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Energy Procedia 00 (2016) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

Comparing energy improvements and financial costs of retrofitting interventions in a historical building

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Abstract

In Italy, energy improvements of historical buildings are one of the key aspects to reach the EU 2020 goals on energy efficiency. Many papers are available in literature to recover and retrofit historical buildings, considering different types of interventions aimed to increase energy efficiency in existing building. Considering the most common retrofit interventions in historical building, this paper focuses on the estimation of the energy improvements and related financial costs of four considered scenarios on the building envelope of the "pharmaceutical chemistry" historical building located in the Sapienza University Campus of Rome. Additionally, a cogeneration system and the installation of a PV system have been included among the considered scenarios, in order to analyze their energy performance jointly with feasible retrofitting interventions. Research methods included a dynamic simulation of building thermal loads in the current state and in the scenario after each considered intervention carried out using TRNSYS software. Furthermore, yearly savings, investment cost and payback periods have been evaluated for each considered scenario, taking into account both the purchase prices of the saved energy and the amounts needed to realize related retrofitting interventions. In conclusion, among the feasible interventions in historical buildings, the obtained results provide useful data about what strategy offers the best energy performance improvement if compared with its financial costs. Results could provide recommendations for other historical buildings that need retrofitting interventions for improving their energy efficiency.

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Keywords: Energy efficiency; retrofitting; investment cost; historical building;

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1. Introduction

Improving energy efficiency of existing buildings needs particular precautions for those buildings under historical constraints since they reduce possible interventions [1]. Indeed, a new research line is related to the substitution of fuel supply to reduce the associated carbon emissions [2,3]. Moreover, a preliminary analysis should be conducted by energy planners examining surrounding environmental and urban areas [4-5], and evaluating local availabilities of renewable energy sources such as solar, wind [6] or biomasses [7-8] as well as protected areas to be preserved [9-10]. The target is to manage the current energy transition towards Smart energy and smart buildings [11-12]. Energy efficiency is main part of this strategy but, several barriers occur when it is related to historical buildings.

The difficulty to choose interventions for improving energy efficiency of historical buildings could be even higher in university buildings, mainly due to their multiple intended uses, diversified operating systems and high occupancy. However, previous researches highlighted how to successfully deal with such issues [13-14]. Considering architectural characteristics of those buildings, the solution of optimal interventions aims at reducing environmental impact and at improving indoor comfort [15] as well as outdoor conditions in university campus [16-17]. Currently, the general status of Italian university structures combines architectural values with a building deterioration as well as inadequate energy performance. This statement is supported by recent experimental campaign inside and outside the buildings [18]. In Italy, the interventions for energy efficiency are funded through the Kyoto rotary fund and applied by accounting for the relative economic sustainability rules [19]. These funds will be disbursed after performing energy audits on buildings and emitting the energy performance certificate that witnesses the improvements achieved by the interventions. Historical buildings play an important role in Europe as attractive heritage for tourist presence [20].

The aim of this paper is to assess energy performance and financial costs of some feasible interventions for energy retrofitting and technological renovation of a historical university building, maintaining its historic and architectural qualities. The building object of study is the Faculty of Pharmaceutical Chemistry, including: static and dynamic simulations, the estimation of the overall energy performance, the identification of possible interventions to compare with current status, and a cost-benefit analysis among four identified scenarios pinpointing the most effective considering investments and return times. The cost evaluation is needed for the production and for the future projections from the consumption side [21]. This study aims to provide an example of requalification intervention to be considered in similar contexts.

2. Materials and methods

The Faculty of Pharmaceutical Chemistry was built in 1962 and it includes two mains intended uses: teaching (classrooms, library and lecture hall) and research (laboratories and offices) activities, as shown in Figure 1.

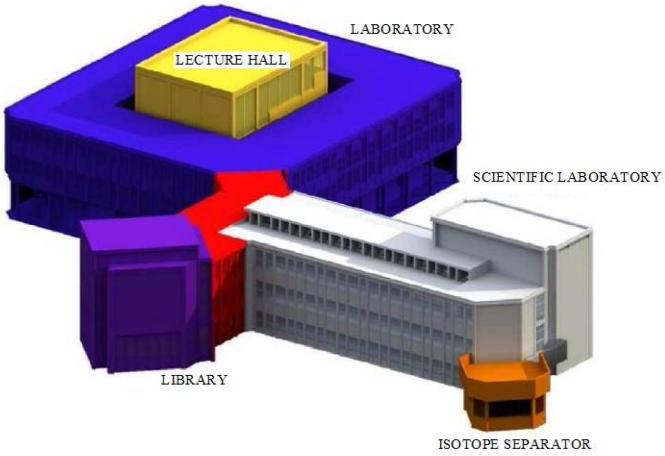

Fig.1. Intended uses of the analyzed building

Although building energy consumptions before the considered retrofit interventions are not available, it can be stated that the building is characterized by high energy consumption mainly due to the current building envelope structure and its high percentage of transparent surface. The external envelope is composed by reinforced concrete while, vertical perimeter wall is composed to sheet panels and single glass fixtures.

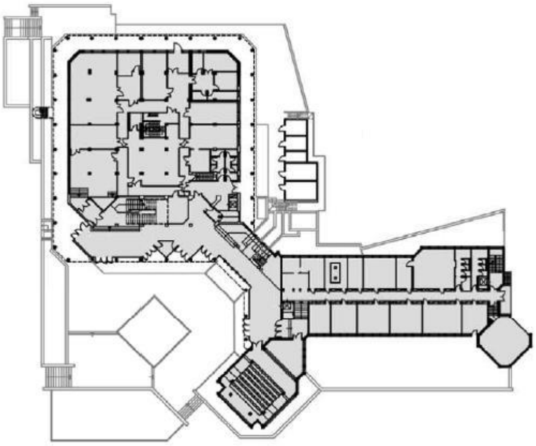

Fig. 2. Plant of ground floor

Considering current energy systems, the building is supplied by a 523 kWt thermal power plant, several heat pumps in the laboratories and an air handling unit (AHU) in the library where the air change rate were not adequate. The AHU was therefore included for compensate the insufficiency of cast iron radiators, improving at the same time the indoor air quality thanks to inlet and shooting jets. Moreover, since the faculty has no cooling systems, the methodology has been set considering only the plant for the heating system.

In particular, the methodology includes the subdivision of each building floor in thermal zones using TRNSYS software taking into account the end uses and expositions. In detail, 59 thermal zones have been identified: 21 at the ground floor, as in Figure 2, 20 at the first floor and 18 at the second floor.

By means of TRNSYS software, it was possible to estimate current heat losses of the envelope structures on hourly base. This analysis pinpointed that more than 50% of the heat losses depends on insufficient thermal performance of window structures, as shown in Figure 3.

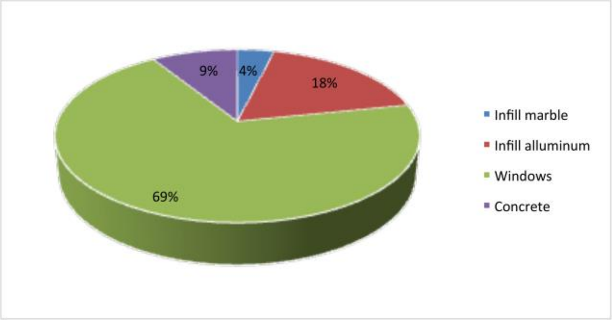

Fig. 3. Heat loss percentages of each building envelope structure

In order to assess exposition effects on building energy performance, the heat losses and energy needs have been compared for heating in two thermal units with the same final use, similar dimensions and envelope structures but, with different exposition, i.e. North and South.

After a first hypothesis of intervention, the energy performance has been evaluated considering the substitution of frame and glasses, external infills and the insulation of roof and ground floor using green building concepts [22-23].

This first scenario has been compared with other three combined interventions scenarios by analyzing energy performance, financial costs and payback periods. The analysis required the use of TRNSYS software and Archienergy for the building energy audit:

- Solution 1: total building envelope improvement (substitution of frame and glasses, external infills and the insulation of roof and ground floor);
- Solution 2: total building envelope improvement as in solution 1 plus integration of a regulation system with thermostatic valves and the installation of a 20 kW PV array;
- Solution 3: solution 2 interventions plus the integration of a 50 kW CHP system as electrical and thermal energy supplier;
- Solution 4: installation of a 20 kW PV array and integration of a 50 kW CHP system as electrical and thermal energy supplier without interventions on the building envelope.

Important contributions can be provided by further renewable share in CHP fuelling as demonstrated in [24-26], already applied in other Sapienza University campus buildings and by the use of experimental Concentrated Solar Panel as shown in [27].

3. Results and discussions

The results obtained by the comparison of heat losses and energy needs for heating in two similar thermal zones with different exposition highlight that the two zones disperse the same energy amount but, the thermal zone exposed to the South requires about half of the primary energy compared to the one exposed to the North for maintain the internal temperature of 22° C, as depicted in Figures 4-5. This difference is due to the solar gain benefits due to incoming solar radiation through the windows that involves a 46% energy saving in the South exposed area.

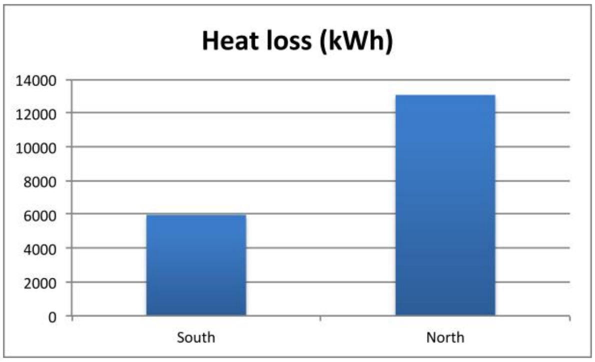

Fig. 4 Sensible energy comparison between south and north exposed thermal zones.

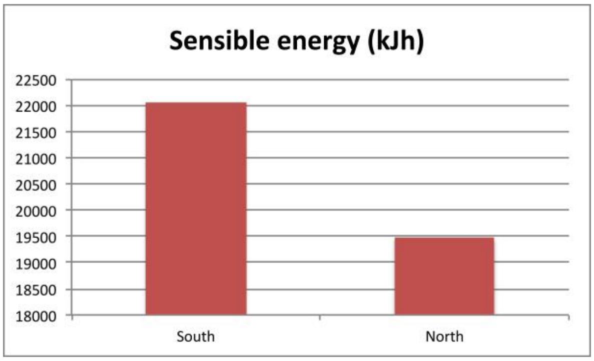

Fig.5 Heat loss comparison between south and north exposed thermal zones.

By means of TRNSYS software, ante and post operam heat losses assessment showed an overall annual reduction of 54%, decreasing from 756,564 kWh/year to 342,752 kWh/year, as reported in Figure 6. Furthermore, annual energy saving for each considered intervention are reported in table 1.

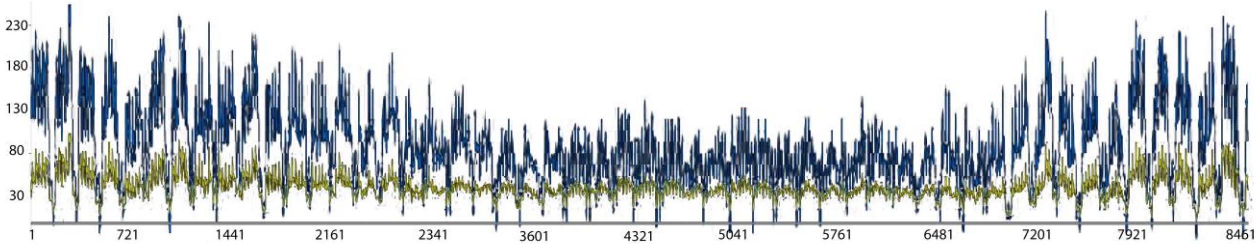

Fig. 6. Annual heat losses trends ante and post operam.

Table 1. Energy saving for each envelope intervention

Building envelope intervention	Energy saving (kWh/y)	Energy saving (kWh/m2y)
Fixtures replacement	109,213.10	89.08
Ground floor and roof insulation	74,572.86	18.79
External infills substitution	72,955.84	36.8
Total annual energy saving	256,741.81	144.05

Comparing sensible heat ante and post operam, a reduction of 60% after building envelope interventions can be found, as shown in Figure 7, while sensible cooling loads have not been considered since the analyzed building doas not include cooling systems.

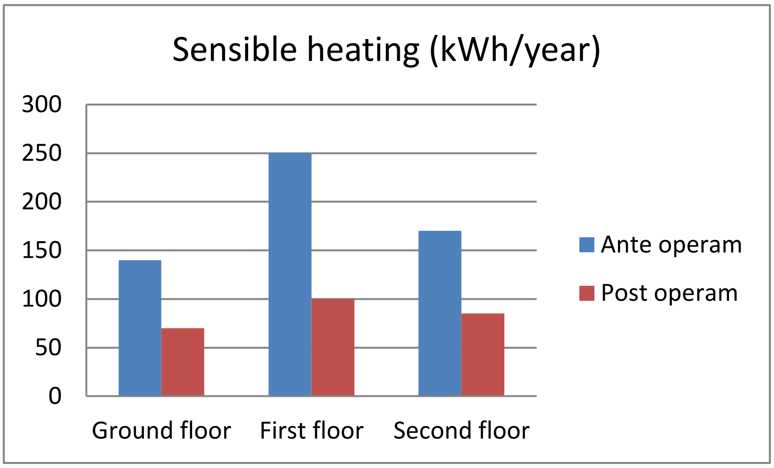

Fig. 7 Comparison between ante and post operam sensible heat demand.

Additionally, Table 2 summarizes the four selected scenarios by pinpointing energy performance, CO_2 emission reduction, yearly savings, investment costs and payback period.

The obtained results highlighted that the first three scenarios, which include building envelope modification, have a payback period higher than 30 years, while only CHP combination with photovoltaic panels have a return times of about 16 years.

From the comparison between the four interventions proposed, it results that solution n.2 is the most complete and advantageous; it produces a 42% saving of the total energy needs and an environmental benefit of a 39% reduction of GHG emissions.

Table 2. Results of the 4 selected scenarios.

	Solution1	**Solution2**	**Solution3**	**Solution4**
Electricity Demand [MWh]	322.00	286.00	286.00	267.00
Heating Demand [MWh]	42.00	31.00	36.00	338.00
Electricity Demand change	11%	-1%	-1%	-8%
Heating Demand change	-87%	-91%	-86%	2%
Epci [kWh/m3y]	14.7	10.5	9.3	35.9
Energy Rating	E	E	E	G
Epci change [%]	-69%	-78%	-81%	-25%
Self-production [MWh]	0	29	43	126
CO_2 emission change	-23%	-39%	-40%	-33%
Yearly savings [k€/y]	62000	77000	76000	25000
Investment cost [k€]	887000	1036000	1113000	276000
Payback period [y]	>30 years	>30 years	>30 years	15.9 years

Lastly, the financial prospectus of solution 2 demonstrates that the effects of building envelope interventions on the total investment is very high (about 40%) and the ratio between financial costs and avoided CO_2 emission is 9.4 €/kg_{CO2}, as in Table 3. In particular the following parameters have been considered to calculate the net present value (NPV): the cash flow statement, the payback period and the internal interest rate. The energy and heating demands, as well as energy self-production were considered for incoming and outgoing cash flows.

Table 3. Financial prospectus of solution 2

	€	Variation (€)
Envelope investment	887,447	+887,447
Power plant investment	175,991	+175,991
Total investment	1,063,439	+1,063,439
Net Present Value at the tenth year	-1,355,963	-5,693,990

4. Conclusions

Energy performance and financial costs comparison highlighted that the most complete and advantageous combined interventions scenario foresees a total building envelope improvement plus the integration of a regulation system with thermostatic valves and the installation of a PV array without the integration of a CHP system.

Indeed, to integrate a CHP system as electrical and thermal energy supplier seems to be too expensive in this building typology, considering maintenance costs and system efficiency.

Furthermore, a critical aspect of the analyzed building is the absence of differentiated windows according to the exposition, entailing thermal discomfort in thermal zones exposed to the North during winter period and in ones exposed to the South during the summer.

Finally, the adopted approach and the obtained results could be used for the energy refurbishment strategy of similar building typologies, aiming to achieve the European 2020 targets on public existing building energy efficiency so as to optimize cost/gain ratio.

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