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Energy refurbishment of a University building in cold Italian backcountry. Part 1: Audit and calibration of the numerical model

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Abstract

The study provides a methodological approach for designing energy refurbishment measures of buildings, enabling to understand the uncertainty of using numerical modelling and the real impacts due of adopting some energy efficiency technologies. The case study is a University building of the centre of Italy, and the reference scenario has been supported by various in-situ surveys, investigations and evaluations of the indoor comfort. Collected data, together with a comparison with energy bills, has allowed a proper calibration of a numerical model simulated by means EnergyPlus. All this phase is described in this paper, while a second part will discuss the energy retrofit and the building energy optimization.

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Keywords: Energy audit; Energy simulation; Modelling calibration; Energy saving; Occupant behaviour; University building.

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1. Introduction

The refurbishment of public buildings is one of key factor of energy efficiency policy of European States. In this context, the recent literature has focused mostly on the economic viability of the energy retrofit in buildings [1]. Bonomolo *et al*. [2], by applying the cost-optimal methodology, have selected the best retrofit actions for lighting systems for two existing educational buildings. Regnier *et al*. [3] have quantified the benefits of the Integrated System retrofit approach. Hong *et al*. [4] have presented an energy retrofit analysis toolkit which calculates the energy use of a building, by providing three levels of retrofit analysis related to the user background and the degree of the input data. Moreover, Sesana *et al*. [5], for the energy refurbishment of two university campuses in Milan, have presented an overview in retrofitting approaches for educational communities. Several studies proposed the energy retrofit of existing buildings, but often, not accurate or calibrated models are used to estimate energy performances of buildings. Really, when the aim is the evaluation of refurbishment measures, the energy audit must to be realized and a simulation model must be built and calibrated basing on experimental data. About this matter, Hassouneh *et al*. [6] used energy audit to reduce energy consumption of an existing building and Lo Cascio *et al*. [7] implemented and validated a simulation building model based on information from energy audit. Ascione *et al*. [8], to investigate the performance of historical buildings, carried out detailed energy diagnoses by means of in situ test and surveys. Also, Synnefa *et al*. [9], to describe an energy efficient retrofit, developed and validated a model by using a set of experimental data. In the same vein, Liu *et al*. [10], by using a real building as case study, shown that the actual energy saving of retrofit projects are lower than the expected values. Analogously, Webb *et al*. [11] found that the occupant behavior can offset energy saving from physical retrofit in both positive and negative ways. Rodrigues *et al*. [12] performed an integrated (cost, environmental and energy) life-cycle assessment, to assess the performance of buildings retrofit strategies, by assuming different occupancy patterns, defined by type of use (residential and office) and occupancy schedules (low and high occupancy level). Also, Ganic Saglam *et al*. [13] presented a cost-optimal approach for a building retrofit, which includes the occupants' behaviour effect. Finally, Sun *et al*. [14] introduced a simulation framework to quantify the impact of occupant behaviours on energy saving.

In general, main critical issues concerning the building energy modelling are: a) adoption of old or standardized weather data; b) building envelope is described without a deep investigation on materials; c) nominal values for HVAC performance parameters; d) occupancy schedules, internal loads and interaction of the occupants with components like windows or plant systems are described with deterministic schedules. Data about occupant behaviour represent some of the largest variables during the energy modelling. This problem is surely difficult to examine and to solve. Indeed, a probabilistic approach should be used to describe these variables since deterministic methods are not representative of human behaviour. Today, the great part of commercial tools provides to designers a library of possible schedules that allow description of thermal zones. But in most cases, users do not pay close attention to diversify thermal zones and to modify or to adapt predefined profiles, and results of designing are affected positively or negatively without any alarm about it.

This investigation (i.e., part 1 and part 2 of the paper), through an own calibrated building energy model, wants to evaluate the impact of these simplifications, both on the evaluation of the building's performance that on evaluation the energy saving and economic, deriving from the energy retrofit measures.

2. Methodological approach for proposed analysis

The study discusses the critical issues of the energy refurbishment of educational building, enabling stakeholders to understand the uncertainty to use numerical modelling and the real environmental and economic impacts of adopting some energy efficiency technologies. The case study is a building of University of Molise (Figure 1), in the center of Italy. In the first part of study, all the information acquired by means in-situ surveys, interview with occupants, in-field measurements, allowed the complete and deep characterizations of building, HVAC system, indoor conditions. All information and data acquired during the audit phase have been used to define a Reference Building as numerical model and it has been simulated in EnergyPlus [15] through the DesignBuilder interface [16]. The collected data, together with a comparison with energy bills, allowed also a proper calibration of a numerical model suitable for the hourly energy simulation. The approach proposed by M&V Guideline [17] has been used to calibrate the model. Here, the adopted statistical indexes are the error in the monthly energy consumption (ERR_{month}), the coefficient of variation of the root mean squared error CV(RMSE) and the bias errors (MBE). Typically, models are declared to be calibrated if these produce ERR_{month} within ±15%, CV(RMSE) within ±10% and MBE within ±5%.

Then, in the second part of study, the calibrated dynamic simulation model, has been used both to evaluate the energy performance of several refurbishment scenarios, that to make a sensitivity analysis to evaluate the incidence of modelling assumption on the estimation of present and potential performance of simulated building. In detail, the energy efficiency measures considered are renewable sources integrations, HVAC systems and envelope technologies. According to the main criticalities evidenced during the audit phase, occupant's requirements about indoor comfort and administrative needs of reducing operational costs have been considered too. Moreover, will be discussed a sensitivity analysis made both on the envelope characteristics (by varying the value of thermal trasmittance of the walls) than on occupation patterns, internal load and lighting system (by varying the schedules with which are described into the model).

Figure. 1. a) Map of Campobasso with building location, b) picture and c) building geometry, d) model, e) position of Campobasso in Italy

3. Case study: building audit and energy modelling

The investigated building (six floors, Figure 1) was built in the early '90s. It is a university building located in Campobasso, one of the coldest cities of center Italy. The most important climatic characteristics of site, building and thermo-physical properties of the building envelope are summarized in Table 1. For what concerns the building energy performance, the envelope audit has been supported with no-intrusively diagnostic techniques, like infrared thermography and by in-situ measurements of thermal transmittance. It presents different types of external walls, mostly made of hollow brick, air cavity, insulation material and full-block or aluminium layer as outer layer. At the present state, the studied building has not good value of thermal transmittance and periodic thermal transmittance (see Table 1), compared to the values established of Italian legislation for new or refurbished buildings. This causes high heat losses transmission and, moreover, also a negative impact on heating needs and on the comfort conditions for occupants. Conversely, during the summer period, the building envelope does not prevent overheating of indoor environments. The building has four types of window elements. The first type is glass blocks, used in the entrance at ground floor and for the hallway at the first floor (north-west exposure). The second type is a double clear glazing, which composes the skylights of the roof. Only the glass walls at the entrance are made of single clear glass, with an aluminum frame. For these types of windows, there are not shading systems. Finally, all other windows are realized with an aluminium frame and double clear glazing (6mm glass/12mm air/6mm glass). Most of this type of windows has an inner shading system, made by white vertical lamellas.

Infrared thermography surveys (figure 2) were carried out during winter period, in optimal measurement conditions such as an overcast sky. Moreover, this survey has been used to identify a proper positioning of the sensors for the measurements of thermal transmittance, according to the standard ISO 9869 [18]. The difference between the value of the measured thermal transmittance and the value derived by analytic calculation is around 35%.

Table 1. Site and building features

Campobasso (Elevation 701 m)	Latitude		41°33'36''	Longitude	14°39'37''
Winter Design Day	Temperature		-4 °C	Relative humidity	48.8
Summer Design Day	Temperature		29 °C	Relative humidity	50.0
Heating degree-days (calculation baseline 20°C)	2346	Horizontal monthly average irradiance (month of maximum value)			307 W/m^2
Total building floor area (m^2)	21314	Total volume (m^3)			66520
Net conditioned floor area (m^2)	12280	Conditioned total volume (m^3)			34468
Building Geometry	Total	North	East	South	West
Gross wall area (m^2)	11092	3589.18	2080.60	3408.89	2013.66
Window opening area (m^2)	1705.12	2108.09	2038.03	3170.17	1854.83
Net window-wall ratio (%)	16.76	16.62	20.02	14.19	17.84
Building envelope	T (m)	U (W/m^{2}K)		T (m)	U (W/m^{2}K)
Wall with external block	0.615	0.308	Auditorium roof	0.275	0.337
Wall with external brick	0.310	0.428	Transparent envelope	U_f (W/m^{2}K)	U_w (W/m^{2}K)
Internal wall	0.580	0.427	Skylights	5.88	2.67
Floor	0.466	0.529	Glass walls	5.88	3.09
Sloped roof	0.390	0.963	All other windows	5.88	2.69

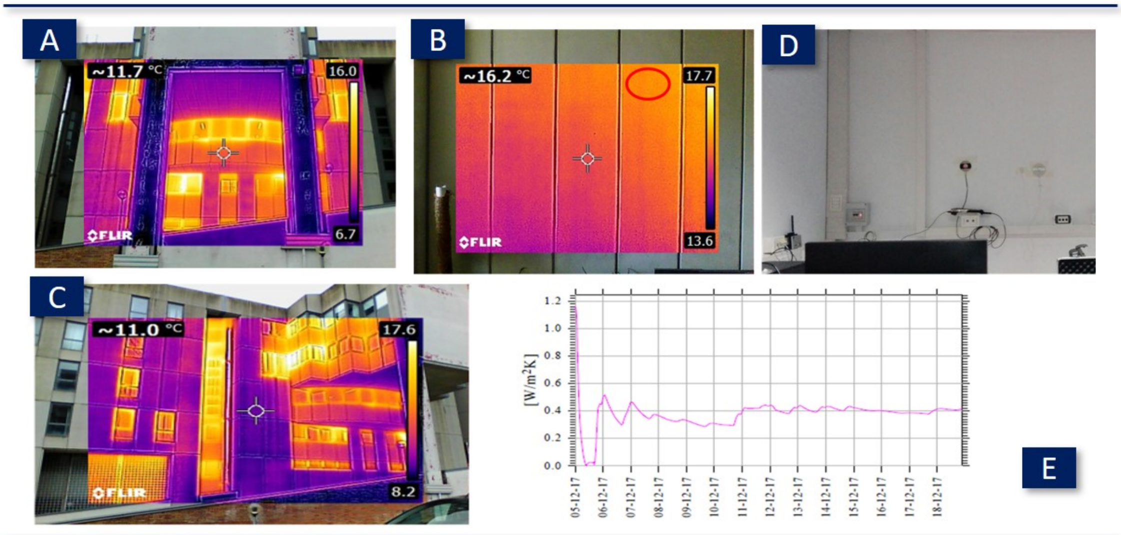

Figure 2. a), b) and c) infrared thermography; d) and e) measures with heat flow meters

All offices, lecture rooms, bar, circulation zones, and most classrooms have a mixed air/water system, given by combination of fan-coil and air handling units. This system provides heating, cooling and ventilation requests. Only toilettes have a heating and cooling water system. The six biggest classrooms, which are placed in the central part of the structure, have an all air system, which provides both heating, cooling and ventilation needs. The hot water, also for sanitary uses, is produced by two traditional boilers with nominal power of 1100 kW. The chilled water is supplied by two electric air chillers with nominal power of 840 kW. There are also five air handing units, two of these provide only ventilation. Finally, there is one hot water storage with a volume of 1500 liters. Thermographic studies, coupled with other instruments, were performed also for generation equipment and emitters, as well as these have been performed for supporting measurement of air speed and temperature. These indicated that the speed is always in comfort zone, while the temperature is higher than conventional values for mixed air-water HVAC. About it, it should be specified that the only one regulation criterion is a climatic compensation of temperature of supply water. For this reason, the temperature inside the building is often too high and this causes high consumption of the building and a negative impact on the comfort conditions for occupants can be found.

For what concerns other equipment, on the building roof there is a photovoltaic system of about 19 kW_p, while, the lighting systems consist of fluorescent lamps of 36 W, with an average installed lighting power of 6 W/m^2.

In the simulation model, the HVAC system has been created according to the aforementioned surveyed details. The operation schedules have been created according to manager and occupant information. Thus, the heating period starts on 15th of October and it finishes on 15t^{h} of April, the cooling period is 25th June – 5th September, while the ventilation is always turned on. The operational hours are in the time period 7:00 - 18:00, with possibility to turn on the heating system when the external temperature is too low during the night. During the weekends and holiday periods, all systems have been considered turned off.

Through an accurate inspection, the use of each room has been verified. At the ground floor, there are the entrance and information point. At the first floor there are classrooms, bar and copy shop. Also, the second and third floor host classrooms and some administrative offices. At the fourth and fifth floors there are mostly professor's offices. Finally, the auditorium is located in an adjacent structure, outside the building.

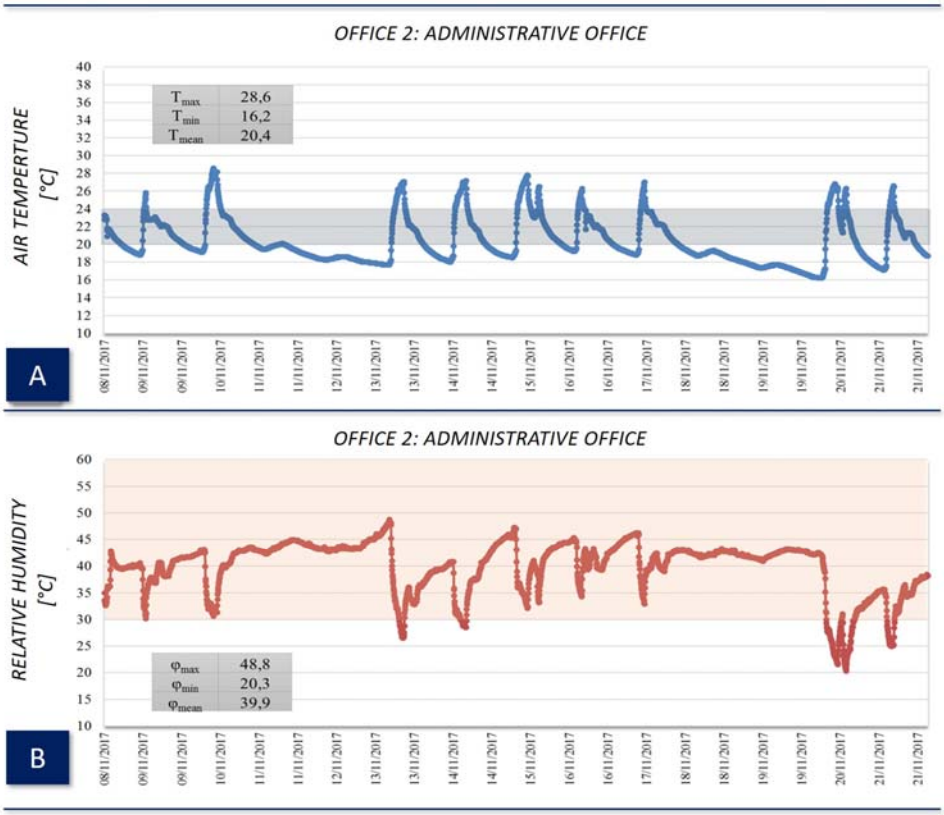

Figure 3. Office 2 - administrative office: a) trend of air temperature; b) monitoring of relative humidity

In order to describe, as accurately as possible, the real conditions inside the building, some questions were asked to office occupants and students, contextually to a survey for verifying the thermal zone distribution. More in detail, the questions concerned: a) the time spent daily in the building, b) how many hours are spent by working at a computer, c) conditions of comfort or discomfort for what concerns the indoor microclimate and d) the list of the most important criticalities of the building.

Occupation rates, equipment schedules and lighting systems usages have been described into the numerical model of the building by taking into account the achieved answers. Moreover, for some significant rooms, also a monitoring of air temperature, relative humidity and lighting levels has been performed, with the aim to describe the actual thermal and visual indoor conditions. More in detail, the significant rooms have been selected according to kind of use and internal loads, exposure, envelope resistance, type of HVAC system, lighting source and indication of occupants.

In this paper, analyses of monitoring results are discussed only for one administrative office (Office 2). In detail, during the monitoring period, from 8th to 21th of November 2017, air temperature and relative humidity have been recorded with a time step of 5 minutes. The recorded values for air temperature are shown in figure 3a: here, it is also evidenced the reference value of comfort range (19-23°C) and calculated mean value (T_{mean}), maximum (T_{max}) and minimum ones (T_{min}). Analogously, for the relative humidity, the comfort range and the mean, minimum and maximum values monitored in the Office 2 are reported in Figure 3b. Briefly, the humidity values are usually very low, and always below the optimum design value of 50%. Indeed, the air system does not balance the latent load and, moreover, the air temperature are too high. Similar trends have been recorded for the other selected areas and these confirm that often the air temperature and relative humidity are outside the range of comfort recommended by current standards [19]. Indeed, from interviews to occupants, frequent discomfort conditions have been arisen.

Figure 4. Installed sensor for light level measure: a) desk1; b) desk2.

Table 2. In field measured of lighting level.

Illuminance		I_M	I_m	I_{Mm}
Desk1				
Scenario 1	08/11/2017 17:04	306	284	304
Scenario 2	15/11/2017 15:08	65	38	51
Scenario 3	15/11/2017 15:23	384	363	381
Desk2				
Scenario 1	08/11/2017 17:10	306	302	304
Scenario 2	15/11/2017 15:15	134	80	131
Scenario 3	15/11/2017 15:27	347	334	336

For what concerns the luminance level, some punctual measurements have been done in correspondence of working surfaces (around 90 cm of height) and by considering different natural and artificial scenarios with a sampling time of 10 minutes. These measures have been compared with illuminance values indicated by the standard UNI EN 12464-1 [20], that suggests 300/500 lux for classrooms/office. Always referring to Office 2, the measurement was carried out on the two work-surfaces (at the centre of desks) as shown in Figure 4. Different scenarios have been considered, by taking into account the external conditions and lighting system consisting of 6 lamps (36W). In detail, the following conditions were considered: scenario 1) opened drapes and lighting system turned on, without sunlight (evening); scenario 2) opened drapes and lamps turned off, whit covered sky; scenario3) closed drapes and lamps turned on, with covered sky.

Table 2 shows the results of measurements, and it is shown that, both artificial lighting system and natural scenario provided lighting levels discorded to the standard [20]. This result has been confirmed also in some other selected rooms, and it means that people have visual discomfort.

In the building model, in order to define reliable thermal loads, several typologies of thermal zones have been created and they were detailed according to the specific use of zones, in terms of occupancy and installed power. In detail, occupancy schedules, installed equipment and lighting have been created according to surveyed characteristics. Moreover, additional air change equal to 0.35 vol/h has been considered in order to take into account infiltration due to opening of windows and doors.

The last step of energy audit has been an accurate analysis of the historical energy requests, by collecting data about the last three years (i.e., the available bills) of the electricity and natural gas demands.

4. Definition and Calibration of the energy model

All information and acquired boundary conditions about the building uses, have been adopted for defining and calibrating the numerical energy model of the building. Table 3 shows the evaluated indexes and tolerance ranges (in the last line) for natural gas (E_G) and electric demand (E_{El}) for all building uses. The results are always within the tolerances, thus the energy model can be considered well-calibrated and well-representing the present energy demands.

Table 3. Evaluation of Indexes of calibration

	% MBE		CV(RMSE)	
	Energy Demand of Natural Gas	Energy Demand of Electricity	Energy Demand of Natural Gas	Energy Demand of Electricity
	3.4%	2.5%	13.1%	6.9%
Admitted threshold for calibrated models [17]	±5%		+15%	

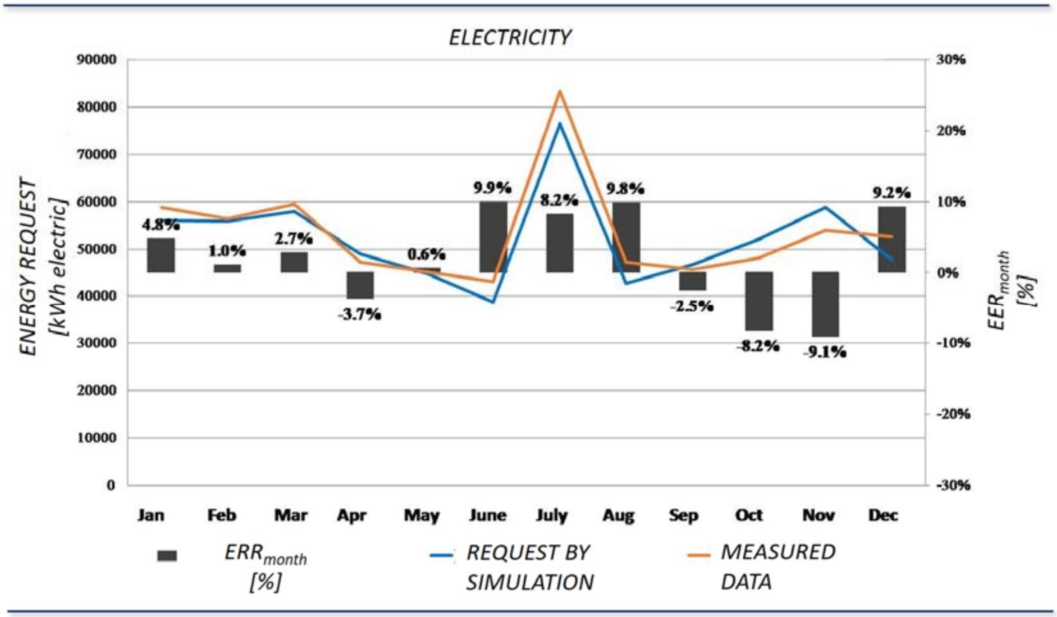

Figure 5. Calibration: electricity energy request.

Moreover, in Figure 5 the comparison between the electricity request of the real building and of the simulated model is reported, with also the indication of monthly gaps. The same analysis for gas request has been performed too. According to the M&V Guidelines, the MBE (Mean Bias Error) and the CV(RMS) (Coefficient of variation of the root mean squared error) have been calculated and these resulted lower than the maximum admitted values. All told, the numerical model is enough in agree with the real building usage. This means that the simulation model describes, as accurate as possible, the real building performances. Indeed, it is important to underline that in this study also the behavior of the occupants and the use of the equipment, which are often not considered, has been adequately modeled as aforementioned.

In the second part of the study, a sensitivity analysis will be presented, to understand which is the error due to wrong characterization of the envelope or to aleatory assumptions about the behaviour of occupants. Will be shown, that a wrong modelling approximation, can move away results of simulated model from the energy performance of real building. Analysing results, shown in the second part, will be clear the importance of the accurate audit phase as aforementioned in this first part, to describe as accurately as possible, the real condition inside building, focusing in particular on occupant rates, equipment schedules and lighting system usage, which are often not taken in account. Then, a suitable and feasible optimization of energy retrofit, and energy performances will be performed and discussed.

Conclusions

The first part of this study discussed a methodological approach, combining experimental and analytical methods, to design the energy refurbishment of building based on a deep energy diagnosis, with in-situ measurements that allow the complete characterizations of building/HVAC systems and indoor conditions. A deep literature state of art was proposed, as well as all boundary conditions and details of surveys, inspections, questionnaires and investigations performed in order to have an accurate energy audit of the building. In this way, a very accurate numerical model of the building was created and also a correct calibration is obtained, then the resulting reference model is presented. While all issues concerning the building energy refurbishment, the feasibility studies and some sensitivity analyses will be described in the second part.

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