2014

On the Energy Performance Design of a Skilled Nursing Facility Building

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Curculacos, Giovanni; Turchetto, Gianluca; Mazzali, Ugo; Peron, Fabio; Romagnoni, Piercarlo; Cappelletti, Francesca; Bauman, Fred; and Scarpa, Massimiliano, "On the Energy Performance Design of a Skilled Nursing Facility Building" (2014). *International High Performance Buildings Conference.* Paper 119.
http://docs.lib.purdue.edu/ihpbc/119

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On the Energy Performance Design of a Skilled Nursing Facility Building

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ABSTRACT

In Europe, the criteria for designing new buildings are regulated by a set of European Directives and national laws having as a goal the creation of net zero energy buildings by the year 2020. Moreover, according to 2010/31/EU Directive after 31 December 2018, new buildings occupied and owned by public authorities must be nearly zero-energy buildings. The low energy consumption must be accompanied by well-defined thermal characteristics of the building envelope (both opaque and transparent components) and HVAC systems, and must ensure acceptable internal thermal comfort conditions.

An interesting case study, proposed in this work, is represented by the elderly nursing building "RelaXXI" which hosts dependent people who require 24-hour special assistance and medical care. Designers focused on the indoor environmental quality as the main goal of the project and the HVAC system has been designed pursuing the maximum integration with the building and its architecture.

The aims of this paper are to (1) describe the main design characteristics of the RelaXXI building, (2) analyze the results obtained by dynamic simulation of heating and cooling energy demands, and (3) present the results of performance monitoring completed to date.

1. INTRODUCTION

Buildings account for 40 % of total energy consumption in the European Union (Directive 2010/31/EU). The sector is expanding, which is bound to increase its energy consumption. Therefore, reduction of energy consumption and the use of energy from renewable sources in the building sector constitute important measures needed to reduce the Union's energy dependency and greenhouse gas emissions. Together with an increased use of energy from renewable sources, measures taken to reduce energy consumption in the European Union would allow the Union to comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), and to achieve its commitment to reduce, by 2020, overall greenhouse gas emissions by at least 20 % below 1990 levels, and by 30 % in the event of an international agreement being reached. Italy approved several decrees in order to make the application of the European Directives since 2005, when the regulations required by the previous European Directive 2002/91/EC (Directive 2002/91/CE) entered into force. During the last 10 years the new Italian buildings are characterized therefore by significantly reduced energy use achieved with a high-quality envelope and excellent performance of the HVAC system. In buildings, the energy used for cooling and heating systems accounts for a substantial part of the total energy consumption. In the proposed case study, the considerations relating to the energy performance of the building are complicated by the designated building use and occupancy (it is an elderly nursing home): the indoor environmental quality is required 24/7. As a consequence, HVAC system choice shall take into account the IEQ requirements and the primary energy level shall accomplish the National and European standards.

Based on these considerations, the building design, the logic of the operation, management and control of the HVAC system shall be carefully examined; moreover the maintenance of the building will be carefully planned. Measurements of energy use and peak demand through collection of the utility bills and collection of basic building characteristics are the foundation for better understanding building performances (ASHRAE, 2012). The adoption of a protocol for energy measurement can help to verify the building performance, the functioning mode of thermal plant and can provide an opportunity to identify potential improvements.

The aim of this paper is to describe the main design characteristics of the new building, to analyze the results obtained by dynamic simulation of the energy performance of the building.

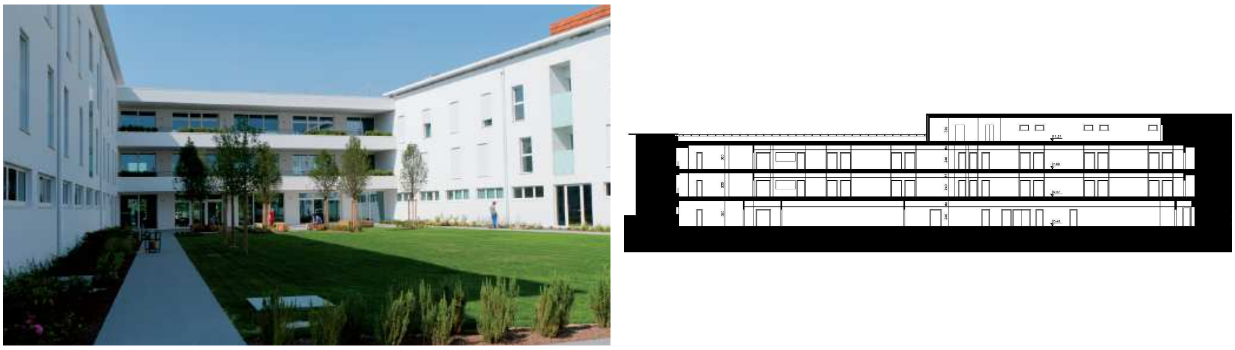
2. THE BUILDING

2.1 The building envelope characteristics

The RelaXXI building is located in Noale (a little town 20 km away from Venezia, Italy), in Northern Italy in typical humid subtropical climate Cfa, according to Köppen climate classification. It is a skilled nursing facility designed to house 160 elderly residents who require 24-hour special assistance and medical care. The building configuration is a U-Shaped, 3-story building, as shown in **Figure 1**. The area of each floor is about 7400 m^2 and the conditioned volume is 23,680 m^3.

The ground floor hosts the main public activities such as offices, kitchen, gym and ambulatories. The East and West wings of the second and third floors contain the patient rooms, a large central living room and two dining rooms (one per wing). Each patient room is provided with a toilet.

The main thermal parameters of the building envelope are listed in Table 1.



a) b)

Figure 1: The RelaXXI building: a) External view, b) Section view

Table 1: Main thermal parameters of the building envelope

Category	Specification	U-Value [W/(m^2 K)]	Optical parameters	
			SHGC [-]	τ_{Vis} [-]
Opaque constructions	Slab-on-grade floor	0.29	-	-
	External wall	0.23	-	-
	Roof	0.18	-	-
Windows	Glass	0.6	0.43	0.66
	Frame	1.3	-	-

2.2 The HVAC system

One of the possible technical solutions for buildings that contribute to a reduction of the energy consumption is an active chilled beam system (Loudermilk, 2009), (Afshari *et al*.,2009), (Alexander and O'Rourke, 2008), (REHVA, 2007), (Roth *et al*., 2007). Actually this system, if correctly designed and installed, can reduce energy consumption and can provide a comfortable indoor climate with low acoustic signatures.

Although active chilled beams are an in-room space conditioning device, they are also the room air diffusion device, so sizing and locating the beams is vital to providing acceptable levels of occupant thermal comfort as established by thermal comfort standards, such as ASHRAE 55 (ASHRAE, 2013). A chilled beam system can be an effective method for providing cooling and heating to a space while promoting a high level of occupant comfort and energy efficiency. The system integrates hydronic cooling and heating with the primary ventilation system. The enhanced heat capacity of water reduces the required transport energy in comparison to all-air systems, resulting in a reduction in fan energy use. A dedicated outdoor air system (DOAS) delivers the required minimum ventilation airflow quantity along with any required dehumidification. This hybrid air/water system allows primary airflow rates to be reduced while also providing high indoor air quality due to the 100% outdoor air system.

Active chilled beams can be selected to remove large amounts of sensible heat while substantially reducing primary airflow requirements. However, this must be done with consideration of the occupant thermal comfort and space dehumidification. While primary airflow reduction opportunities are an inherent characteristic of chilled beams, the reduction of such should be limited to that required to provide adequate space humidity control. All-air systems almost always deliver a sufficient amount of dry air to satisfy the space sensible load; therefore, engineers often do not consider space latent loads in their selection. Individual space latent loads should be considered when designing chilled beam systems.

The main items and characteristics of the HVAC system are described in the following list:

- 2 multifunctional air-to-water heat pumps:
  - Nominal cooling capacities: 340 kW and 235 kW with COP of 2.94 and 2.96, respectively
  - Nominal heating capacities: 264 kW and 176 kW with COP of 2.96 and 3.24, respectively
- 1 Gas condensing boiler: to meet peak loads and for recovery purposes
- Photovoltaic system:
  - Total installed nominal capacity: 95 kWp
  - Placed on the roof
- Air loop:
  - 3 air handling units whose main characteristics are listed in **Table 2**.
  - Heat exchangers in the air handling units of the West and East wings:
    - Rotary air-to-air enthalpy wheels
    - Heat recovery efficiency: sensible 71%, latent 65%
  - Each floor is equipped with 4 VAV boxes, two per wing.
  - In winter, according to field surveys, VAV boxes supply into the room two levels of air flow rates, manually scheduled: 2700 m^3/h per VAV box during the day and 600 m^3/h per VAV box during the night.
- HVAC terminal units: 4-pipe constant flow active chilled beams, with air induction ratio equal to 3
- Shading control:
  - In patient rooms, on the external side of the windows, acting on the upper half section
  - Reference external maximum level of light: 30000 lux measured on an horizontal surface with an external light sensor placed on the roof

Table 2: Main characteristics of the installed air handling units

	Supply Air Flow Rate [m^3/h]	Exhaust Air Flow Rate [m^3/h]	Supply Fan Pressure Head [Pa]	Return Fan Pressure Head [Pa]	Supply Fan Power [kW]	Return Fan Power [kW]
East Wing AHU	17000	15300	800	800	13.7	7.3
West wing AHU	13000	11700	800	800	9.5	5.5
Kitchen AHU	8000	-	500	-	3.7	-

3. METHODS

Two simulation methods are compared in the frame of this paper:

- A detailed method based on dynamic building energy simulation tool EnergyPlus
- A quasi-steady state method aimed at energy certification in Italy.

In the following subsections detailed information about the simulation procedures is provided.

3.1 Climatic data

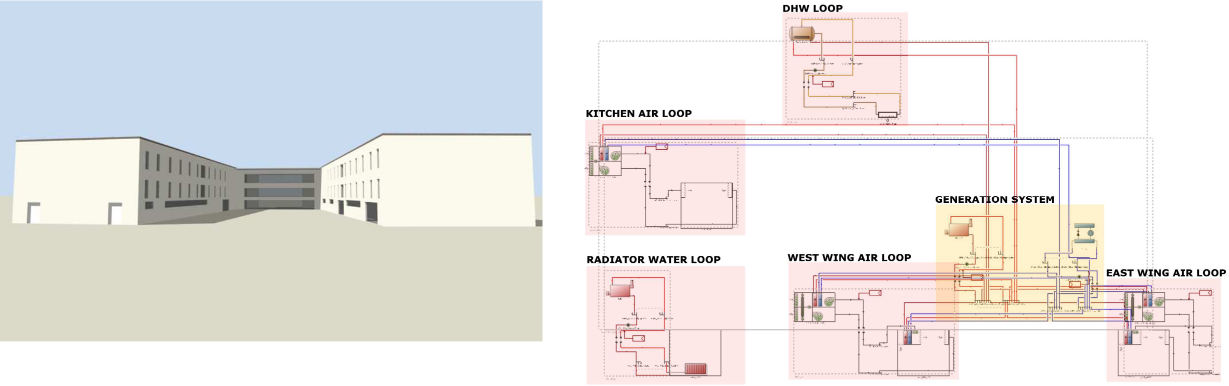
The test reference year of the nearest weather station (Treviso) was used for the analysis annual behavior of the building and HVAC system. For the comparison with measured data, an hourly weather data file was prepared starting from real weather data collected during the first months of 2014, from January to March.

3.2 Detailed simulation model

The RelaXXI building consists of 290 rooms: 64 on the ground floor, 113 on the first floor and 113 on the second floor. For building energy simulation purposes, the rooms mentioned above were grouped into thermal zones, basing on thermal loads and HVAC system analogies. Overall, 57 thermal zones were considered. The following basic principles of thermal zoning were observed:

- Same setpoint temperatures
- Same window orientation
- Thermal zones have window area equal to the sum of the window areas of the pertaining rooms
- Thermal zones have floor area equal to the sum of the floor areas of the pertaining rooms
- Similar HVAC terminal units
- Similar internal loads

The simulation model was achieved through DesignBuilder (envelope and first draft of the HVAC system) and EnergyPlus (fine tuning of the simulation) simulation tools. The modelled geometry and HVAC system are shown in **Figure 2**.



a) b)

Figure 2: The simulation model: a) envelope; b) HVAC system

Three main kinds of terminal units were identified and associated to the related thermal zones:

- Direct air terminal units: kitchen
- Radiators: toilets
- Active beams: all other zones

In order to provide the full simulation of the actual control system and heat pump performance, the heating/cooling generators in the EnergyPlus simulation consist of District Heating and District Cooling, in order to get the heating /cooling loads to be met by the actual multifunctional heat pumps, fully simulated by means of a post-processing model. The characteristics of the simulated air loops are briefly summarized as follows.

Table 2 - Main characteristics of the simulated air loops

	Supply Design Volume Flow Rate [m^3/s]	Heating coil [Yes/No]	Cooling coil [Yes/No]	Supply|Return fans [Yes/No|Yes/No]	Heat recovery [Yes/No]
Kitchen	2.22	Yes	Yes	Yes|No	No
West wing	4.7	Yes	Yes	Yes|Yes	Yes
East wing	3.6	Yes	Yes	Yes|Yes	Yes

Two water loops were simulated:

  - High temperature water loop serving the radiators installed in the toilet zone. A gas-fired boiler system provides the related heating energy.
  - Heating/cooling water loop supplying hot/chilled water to the AHUs and active beams.

As far as Domestic Hot Water (DHW) is concerned, a DHW loop was modelled, considering a daily water need of 90 l/day per bedroom, with a 25 K temperature difference between supply and return and arranged into 3 main supply periods:

- two hours in the morning
- two hours in the afternoon
- two hours in the evening.

The resulting maximum hot water flow rate is 1000 l/h.

Active beams were modelled in detail by means of one EnergyPlus object Four Pipe: Induction Unit per room, providing the sum of supply air flow rates designed for each room included in the thermal zone.

Finally, the generation system was considered in detail in a post-processing calculation procedure. The COP and EER of the two multifunctional heat pumps were calculated in detail at specific part load and operating conditions. The information provided by the manufacturer has been inherent to the capacities and efficiencies with reference to both units and at the conditions specified below:

- Heat pump air-to-water running; technological water produced at +45°C:
  - External air from -5°C to 25°C step 5°C and full load (4 compressors on)
  - External air +5°C and load at 75% (3 compressors on)
  - External air +5°C and load at 50% (2 compressors on)
  - External air +5°C and load at 25% (1 compressor on)
- Chiller air-to-water running; technological water produced at +8°C:
  - External air from +15°C to +35°C step 5°C and full load (4 compressors on)
  - External air +35°C and load at 75% (3 compressors on)
  - External air +35°C and load at 50% (2 compressors on)
  - External air +35°C and load at 25% (1 compressor on)
- Multifunctional water-to-water running; technological heating water produced at +45°C and cooling water produced at +8°C simultaneously and full load.

The variation of the performances on the outside temperature has been successfully approximated by mean of polynomials of third or fourth order; the coefficients have been obtained by approximation to the Weighted Least Squares.

According to design data and field surveys, actual annual heating and cooling setpoints were considered in the simulation. A summary of the main setpoint and setback temperatures, during the whole year, is reported in **Table 3**.

Table 3 – Heating and cooling setpoint temperatures

	Locker Room	Patient Room	Church, Gym, Ambulatories, Dining, Living	Toilets	Office Room	Entrance Hall
Heating setpoint temperature [°C]	24	20	22	20	23	23
Cooling setpoint temperature temperature [°C]	28	25	26	20	26	28

The internal heat gains considered in the simulation are listed below:

- Occupancy:
  - Patient rooms: 2 people per room
  - Other rooms: set according to field surveys
- Lights:
  - Patient rooms: 1.6 W/m^2, from 7:00 to 9:00, from 13:30 to 15:00 and from 20:30 to 21:00
  - Toilets: 8.5 W/m^2, from 7:00 to 8:00, from 13:00 to 14:00, and from 21:00 to 22:00
  - Kitchen: 12.5 W/m^2, from 7:00 to 16:00 and from 18:00 to 21:00
  - Office: 9.4 W/m^2, from 9:00 to 13:00 and from 14:00 to 18:00
  - Emergency lights: always on, 24 hours per day
- Plug loads:

- Kitchen: 50 W/m^2, due to washing machinery, microwave ovens and other typical kitchen equipment used during the day, measured during the energy monitoring campaign currently in progress
- Offices: 5 W/m^2

3.3 Quasi steady state simulation model

A Quasi-steady state model was used for preliminary assessments. The building was modeled as one single thermal zone. The simulations were performed using, as outdoor conditions, hourly monthly average conditions as proposed by Italian National Research Council (CNR, 1982). A simple computer code using the transfer function method (McQuiston *et al.*, 1992) was adopted for calculation; 24-hour profile for a design day are considered as sinusoidal functions. The internal loads are evaluated on the whole internal floor area; the scheduling is defined hour by hour. The hourly performance of cooling equipment is evaluated by means of its efficiency as a function of the refrigerant temperatures. The various operating conditions have been calculated according to the relations published in (Cavallini, 1995):

$$\text{Heating mode: } \frac{\dfrac{\partial\, COP}{\partial\, T_{ev}}}{COP} \approx \frac{\dfrac{\partial\, COP_{Carnot}}{\partial\, T_{ev}}}{COP_{Carnot}}\; ; \qquad \text{Cooling mode: } \frac{\dfrac{\partial\, EER}{\partial\, T_{cond}}}{EER} \approx \frac{\dfrac{\partial\, EER_{Carnot}}{\partial\, T_{cond}}}{EER_{Carnot}}$$

The approximations specified above are acceptable within a limited range of temperature referring to the standard conditions (i.e. ± 5 ° C) (Scarpa, 2010). However, the approximation has been extended to the whole range of expected operation conditions.

4. RESULTS AND DISCUSSION

In the following sections the results of the two simulation models are presented. A first comparison against field measurements is shown as well.

4.1 Quasi steady state method results

Using the load profiles of the building and the hourly performance curves of the equipment, it was possible to calculate the hourly energy consumption profiles and, as a consequence, the whole energy consumption.

- Energy consumption for air conditioning and hot water production: 458073 kWh$_{el}$ / year
- Energy consumption for lighting services: 210912 kWh$_{el}$ / year
- Natural gas consumption for air conditioning and DHW: 14492 Nm³ / year

Figure 3a and 3b show the thermal capacity variation for typical days in January and July

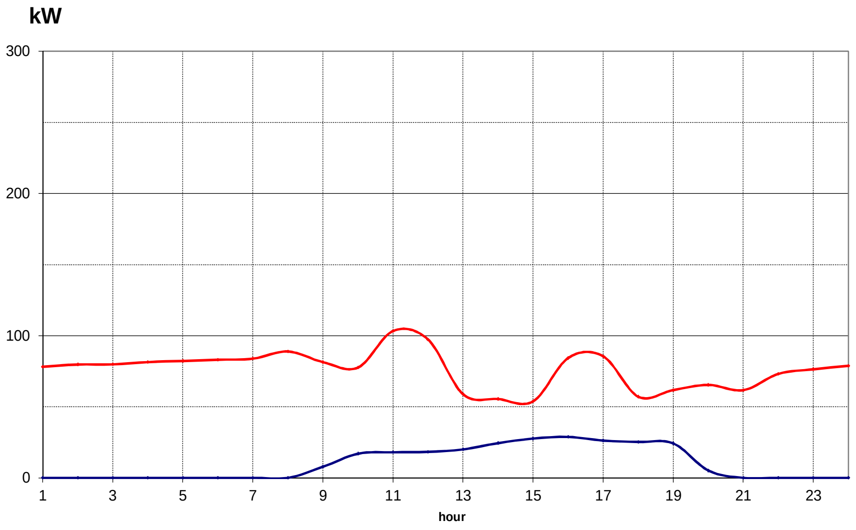


Figure 3a: Thermal capacity (red line = heating; blue line = cooling) variations during a typical day in January.

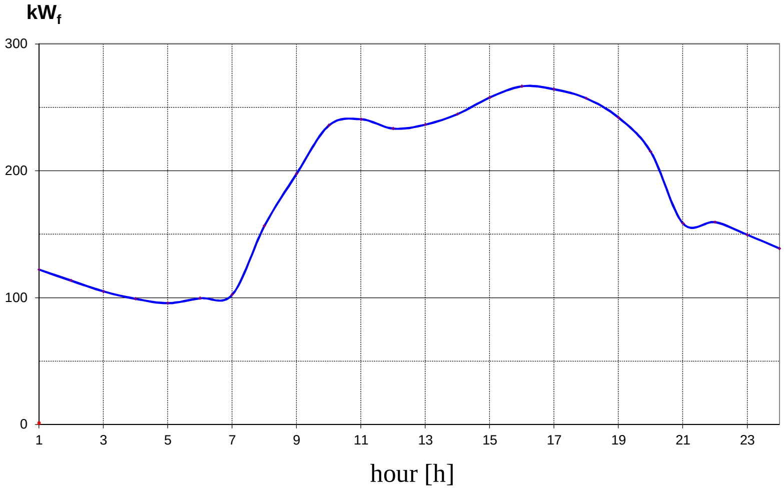
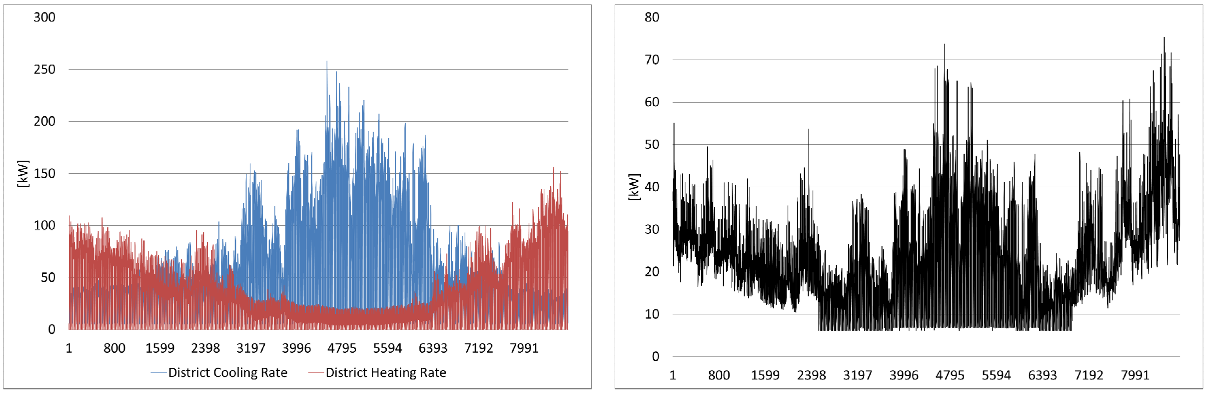


Figure 3b: Thermal capacity variation during a typical day in July

4.2 Dynamic simulation results

A first simulation performed in the frame of this work analyzed the building energy consumption related to design conditions in which multifunctional heat pumps are always on and provide heating or cooling according to the building demand, no matter what the season is. Resulting hourly thermal capacity and electricity power are visible in Figure 4. The district heating and cooling capacity visible in **Figure 4a** represents the ideal heating and cooling need of the building, this value doesn't account for HVAC plant and multifunctional heat pumps efficiencies. Introducing the heat pump characteristics by means of the calculation and assumptions explained above, the electricity use of the whole HVAC system can be estimated and it is visible in **Figure 4b**. Peak hourly values of around 70 kW are visible for the winter period at the end of the year. Peak hourly values of around 70 kW are visible for the summer period. As it is possible to see a minimum value of 6 kW is maintained along the summer period due to multifunctional fans. The total simulated annual energy demand for the HVAC system is around 203 MWh/year corresponding to an energy performance indicator equal to 33 kWh/m^2 year.

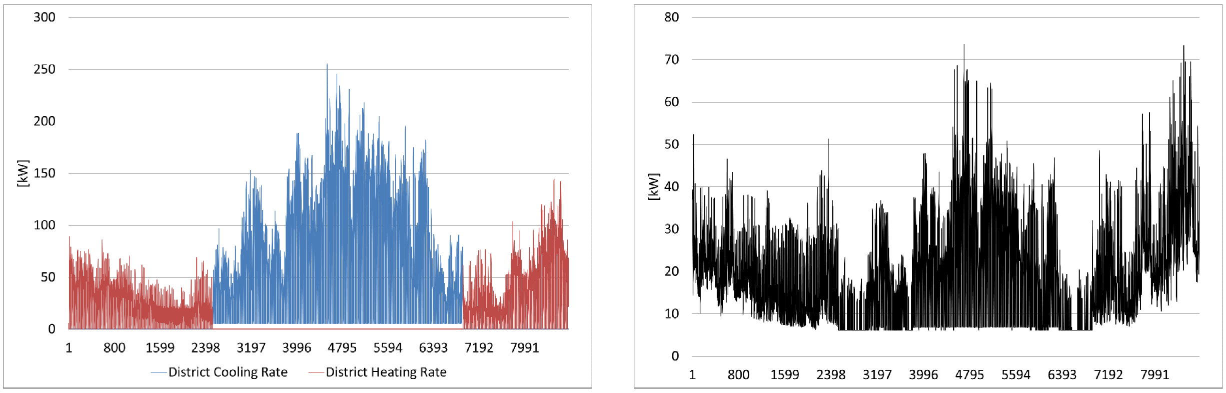


a) b)

Figure 4: Hourly Capacity during the whole year. a) District heating and district cooling energy demand, b) Multifunctional heat pump demand

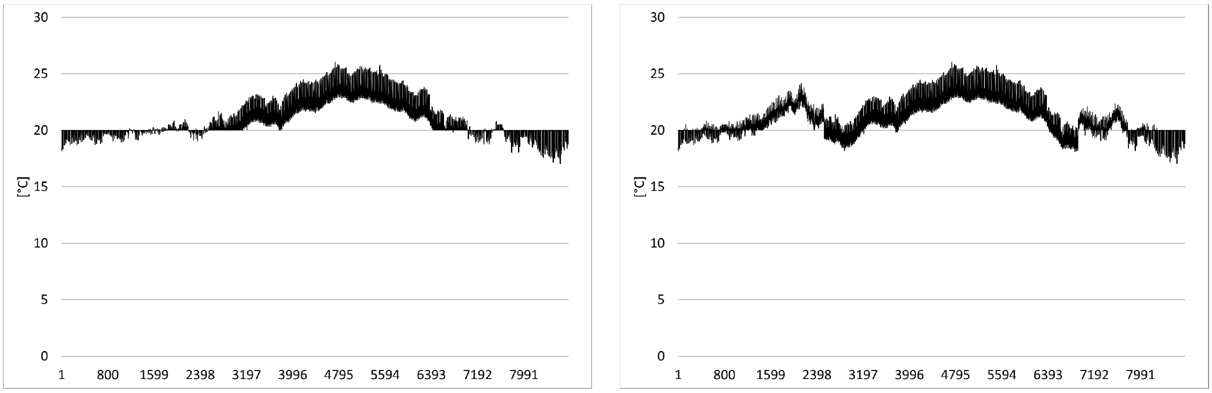
A more realistic behavior of the building is shown in Figure 5. The heating plant is considered off during the summer season and the cooling plant is considered off during the winter period. This behavior is consistent with actual building usage as revealed by the field surveys. Peak values are very similar to the first session of simulations (always on), but the total energy demand along the whole year is reduced to 175 MWh/year (28 kWh/(m^2 year)).

However, even under these operating conditions, the room occupancy comfort must be preserved. In regard to this, Figure 6, reporting the calculated air temperature of a reference patient room at the second floor, shows that comfort conditions are maintained in both cases.



a) b)

Figure 5: Hourly profiles of heating/cooling capacities (a) and HVAC electricity consumption (b) during the whole year, in case of heating and cooling are available only in winter and summer respectively.



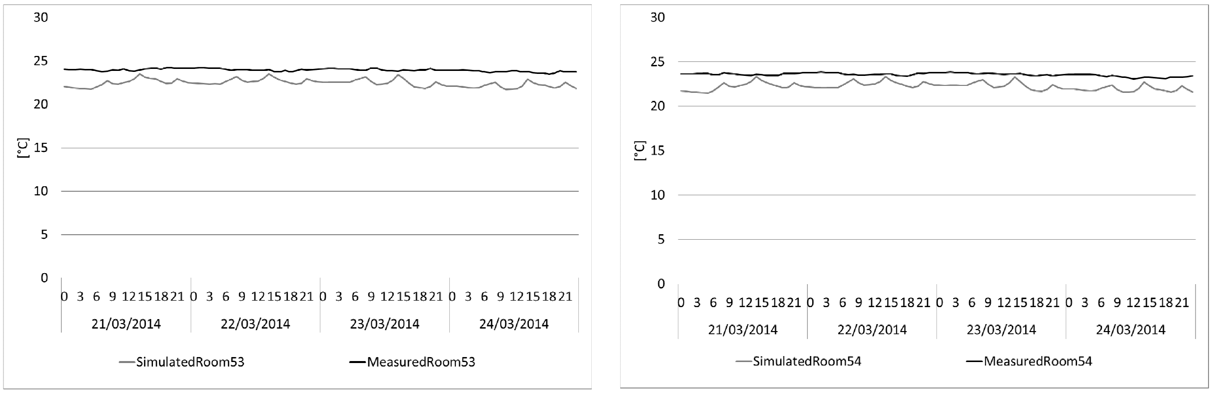
a) b)

Figure 6: Indoor air temperatures for the assessment of comfort acceptability in case of heating/cooling always available (a) and heating and cooling available only in winter and summer (b), respectively.

The photovoltaic system (nominal capacity: 95 kWp) installed on the building provides about 95 MWh/year of electricity production, contributing to lower the specific electric energy needs for heating/cooling down to about 13 kWh/m^2 year, which is a very good energy demand considering this particular kind of building, approaching the Near Zero Energy Building definition of 2010/31/EU Directive (Directive 2010/31/EU).

4.3 First simulation comparison against measured data

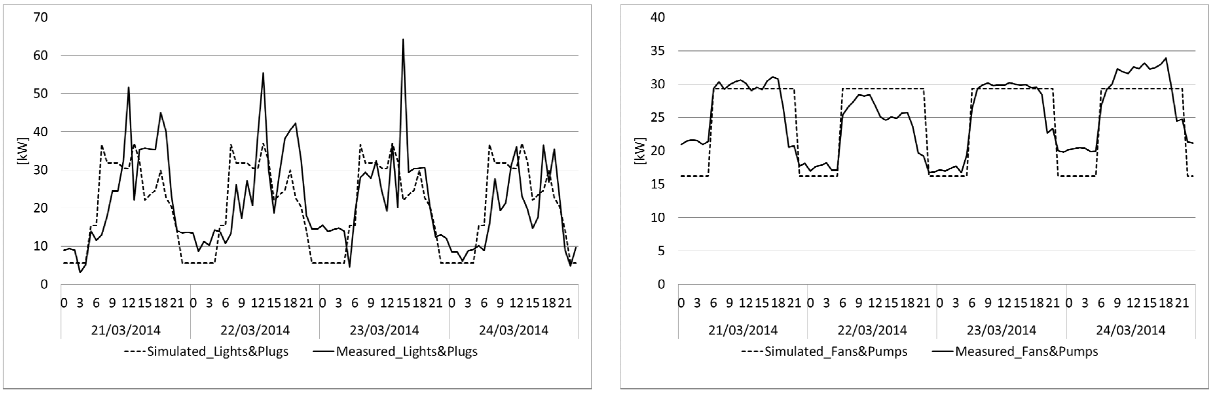
The electric energy monitoring of the facility is currently in progress, thus the first comparisons between simulation results and monitored values can be performed. For this purpose we refer to the period between March 20th and March 25th, 2014. In particular, measured room air temperatures are compared against the simulated ones, with reference to two differently exposed representative rooms. Figure 7 shows that largest differences in room air temperatures are around 2 K. However, in both cases the room air temperature is properly controlled between the heating and cooling setpoint temperatures equal to 20°C and 25°C, respectively.



a) b)

Figure 7: Simulated vs. measured indoor air temperatures: a) Second floor, East room, b) Second floor, West room

More comparisons were carried out about internal loads and auxiliary devices such as pumps and fans. **Figure a** represents the first comparison of internal loads of measured lights and plugs against the simulated ones. The general behavior of such loads is followed. Some electricity consumption peak values around 12:00, 13:00 and 15:00 are under investigation and they are probably due to some kitchen equipment activation. **Figure b** shows good correspondence in the comparison of the measured values of electric energy consumptions of water pumps and AHUs fans against the simulated ones. In the current HVAC system management, the air flow rates are manually controlled and probably the amount of outdoor air must be aligned according to manual variations, in order to get a better accuracy in the simulation results.



a) b)

Figure 8 - Simulated vs. Measured electric consumptions of lights and plug loads (a) and fans and pumps (b)

5. CONCLUSIONS

For a large building energy design, quasi-state simulations allow for a first evaluation of the building and HVAC system behavior, i.e. if heating and cooling loads are satisfied by the designed equipment and if heating and cooling loads are needed at the same time. Dynamic simulations allowed a more detailed description of the building and HVAC system.

First detailed simulation results seem to highlight an intensive use of cooling equipment and critical electrical energy consumption even if the specific values of total energy demand are acceptable. Indoor comfort temperatures seem to be in line with the design data. Future simulations shall try to analyze the indoor air humidity variation and the IAQ. However, the data obtained from the field measurements provides evidence of the necessity for a better comprehension of HVAC management system operating mode. If a good correspondence in the comparison of the measured values of electric energy consumptions of water pumps and AHUs fans against the simulated ones has been obtained, some peak values of electric energy consumptions aren't justified by the time scheduling of lighting and equipment.

The most important aim of this work will provide important feedback for validation of model inputs; and, once validated, will allow the model to be used to assess the sensitivity of the system to various parameters related to controls (set points, dead bands) and operation, with a view to monitoring the performance on the field too often neglected.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Mauro Cazzaro, Attilio Scudiero Franco Bressan for supporting this research project with funds, time, and technical competence.

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