances as zone thermostats are present in the building. There are no installed cooling and mechanical ventilation systems: air changes are ensured by infiltrations and natural ventilation (windows opening) during daily occupancy. Rooms lighting is provided by the use of fluorescent lamps when the natural light coming from windows is not sufficient. Presently, the total number of students is 577, divided in 25 classrooms; teachers and school staff is composed by 51 units. The occupancy schedule of the building is the following: 8:00-16:00 from Monday to Friday for students, while school staff operating schedule is 7:00-17:00 from Monday to Friday and 8:00-14:00 during Saturday. Finally, the heating system set schedule is based on school occupancy: since no internal temperature control is present within school areas, HVAC system is controlled by means of a programmable thermostat, regardless of current thermal loads and internal conditions. Actually, boilers operating schedule is 6.00-19.00 during workdays, 6.00-14.00 on Saturday and no schedule on Sunday.

3. Building energy performance analysis

In order to assess the energy performance of the school described in Section 2, the analysis was carried out under dynamic conditions by means of an hourly simulation model of the building.

3.1. Development of building simulation model

The dynamic simulation of a building allows to obtain a very detailed and useful model, able to assess the energy performance of the considered building as a function of internal and external inputs, by evaluating the dynamic behavior of all described components (envelope and HVAC system). The school modeling was performed by using the simulation software TRNSYS 17 [9], which employs a standard component library, validated by TRNSYS developers, in order to reproduce a large number of systems; these elements (well known as Types) can be combined and linked together within a graphical interface. TRNSYS has been employed by many researchers in past years within their studies, and they have reported the accuracy of results obtained by means of developed models with respect to measured data [6-7, 11].

In order to evaluate the building performance during the heating season and to estimate the energy saving potential related to heating system refurbishment, the school was simulated as a multizone building within TRNBUILD plug-in. According to the geometrical data reported in Table 1, the building model was developed by considering five different typologies of thermal zones, in order to take into account the variety of equipment, occupancy profile and thermal loads: classrooms, offices, corridors, toilets and the gym. Twenty-four different thermal zones were created in the model; as an example, layout, orientation and zoning of the school first floor are shown in Figure 2.

The building was simulated by using a simulation time step equal to 1 minute and by considering the standard heating season as simulation duration (i.e. from October 15th to April 15th, 183 days). The Typical Meteorological Year (TMY) that represents the climate of Bologna, included within TRNSYS weather data file, was employed as climatic input data. Most of the components included in the developed model are present within TRNSYS standard library, as the multi-zone building (Type 56), the differential controller with hysteresis (Type 2), the condensing boiler (Type 700), shading effect calculators (Type 34 and Type 67), pumps (Type 114) and radiators (Type 1231). On the other hand, new TRNSYS components were developed for the assessment of heating system renovation, as pointed out in the following sections.

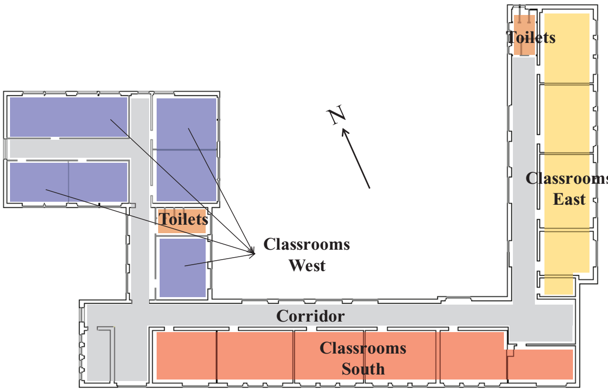

Fig. 2. Layout, orientation and zoning of the first floor of the school

3.2. Calculation of total energy need for space heating and assessment of indoor thermal comfort

The school energy consumption for space heating during the standard heating season was calculated. Specifically, the parameter used for the energy performance assessment was the Energy Performance Index for heating (EP_H), reported by Italian Standard UNI TS 11300-2 [12]: it is defined as the ratio between the total primary energy requirement for heating and the total net floor area of the building. Results point out a total energy need of 359146 kWh of primary energy during the heating season, corresponding to an EP_H value of 80.8 kWh/m^2. This value reflects the current operating conditions of the heating system (i.e. the working schedule reported in Section 2 and the absence of zone temperature control), and it is suitable for the analysis of the building energetic requalification proposal. On the contrary, a calculation performed under steady-state conditions, as the one imposed by law for building labeling, is not reliable for a correct energy saving evaluation: according to this procedure, the building energy needs are calculated by considering a constant internal temperature of 20°C and the heating system that works 24/7. In order to compare the school energy performance calculated via the dynamic and the steady-state approaches, a stationary model of the building was developed by employing EC-700 [13], a commercial software certified by the Italian Thermotechnical Committee (CTI). Results obtained under stationary conditions show an overall primary energy consumption for space heating equal to 749366 kWh, corresponding to an EP_H of 168.6 kWh/m^2. It is evident that the steady-state model overestimates the real building energy needs, according to a heating system that operates continuously. The use of the standard stationary model can be misleading in case of a feasibility study on a specific energy saving measure: the overestimation of total energy consumptions may cause the failure of the proposed business plan.

Finally, the analysis of school users thermal comfort during heating season was performed. The Predicted Mean Vote (PMV) and the Operative Temperature (T_{op}) were selected as reference indicators for thermal comfort assessment. According to UNI EN ISO 7730 [14], the reference indexes were calculated as a function of internal air temperature, humidity and mean radiant temperature. The air velocity was fixed equal to 0.2 m/s, while school occupants metabolic rate was estimated in 1.2 met (sedentary activity); a typical winter clothing (1 clo) for building users was assumed. The assessment of students thermal comfort was performed by considering the first floor of the school as a sample (see Figure 2): the bin distribution of operative temperature calculated for classrooms is reported in the following Figure 3. According to building orientation shown in Figure 2, classrooms located at the first floor of the school were divided into three groups, depending on their orientation. The first set of classrooms, named as "South" and represented by red columns, deals with rooms facing south (at the bottom of Figure 2), while data related to classrooms facing east and west (right and left side of Figure 2, respectively) are represented by yellow and blue columns, respectively.

It is evident from Figure 3 that operative temperature distribution has different trends within the considered groups of classrooms. The operative temperature calculated for South and East classrooms falls more frequently within the range 19-25°C; on the other hand, rooms facing west are characterized by a larger thermal discomfort: result points out that operative temperature falls below 17°C for about 40% of the school occupancy period. Worse results were obtained for West classrooms due to the low solar gains through the building envelope: the highest incident solar irradiation is reached in the afternoon, while lessons end at 16.

Such a discomfort condition is mainly caused by the heating system control strategy. As reported in Section 2, the control system consists of a climatic compensation coupled to a programmable thermostat; therefore, the building internal conditions are not monitored and the heating system follows the fixed set schedule described previously. To be noted that during idle night hours the internal temperature strongly decreases because of the poor quality of the building envelope; for that reason, a strong thermal discomfort is observed during the morning, due to low values of the operative temperature. School staff and students confirmed this evidence: interviews conducted during the survey of the building highlighted occupants complaints about high discomfort levels in the morning.

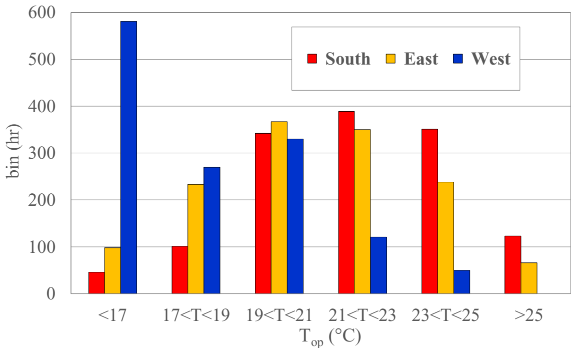

Fig. 3. Bin distribution of operative temperature for classrooms located in the first floor of the building

4. Heating system refurbishment

As reported before, the dynamic model of the school represents the best tool to perform a detailed analysis of an energy saving measure. For that reason, a strategy to improve the building energy performance was evaluated by means of the developed dynamic model. Specifically, a multi-compressor air-to-water heat pump was considered to satisfy energy requirements for space heating in place of actual condensing boilers. According to generators renovation, high-temperature radiators were replaced with low-temperature aluminum radiators and the heating system control strategy was improved. The retrofit proposal is focused on the heating system renovation rather than the building envelope refurbishment because the external insulation of the building envelope or the replacement of the windows are very expensive interventions, due to the large external area of the school and the large number of windows. Previous feasibility studies carried out on this building pointed out that the Pay Back Time for both envelope insulation and windows enhancement can be longer than 20 years.

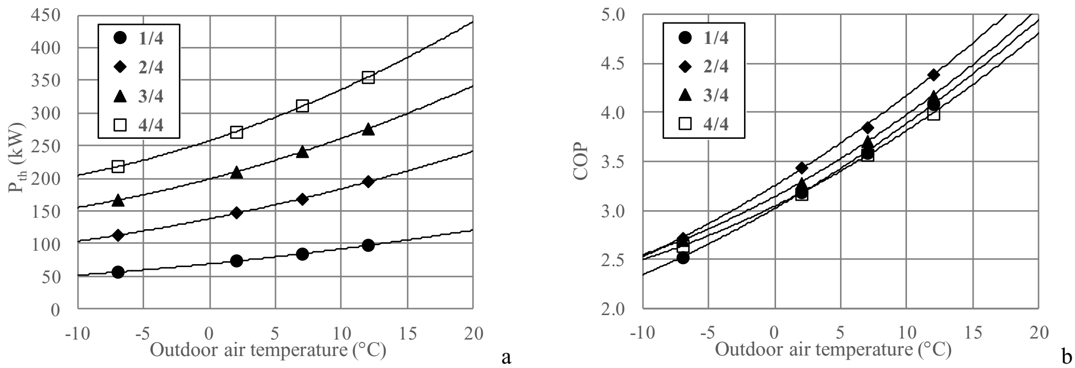

Fig. 4. Heating capacity (a) and COP (b) of the considered heat pump as a function of outdoor air temperature and number of working compressors

The selected heat pump employs R410A as refrigerant fluid and it consists of four on-off scroll compressors; heat pump rated performance at full load are the following: heating capacity and COP equal to 311.1 kW and 3.57, respectively (rated conditions: outdoor air temperature = 7°C and outlet water temperature = 45°C). Figure 4 shows heat pump heating capacity and COP data for several values of outdoor air temperature (-7, 2, 7, 12°C), by scaling from four to one working compressors; reported data are evaluated for a water outlet temperature fixed to 45°C and are given by the manufacturer. It is evident from Figure 4 that the heat pump is characterized by the best efficiency when it operates with two compressors switched on (i.e. 2/4 data series), within the whole air temperature range.

Several models of heat pumps were previously included by TRNSYS developers within the software standard library: air-to-air heat pump (Type 954), air-to-water heat pumps (Type 954) and water-to-water heat pumps (Type 919); unfortunately, the above-mentioned models reproduce single stage units only. In order to simulate a four-stage heat pump, a new component based on Type 941 (air source heat pump) was developed; this component evaluates the current thermal load required by the building and calculates the effective heating capacity of the heat pump, taking into account the temperature of heat pump heat sources (outdoor air and plant water) at each timestep. The developed heat pump model is able to calculate the effective performance of the unit at partial load and the obtained results are in perfect agreement with manufacturer data.

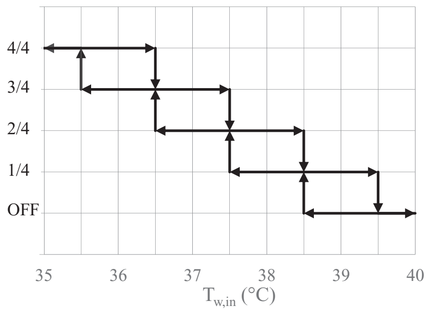

Fig. 5. Heat pump control system behavior

According to the development of the multi-compressor heat pump model, a new control strategy for the heating system was implemented within TRNSYS. Once fixed heat pump design operating conditions (for example outlet water temperature equal to 45°C), the control system of the unit employs the temperature of the water incoming the heat pump ($T_{w,in}$) as the monitoring variable: the number of compressors switched on during a certain timestep depends on the value of $T_{w,in}$. The control system of the heat pump was developed by means of the Type 970, that simulates a N-stage differential controller. The influence of the developed controller on heat pump behavior is reported in Figure 5: the control function that selects the number of working compressors is shown as a function of incoming water temperature. In order to evaluate the number of compressors that the heat pump has to switch on to match the required thermal load, the controller considers the number of working compressors at the previous timestep and compares the current value of $T_{w,in}$ with four fixed set-points (36°C, 37°C, 38°C and 39°C in Figure 5). Each temperature set-point is characterized by a 1 K centered dead-band that induces a hysteresis logic on the control signal, avoiding continuous fluctuations.

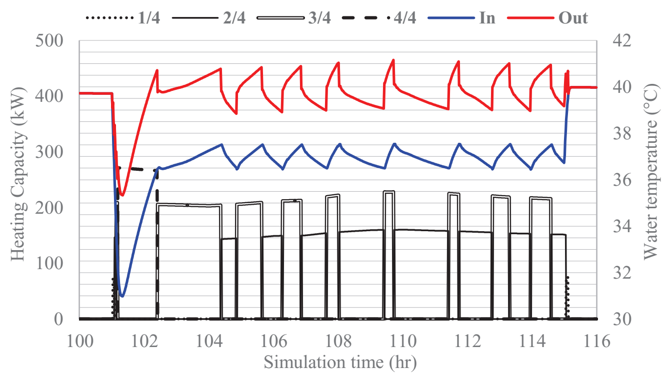

Fig. 6. Influence of control system on heat pump heating capacity and inlet/outlet water temperatures

An example of the effect of heat pump control system is shown in Figure 6: heat pump heating capacity and inlet/outlet water temperatures are reported as a function of simulation time. By observing Figure 6, the impact of the heat pump control strategy is evident: the average thermal load required by the building within the considered interval is about 180 kW and the heat pump operates alternately with two and three compressors switched on. A detailed overview of controller behavior is given by focusing within hours 110 and 112; in correspondence of hour 110, the heat pump operates with two active compressors, but the heating capacity of the unit is lower than the building thermal load, since incoming water temperature decreases with time. When $T_{w,in}$ drops below 36.5°C in correspondence of hour 111.4, the controller switches on a third compressor (see Figure 5) and the heating capacity increases over 200 kW. The delivered heating capacity is now higher than the required thermal load and $T_{w,in}$ rapidly increases: after about 20 minutes it exceeds 37.5°C and the controller switches off the third compressor. To be noted that the heat pump operates at full load (i.e. with four working compressors) only at the beginning of the considered interval, for about one hour. During night, the heat pump is switched off according to the set schedule and water temperature strongly decreases: in the morning, heat pump maximum heating capacity is required and the unit works at full load.

4.1. Analysis of renovated heating system performance

Due to the reasons reported previously, the dynamic model developed by using TRNSYS was employed in order to assess the impact of heating system refurbishment on school energy consumption and indoor thermal comfort. Results point out that the EP_H index decreases up to 43.6 kWh/m^2 after the retrofit of the heating system; this improvement provides a reduction of about 46% in the primary energy requirement for space heating. The considered heat pump is characterized by a Seasonal Coefficient of Performance (SCOP), which is defined as the ratio between the thermal energy provided by the heat pump and its electrical energy consumption, equal to 3.94. This result highlights the importance of heating system renovation on non-residential buildings: by improving the heating system, it is possible to achieve large energy and economic savings.

The dynamic model was finally employed to assess the effect of heating system renovation on thermal comfort conditions during winter. Relevant results are summarized in Figure 7 and Table 3.

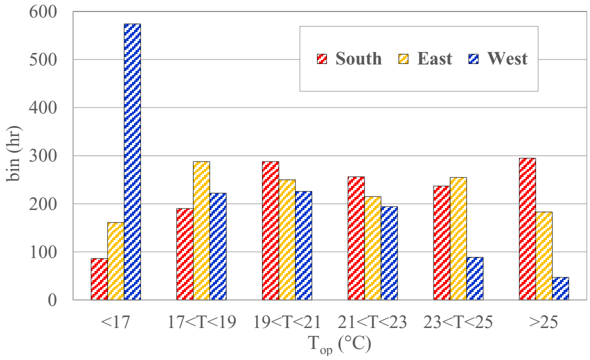

Fig. 7. Bin distribution of operative temperature for classrooms located in the first floor of the building after heating system refurbishment

Figure 7 reports the bin distribution of operative temperature within classrooms located at the first floor of the school, evaluated after the replacement of condensing boilers with the air-source heat pump. The comparison between Figure 7 and Figure 3 shows that the heating system refurbishment has no positive effects on indoor thermal comfort. Classrooms facing west present a slight improvement in indoor comfort conditions: the bin distribution of operative temperature is slightly shifted towards higher values. On the contrary, south and east oriented classrooms are characterized by worse comfort conditions: the operative temperature within these classrooms follows a flat trend and thermal comfort is obtained for only 20% of the heating season. To be noted that the discomfort condition caused by large values of operative temperature becomes relevant for classrooms facing south and east.

Table 3. Cumulative distribution in hours of PMV values before and after heating system refurbishment

	Before heating system refurbishment			After heating system refurbishment		
Orientation	South	East	West	South	East	West
PMV<-1	118	254	800	231	191	764
PMV<-0.5	464	701	1186	560	701	1025
-0.5<PMV<0.5	817	607	166	582	528	290
PMV>0.5	71	44	0	210	123	37
PMV>1	0	0	0	52	50	0

The different control strategy of the renovated heating system is the main cause of operative temperature trends reported previously. Actual control system affects the supply water temperature according to a climatic compensation; for this reason, the impact of control strategy on energy consumption and thermal comfort is more relevant during intermediate seasons, when external climate is milder. Since outdoor temperature increases, supply water temperature decreases by following a linear correlation; radiators reduce their thermal emission and it is possible to avoid classrooms excessive overheating. On the other hand, the multi-compressor heat pump operates by following the design supply water temperature: when the building thermal load becomes lower, the temperature of supply water only slightly decreases and indoor thermal comfort worsens because of classrooms overheating.

The cumulative distribution of PMV across the three reference classrooms confirms the negative impact of heating system refurbishment on indoor thermal comfort. Values reported in Table 3 show that before heating system retrofit, indoor thermal comfort is ensured (i.e. -0.5<PMV<0.5) for about 60%, 45% and 12% of heating season for South, East and West classrooms, respectively. PMV values lower than -0.5 were calculated for more than 1100 hours for West classrooms, while PMVs above 0.5 were calculated during few hours. The impact of heating system retrofit is relevant, since a strongly reduction of comfortable hours can be noted: PMV values within (-0.5; 0.5) range were evaluated for 43%, 39% and 21% of the heating season duration. Furthermore, one can observe that classrooms overheating becomes significant for zones facing south and east.

5. Conclusions

This paper deals with the energy performance assessment of an educational building located in Modena, Italy. The school consists of a four-storey structure and it is characterized by a poor quality envelope. Space heating is provided by a traditional hydronic heating system, composed by condensing boilers coupled to high-temperature radiators. The investigation of building energy performance was performed under dynamic conditions: the school was simulated as a multizone building by means of the dynamic software TRNSYS 17. The developed dynamic model was employed in order to evaluate the actual energy requirement for space heating and to assess indoor thermal comfort of students.

The paper highlights the impact of the heating system refurbishment on the reduction of school energy consumption: condensing boilers were replaced by a four-compressor air-to-water heat pump and the plant control strategy was improved, too. TRNSYS standard component library does not include a multi-compressor air-source heat pump; for that reason, a new component that simulates the behavior of a multi-stage air-to-water heat pump was developed. The implemented component calculates heat pump performance at partial load, taking into account the influence of heat source temperatures (outdoor air and plant water) on heating capacity and COP of the unit. The heat pump control strategy is based on the temperature of incoming water: a differential controller monitors that temperature and the unit is able to fix the required building thermal load by activating the correct number of compressors. Results point out that the air-source heat pump can be a suitable technology to enhance building energy performance: the primary energy need of the school during the heating season decreases of about 46%.

The assessment of indoor thermal comfort highlights the influence of heating system control strategy on indoor conditions. The lack of temperature control within the building affects the system capacity to ensure high thermal comfort for students: a fixed set schedule for the system, characterized by idle hours during unoccupied periods, causes a strong decrease of operative temperature during morning and it induces high discomfort level. On the other hand, the adoption of a climatic control on supply water temperature is very useful to avoid an excessive overheating within classrooms, especially during milder seasons.

References

[1] D. Cortés-Borda, A. Ruiz-Hernández, G.Guillén-Gosálbez, M. Llop, R. Guimerà, M. Sales-Pardo, Identifying strategies for mitigating the global warming impact of the EU-25 economy using a multi-objective input-output approach, Energy Policy 77, (2015) 21-30.

[2] European Parliament, Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings, Official Journal of the European Union 1 (2003) 65-71.

[3] European Parliament, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, Official Journal of the European Union 53 (2010) 13–35.

[4] European Parliament, Directive 2012/27/UE of The European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC, Official Journal of the European Union 55 (2012) 1–56.

[5] Ministero dell'Istruzione, dell'Università e della Ricarca, Anagrafe dell'Edilizia Scolastica, Rome, August 2015.

[6] A. Genco, A. Viggiano, G. Rospi, N. Cardinale, V. Magi, Dynamic modeling and simulation of buildings energy performance based on different climatic conditions, International Journal of Heat and Technology 33 (2015) 107-116.

[7] F. Calise, thermoeconomic analysis and optimization of high efficiency solar heating and cooling systems for different Italian school buildings and climates, Energy and Buildings 42 (2010) 992-1003.

[8] F. Ascione, N. Bianco, R. F. De Masi, F. De'Rossi, G. P. Vanoli, Energy retrofit of an educational building in the ancient center of Benevento. Feasibility study of energy savings and respect of the historical value, Energy and Buildings 95 (2015) 172-183.

[9] S. A. Klein et al, TRNSYS 17: A Transient System Simulation Program, Solar Energy Laboratory, University of Wisconsin, Madison, USA, (2010).

[10] Italian Parliament, Legge ordinaria del Parlamento n° 373 del 30/04/1976 "Norme per il contenimento del consume energetic per usi termici negli edifice, Gazzetta Ufficiale Italiana 148 (1976).

[11] C. Romeo, M. Zinzi, Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study, Energy and Buildings 67 (2013) 647-657.

[12] Italian standard UNI/TS 11300 1-2-3-4: Energy performance of buildings, (2010-2014).

[13] Edilclima. Termotecnica-Energetica: EC 700 [computer software]. Retrieved 07.07.13, from ⟨http://www.edilclima.it⟩.

[14] European standard UNI EN ISO 7730 -2006, Ergonomics of the thermal environment. Analytical determination and interpretation of the thermal comfort using calculation of the PMV and PPD indexes and local thermal comfort criteria, (2006).