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Article

Methodological Approach to the Energy Analysis of Unconstrained Historical Buildings

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Abstract: The goal set by the EU of quasi-zero energy buildings is not easy to reach for a country like Italy, as it holds a wide number of UNESCO sites and most of them are entire historical old towns. This paper focuses on the problem of the improvement of energy performance of historical Italian architecture through simple interventions that respect the building without changing its shape and structure. The work starts from an energy analysis of a building located in the historic center of Tivoli, a town close to Rome. The analysis follows the recommendations of the UNI TS 11300-Part1, which indicates how to evaluate the energy consumptions. The calculations were performed only on the building envelope, based on passive solutions and alternatives. Four passive strategies were examined and applied based on the location of the building and the non-alteration of the structure and the landscape. The obtained results impacted positively on the energy performance of the building: the annual energy saving reached a maximum value of 25%. This work shows how it is possible to improve the energy performance of an existing building achieving a significant energy saving with the respect of the building architecture, shape, function and the surrounding landscape.

Keywords: energy performance; historical building; energy saving interventions; heritage respect

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1. Introduction

The 2010/31/UE directive [1] released by the European Parliament promotes the improvement of the buildings energy performance, indicating it as a priority of the 20-20-20 objectives in the field of the energy efficiency. This directive shows the pathway to reduce energy consumption, proposing possible actions for energy saving. Among these, the most significant interventions are: to introduce building energy performance calculation; to introduce new and innovative incentives linked to energy efficiency; the use of energy from renewable sources, passive solutions for heating and cooling, shading systems, indoor air quality, adequate natural light, and architectural features of building; to include advice in the certificate of building energy performance for improving their efficiency and the reduction of carbon dioxide emissions; to impose a regular energy certification for public buildings.

Moreover art. 9 introduces the near-zero energy building as a very high performing building in which "very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [1]. By the date of 31 December 2020 all new buildings will have to be quasi-zero energy buildings, whereas this date is anticipated to 31 December 2018 for public buildings.

While the goal of EU is to reach the quasi-zero energy building, Italy has to pay close attention to the application of directive concerning this field; indeed Italy holds the record of the countries with the most UNESCO sites in the World and at least the half of them are historical old town centers or medieval villages [2]. This condition requires to balance the need for renovation with the need for historical building conservation, through actions able to make buildings more efficient without changes in their architecture [3–5]. On the other side, it becomes of basic importance to define methods and approaches to evaluate the performance and thermal behavior of buildings, especially ancient and/or historical buildings [6–8].

There is an intense and wide list of references showing the usefulness and the energy convenience of passive strategies [9–12], from ventilation [13–15], to solar chimneys [16,17], from green roof [18–20] to winter gardens [21], as well as the role of active systems [22–24] at a building and district scale [25,26].

The aim of this work is to demonstrate how to obtain considerable energy savings through passive interventions which not alter the shape and the structure of the buildings [27,28].

The work will start from the energy analysis of a historical building, using the recommendations contained in the UNI TS 11300-Part1 [29]; but here only the building envelope has been considered, with possible integration of passive solutions, while excluding the heating system. Then, following the basic principle of preserving the structure and the surrounding environment, energy saving interventions appropriated for the examined building and its location have been selected.

The calculation was performed with a numerical procedure developed by the authors, with the finality of better controlling the whole calculation process and for having the possibility of using real data from the building and real site climate measurements, with the same intent of calculating as real as possible the values of energy consumption, to provide a procedure for energy evaluation adapted to all kind of users.

The results have been analyzed evidencing the savings obtained in summer and in winter periods with each intervention and the convenience of some of them in respect to others.

2. Methods

2.1. Calculation Procedure

A numerical procedure based on the UNI TS 11300-Part1 [29] was used to calculate the energy requirements for building heating and cooling. Several are the reasons to introduce a new numerical procedure with respect to commercial software: the data input in commercial software follows a default procedure without the possibility of user setup, whereas the numerical procedure allows a wide implementation and integration of data; the software acts in a rigid way with a non-visible and non-accessible program implementation from user. Often software outputs are results of multiple processes in which the user cannot evaluate the single steps, whereas in the numerical analysis the user can intervene in the whole calculation procedure; finally software does not always allows the input of real climatic data.

The following equations were used to calculate the monthly requirement of thermal energy for summer Equation (1) and winter Equation (2) air-conditioning:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} Q_{gn} = \left(Q_{H,tr} + Q_{H,ve}\right) - \eta_{H,gn}\left(Q_{int} + Q_{sol}\right) \tag{1}$$

$$Q_{C,nd} = Q_{gn} - \eta_{C,ls} Q_{C,ht} = \left(Q_{int} + Q_{sol}\right) - \eta_{C,ls}\left(Q_{C,tr} + Q_{C,ve}\right) \tag{2}$$

where $Q_{H,nd}$ is the ideal thermal energy requirement of building for heating; $Q_{C,nd}$ is the ideal thermal energy requirement of building for cooling; $Q_{H,ht}$ is the total thermal exchange for heating; $Q_{C,ht}$ is the total thermal exchange for cooling; $Q_{H,tr}$ is the transmission thermal exchange for heating; $Q_{C,tr}$ is the transmission thermal exchange for cooling; $Q_{H,ve}$ is the thermal exchange due to ventilation for heating; $Q_{C,ve}$ is the thermal exchange due to ventilation for cooling; Q_{gn} is the total heat supply; Q_{int} is the internal heat supply; Q_{sol} is the solar heat supply; $\eta_{H,gn}$ is the heat supply utilization factor; $\eta_{C,ls}$ is the heat loss utilization factor.

Once the calculation was performed the results obtained were verified comparing them with the output of commercial software. Results obtained with the numerical calculation differ less than 2% from the software output: for this reason the data input in the calculation and its implementation was considered correct, so only these results will be shown.

2.2. Data

The energy evaluation of the building was performed with an asset rating system based on the calculation in standard use conditions: the used data derived from the analysis of the real building envelope acquired *in loco*.

Data concerning the building typological characteristics were derived from the architectural plans, while thermal and constructive data were selected from the lists contained in the UNI TS 11300-Part1 standard [29], that can be used when the exact data and specific information are missing; the energy calculation was performed with real climatic data, properly treated, provided by the Areonautica Militare Italiana (AMI). The interior building (design) temperatures were chosen according to [29]: they resulted to be 20 °C and 26 °C for winter and summer conditions respectively.

2.3. Heating and Cooling Seasons

The evaluation adapted to users was selected to determine the heating and cooling operative periods: it takes into account the real periods of heating and cooling, as the period during which heat or cold must be supplied through the air-conditioning system to maintain the interior temperature in a range ± 0.5 around the design temperature.

Differently from what proposed in the standard evaluation, using the evaluation adapted to user, the months of May and October too were considered in the calculation of the annual energy for the winter air conditioning, even if these consumptions are very low. This was essentially due to use of the real temperatures that are about one degree lower than in [29].

This evaluation can be performed using the following equations, respectively for heating Equation (3) and cooling Equation (4):

$$\theta_{e,day} < \theta_{i,set,H} - Q_{gn,day} \, / \, H \, t_{day} \tag{3}$$

$$\theta_{e,day} > \theta_{i,set,C} - Q_{gn,day} \, / \, H \, t_{day} \tag{4}$$

where $\theta_{e,day}$ is the average of daily external temperature; $\theta_{i,set}$ is the setting interior temperature; $Q_{gn,day}$ corresponds to interior and solar mean daily supplies; H is the global thermal exchange coefficient and t is the length of the day.

3. Materials

3.1. The Building

The building under examination is the ancient public library dating back to Fifteen Century and located in the historical center of Tivoli, a town in the district of Rome. It has a rectangular plan, with the main front along the North West-South East axis, and it is composed of three floors, each one having an area of about 190 m^2 and height of 3.5 m. The perimetral walls are made in masonry of semisolid bricks and tuff, and their thickness varies in the range 0.5 m–0.6 m; the roof is wooden made. Fixtures and frames are made of wood too, while the glazings are single glasses without any superficial treatment; no shading system or movable shield device exist. All the doorways existing in the four facades are wooden made. Further, the building cross sections are presented in Figures 1–4.

Figure 1. North-West front.

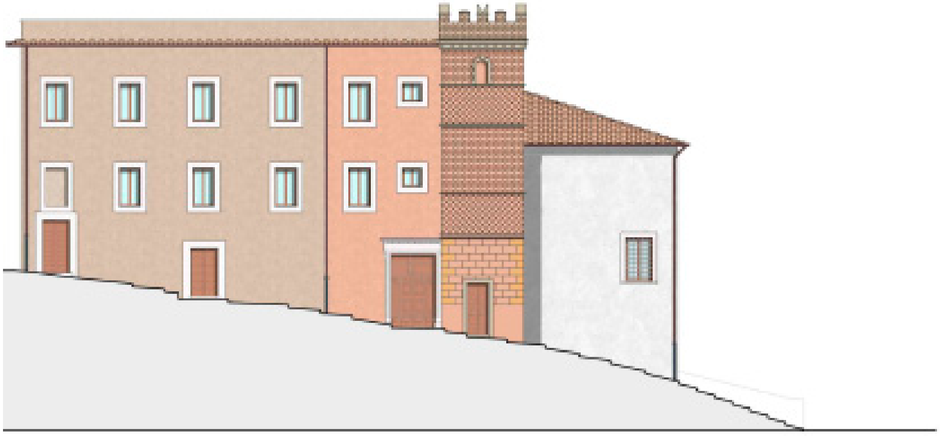

Figure 2. North-East front.

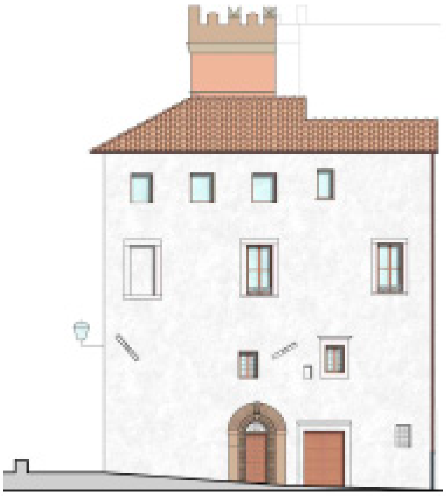

Figure 3. South-West front.

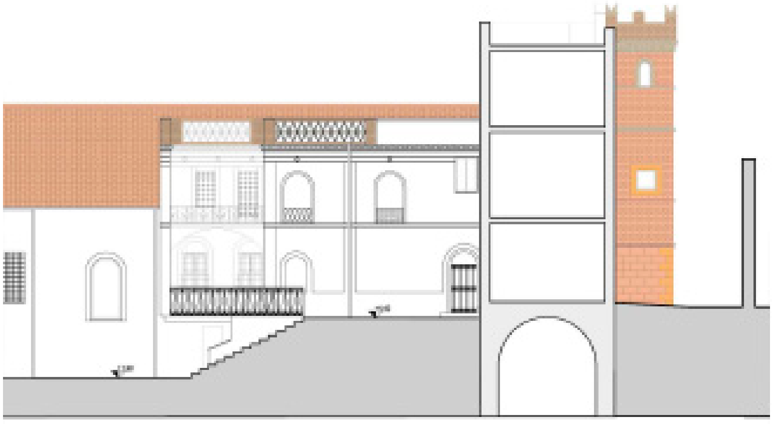

Figure 4. South-East section.

3.2. Feasible Interventions

A list of possible energy requalification interventions on the building envelope were evaluated with the aim of selecting the best available actions, considering the obtained energy saving, as well as their impact on the historical building and on the surrounding landscape:

(1) wall isolation through outside coating;
(2) wall isolation through inside coating;
(3) wall isolation through interspaces with insulating material;
(4) double screen facade;
(5) insulating plaster;
(6) change of roof color;
(7) fixture substitution;
(8) installation of shading devices;
(9) application of solar films;
(10) thermal bridge reduction;
(11) green-roof or water-roof;
(12) roof insulation from inside.

The first four interventions probably are the most convenient in terms of energy savings, but they were not taken into account as they would have altered the internal and/or external layouts, that are considered not modifiable for their historical value. The actions involving the roof were not realizable, as they would have changed the exterior image of the building that, being in the historical center, has to be preserved; for the same reason the installation of shading devices is not permitted. Insulating the underside of the roof increases the volume of the thermal envelope of the building, thus making this treatment inherently less energy efficient.

Among the shading devices there are special glasses as absorbing, reflective, photochromic, thermochromic, electrochromic or LCD glasses. These kinds of glasses was discarded during the interventions choice for the following reasons:

(1) Absorbing glasses can cause glare discomfort phenomena, non-uniformity in the light distribution, reduced availability of daylight and an altered view to the outside from a chromatic point of view;
(2) Reflective glasses cause glare discomfort in the outdoor environment around the building, altered daylight color characteristics and non-uniformity in the light distribution;
(3) Photochromic, thermochromic, electrochromic, or LCD glasses are very expensive and not easy to find on the market. In addition, they cause non-uniformity in the light distribution, sudden lighting variations (thermochromic and LCD glasses), altered daylight color characteristics (photochromic and thermochromic glasess) and they also impede the view to the outside.

The only feasible interventions are the application of insulating plaster, the substitution of fixtures, the installation of solar films and the reduction of thermal bridges, as they can be respective of the cultural heritage existing in the building.

3.2.1. Plaster Substitution

The application of insulating plaster is an action of energy requalification that is easy to realize, that do not alter the external wall of the building, being already plastered. The easiness of realization is due to the fact that the insulating plaster has the same aspect of the traditional one and its application does not require skilled manpower.

The plaster existing on the external walls was a traditional type with the function of protective coating of the masonry; its characteristic parameters were, according to [29], a density of 1800 kg/m^3 and a thermal conductivity of 0.9 W/mK.

The insulating plaster selected for the requalification has elevated hygroscopic and transpiring characteristics, high performance of thermal-acoustic insulation, and absence of resins, solvents, radio emissive aggregates; the components were hydraulic lime, botticino, kaolin, calcic casein, Vichy salt, calcium carbonate, tartaric acid, ammonium salts, expanded pearlite, cork flour, and natural fibers. Its technical applicative characters, derived from market investigations, were average density of 540 kg/m^3, thermal conductivity of 0.056 W/mK, and a fire classification of 0.

These characteristics were evaluated for the building under examination: the thermal conductivity was more than 90% lower respect to the value of the original plaster; moreover, being a fireproof material, it would protect the building facade in case of fire.

To obtain significant energy savings, a thickness of 4 cm of the selected insulating plaster was applied.

3.2.2. Substitution of Fixtures

The original fixtures mounted on the building were wooden frame with a single layer glass without superficial treatments; as the trasmittance values of these elements were unknown, the values suggested in the norm UNI TS 11300-Part1 [29] were used for calculation.

The intervention considered the substitution of the frames and the application of low emission insulating glasses. Several possible typologies of frames exist, each with specific characteristics: the PVC frames and the aluminum frame have high resistance to atmospheric agents, while the wooden frame has the best thermal qualities. Even though the choice of a mixed frame, PVC and wood or aluminum and wood, would have synthesize the above mentioned characteristics, the wooden frames were selected with the aim of respecting the history and the original structure of the building [30,31].

A double glass containing air and provided of a low emissive third face was utilized; the 4-18-4 window system, allowed to obtain a transmittance of 1.4 W/m^{2}K, compared to 5 and 5.7 W/m^{2}K of the original fixtures.

3.2.3. Application of Solar Films

The application of solar films had the aim of reducing the solar radiation entering inside the building, as it is placed in a high sunny location; with this intervention summer cooling loads for air-conditioning were reduced.

The chosen solar film is the SB341EXSR produced by Serisolar. This company declares that this solar film transforms the outer glass of 4 mm thickness in a safety glass as requested by the Law 81-08, with certification normed by UNI EN 12600 in B3 class.

The changed parameters in the energy analysis are shown in Table 1.

Table 1. Thermal and lighting characteristics of the glass before and after the intervention.

	Before	**After**
Transmittance [W/m^{2}K]	5.7	1.4
Emissivity	0.837	0.1
Solar heat gain coefficient	0.765	0.22
Shading coefficient	1	0.25

The operation of the solar film is shown in Figure 5.

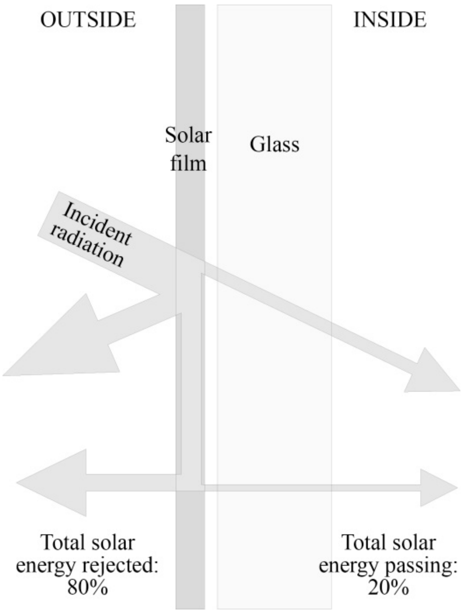

Figure 5. Solar film scheme.

The use of special glasses (absorbing, reflective, photochromic, electrochromic, thermochromic, LCD) were other options for shielding the solar radiation, solutions that were rejected as they can cause glare, non-uniformity of light distribution, reduced natural light and external view; moreover, many of them have a high cost.

The reduction in daylight contribution does not influence a library much, where the artificial lighting is turned on during all the day. For this reason this problem was not investigated in detail.

The application of solar films was selected and it was considered in combination with the intervention of fixtures substitution: to install the solar films on the original glass was not energy convenient.

3.2.4. Reduction of Thermal Bridge

The intervention for the reduction of the thermal bridges derived from a thermographic study of the examined building; this method is a non-destructive technique (NDT) used for a number of scientific and technical analyses [32–35] and here it was used for visualizing and evaluating the distribution of temperatures on the external surface of the building envelope.

The thermographic camera is a tool able to measure the infrared radiation density and convert this value in an electronic signal. This signal is elaborated in real time and return as result an image on the screen of the camera.

The acquisition data procedure is regulated by standard UNI EN 13187 [36]: according to its measures performed during the evening in the 20 of December, without solar radiation, rain, wind and fog, all factors that could have altered the data; the measurements were made by means a Flyr thermalcam (model FLIR T450sc).

Figure 6 shows a thermographic image of the building.

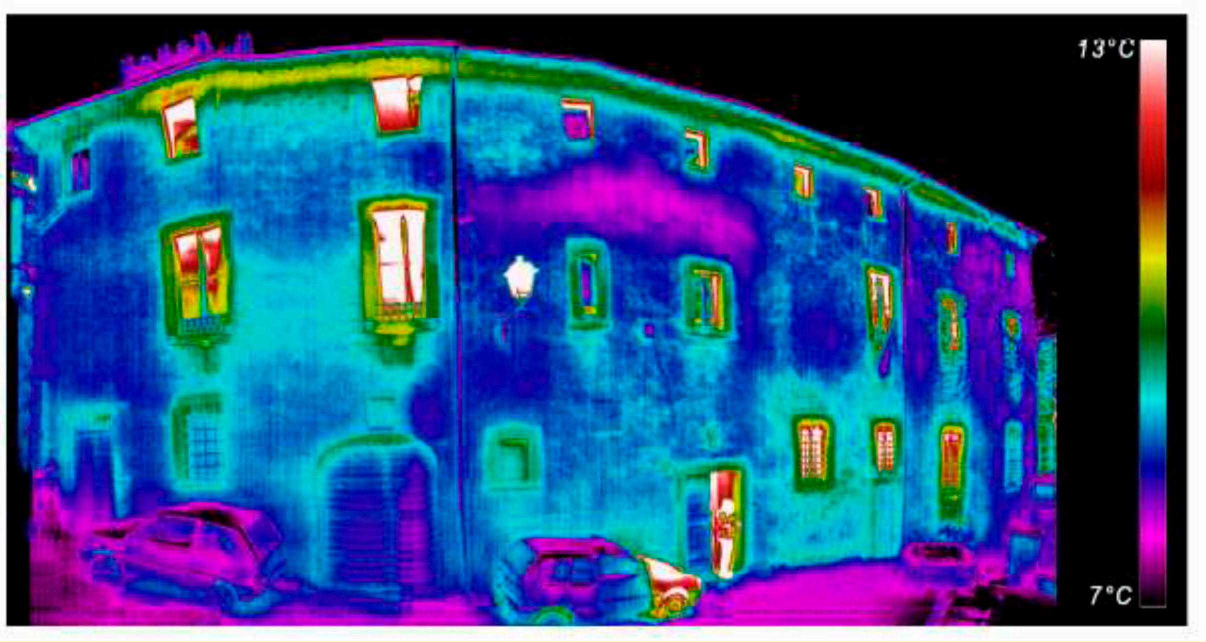

Figure 6. Thermographic analysis.

The building thermographic analysis allows us to identify two areas where the thermal dispersion is high: window fixtures and the connection between roof and walls. An analysis of the fixtures was already presented in Section 3.2.2. The connection between roof and walls shows a thermal discontinuity along the roof perimeter. This problem can be solved applying an insulating layer from the inside or completely renovating the covering.

4. Results and Discussions

The procedure started by first calculating the building ideal requirement of thermal energy for heating and cooling in the original conditions, without the application of any intervention of requalification; then the calculation was performed hypothesizing the application of four interventions of requalification: the insulating plaster, the fixtures substitution and the thermal bridge reduction were considered separately, while the solar film was computed together with fixtures application (Section 3.2.3).

In the original conditions of the building, results of the energy evaluation for the air conditioning, indicated a total energy requirement of 79,377 kWh per year: 67,402 kWh for the winter heating period and 11,975 kWh for the summer cooling period. The amount of energy required in each month is reported in Table 2.

Table 2. Original condition: monthly energy consumption.

kWh	January	February	March	April	May	June	July	August	September	October	November	December	Total
Q_H	14,192	11,938	9694	5720	1768					3317	7596	13,178	67,402
Q_C							6562	5413					11,975

4.1. Interventions

4.1.1. Plaster Substitution

The application of insulating plaster caused a change in the external walls transmittance: this value moves from 1.009 W/m^{2}K, before the intervention of requalification, to 0.586 W/m^{2}K.

This intervention involved two opposite effects in winter and summer: a reduction of transmittance implied lower thermal dispersion in winter and consequently a lower amount of energy request for air conditioning, but in the summer the cooling loads increased for the obstruction that the new plaster opposed to the dispersion of the energy entering through the windows in the form of solar radiation.

The monthly energy consumption following the intervention of plaster substitution is shown in Table 3.

Table 3. Plaster substitution: monthly energy consumption.

kWh	January	February	March	April	May	June	July	August	September	October	November	December	Total
Q_H	12,045	10,097	8108	4715	1415					2737	6353	11,166	56,636
Q_C							6925	5832					12,757

As a result of the application of insulating plaster, the obtained winter energy saving was about 15.97%, while the request for the summer cooling increase of 6.53% (Table 4). This means that the energy for the summer air-conditioning was subtracted from the energy gain obtained in winter: this calculation evidenced a consisting annual energy saving of more than 14%.

Table 4. Plaster substitution: annual energy consumption before and after the intervention.

	Before	After	Before − After	%
Q_H	67,402 kWh	56,636 kWh	10,766 kWh	15.97
Q_C	11,975 kWh	12,757 kWh	−782 kWh	−6.53
Tot	79,377 kWh	69,393 kWh	9984 kWh	12.58

These results, considering the easiness of plaster application too, showed the convenience of the intervention of plaster substitution.

4.1.2. Substitution of Fixtures

The substitution of fixtures and the introduction of low emission window system was an intervention of energy requalification required by the building; in the phase of energy analysis of the original envelope the fact that a high amount of energy dispersion for transmission through the window elements and that their substitution would lead to a noticeable amount of energy saving emerged.

In Table 5 the variation of transmittance and emissivity as a consequence of the intervention of fixture substitution is reported.

Table 5. Fixture substitution: variation of parameters before and after the intervention.

	Before	**After**
Transmittance (W/m^2K)	5; 5.7	1.4
Emissivity	0.837	0.1
Solar energy transmittance	0.765	0.603

The energy saving associated with the fixture substitution gave satisfactory results for the winter air conditioning, and acceptable results for the summer one (Table 6). In the winter period the heat transmission was the factor that mainly influenced the energy loss and on this parameter the low emission insulating glass had an optimal performance, reducing transmittance from 5 and 5.7 W/m^2K to 1.4 W/m^2K (a reduction of 75%); in the summer situation, the main effect was due to the irradiance, which entering trough the transparent elements. Anyway in the summer period, a low amount of energy savings was obtained: the energy consumption for heating decreased from 11,975 kWh to 11,698 kWh (Table 7).

Table 6. Fixture substitution: monthly energy consumption.

kWh	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Total**
Q_H	12,496	10,507	8505	5000	1543					2786	6660	11,592	59,088
Q_C							6377	5321					11,698

Table 7. Fixture substitution: annual energy consumption before and after the intervention.

	Before	**After**	**Before − After**	**%**
Q_H	67,402 kWh	59,088 kWh	8314 kWh	12.33
Q_C	11,975 kWh	11,698 kWh	227 kWh	2.31
Tot	79,377 kWh	70,786 kWh	8591 kWh	10.82

The winter energy saving of 12.33% summed to the summer one of about 2%, for a total annual amount of 10%, indicated that the intervention of fixtures substitution was extremely advantageous.

4.1.3. Application of Solar Films

The purpose of the solar films was a strong reduction of the energy for the summer air-conditioning: this implied less solar gain in the winter and reduced natural lighting that was compensated with artificial lighting. The balance of these two needs to produce acceptable energy advantages.

The variation of parameters implied in the energy evaluation as consequence of the intervention are showed in Table 8.

Table 8. Solar film application: variation of parameters before and after the intervention.

	Before	**After**
Transmittance (W/m^2K)	5; 5.7	1.4
Emissivity	0.837	0.1
Solar energy transmittance	0.765	0.22
Shading factor	1	0.25

As it is possible to notice in Table 9, the energy request as for the winter demand as for the summer cooling diminished as a consequence of the solar films application.

Table 9. Solar film application: monthly energy consumption.

kWh	January	February	March	April	May	June	July	August	September	October	November	December	Total
Q_H	12,832	10,903	9016	5422	1725					3147	6963	11,899	61,906
Q_C							4983	4171					9154

The annual energy saving achievable with this intervention was more than 10%, in which the summer saving is the higher, superior to 20% (Table 10).

Regarding to the winter air-conditioning, the use of solar films allowed to obtain an acceptable energy gain of 8%: this value, even lower than the energy saving obtained with the substitution of fixtures (12%), resulted favorably considering the substantial diminution of request for summer air-conditioning.

Table 10. Solar film application: annual energy consumption before and after the intervention.

	Before	After	Before − After	%
Q_H	67,402 kWh	61,906 kWh	5496 kWh	8.15
Q_C	11,975 kWh	9154 kWh	2821 kWh	23.56
Tot	79,377 kWh	71,060 kWh	8317 kWh	10.48

The installation of solar films on high thermal efficiency glazings resulted very convenient in elevated sunny places like Tivoli, even to the detriment of a small diminution in the winter energy saving.

4.1.4. Thermal Bridge Reduction

The thermographic analysis of the building, allowed us to find out two typologies of thermal anomalies, the first represented by a zone located in the junction between the walls and the roof; the second placed in correspondence of the window frames, due to the dispersion caused by the original fixtures. The measurement of transparent surfaces was not reliable for the different emissivity of the glass. Obtained results are yet presented in Figure 6.

For what concerns the fixtures, an analysis after their substitution was yet carried out (see Section 4.1.2); the thermal discontinuity visible under the whole roof perimeter could be eliminated through the application of a little insulating layer or with a complete renovation of the roof; here the first solution was considered.

As showed in Table 11 the reduction of the energy transmission through the thermal bridges allowed to obtain a small diminution of air-conditioning in all winter months, but an increase of the internal thermal load in two summer months.

Table 11. Thermal bridge reduction: monthly energy consumption.

kWh	January	February	March	April	May	June	July	August	September	October	November	December	Total
Q_H	13,359	11,267	9103	5334	1619					2983	7129	12,448	63,242
Q_C							6762	5624					12,386

The comparison of results obtained with the energy analysis performed before and after the intervention of thermal bridge reduction, evidenced low annual energy savings (Table 12).

Table 12. Thermal bridge reduction: annual energy consumption before and after the intervention.

	Before	**After**	**Before − After**	**%**
Q_H	67,402 kWh	63,242 kWh	4160 kWh	6.17
Q_C	11,975 kWh	12,386 kWh	−411 kWh	−3.43
Tot	79,377 kWh	75,628 kWh	3749 kWh	4.72

From these results emerged that the intervention of thermal bridge reduction was not convenient for the building under exam for the very small gain obtained.

4.2. Analysis

As a consequence of the results presented, the appropriate interventions for the energy requalification of the examined building turned out to be the fixture substitution with the installation of the solar film on glasses and the application of the insulating plaster.

Using the evaluation adapted to users, the energy saving derived from the sum of this three interventions was more than of 18,000 kW/h per year that corresponds to an energy reduction of about 24% (Table 13), if compared with the energy request for the building air-conditioning before the intervention.

Table 13. Annual energy reduction after the interventions.

	Plaster		**Fixtures + Solar Films**		**Tot**	
	kWh	%	kWh	%	kWh	%
Q_H	10,766	15.97	13,810	20.49	24,576	36.46
Q_C	−782	−6.53	3048	25.45	2266	18.92
Tot	9984	12.58	16,908	21.30	−18,301	33.88

The energy gain obtained with the ameliorative interventions are well distributed between summer and winter air-conditioning: the value of energy saving reached in the winter heating was of about 36.46%, while in the summer cooling was of about 19%.

In a town like Tivoli, characterized during summer by elevated values of solar irradiance and hot weather, to obtain a reduction higher than 15% on the summer air-conditioning is a satisfactory result; moreover a gain close to a 35% reduction in the winter air-conditioning, in a location where the external temperature reaches 0 °C, obtained with the easy intervention of insulating plaster application, is a good result.

5. Conclusions

The aim of the paper was to show how to obtain, with easy requalification interventions, consistent energy savings on historical buildings.

As the examined building was built in the 15th Century and sited in the historical center of Tivoli, it was important to study which, among the possible interventions, were easy to realize, and at the same time can ensure an elevated energy saving potential respecting the structure, the image and the history of the building based on the passive strategy approaches.

The energy analysis was performed on the original building wall as considering each single intervention, through the calculation of the annual energy for air-conditioning with the methodology of the evaluation adapted to users indicated in the norm [29]; the real climatic data for the town of Tivoli and the data concerning the envelope derived from the analysis of the real building were used.

The energy requalification interventions applied to the building under exam were: the application of the insulating plaster, the substitution of fixtures, the use of solar films and the reduction of thermal bridges.

The results of the calculations of each single intervention showed that all the four hypotheses produced a reduction of the energy request for the winter air-conditioning, while only with the fixtures substitution and the solar films application we obtained an energy reduction for the summer air-conditioning; in fact the application of the insulating plaster and the reduction of thermal bridge increased the energy cost for cooling, as the consequent transmittance reduction involved an increase of the summer cooling load.

In the case of insulating plaster application, the increase of the energy amount for cooling was widely compensated by the diminution obtained with the heating; the same thing did not happen for the reduction of the thermal bridge that for this reason was considered an inconvenient intervention.

The combined analysis of the three convenient interventions indicated that their execution would produce a considerable energy requalification: the annual gains related to the energy for winter air-conditioning would be more than 24,000 kWh, and those related to the summer situation would be about 2200 kWh, for a total energy saving of about 33% respect to the original situation.

The work developed demonstrated therefore how it is possible to intervene with actions of energy requalification on historical buildings, that form a large percentage of the Italian heritage, obtaining appreciable energy saving and, at the same time, guaranteeing the historical integrity of the building and its correct visual insertion in the surrounding urban texture.

Author Contributions

The study was designed by Chiara Burattini, Fabio Bisegna, Franco Gugliermetti and Andrea de Lieto Vollaro. Fabio Nardecchia and Lucia Cellucci carried out the numerical simulations. Ferdinando Salata and Iacopo Golasi retrieved the data from yearbooks and professional websites and reviewed the literature related to the research. The results were then analyzed by Chiara Burattini, Fabio Nardecchia and Lucia Cellucci. Experimental measurements on the field were carried out by Fabio Bisegna. Model design and English corrections were undertaken by Ferdinando Salata and Iacopo Golasi. Finally, Franco Gugliermetti and Andrea de Lieto Vollaro, the full professors of the research group, supervised the work related to the paper and the execution of its various phases.

Conflicts of Interest

The authors declare no conflict of interest.

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