Measurement of thermophysical properties coupled with LCA assessment for the optimization of a historical building retrofit

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Abstract. Historical buildings are a significant part of the Italian building stock and, in most cases, need deep refurbishment interventions to reach the energy criteria required by the current standards. A workflow that integrates on-site surveys and building modeling is mandatory to obtain effective energy saving measures. This work describes the analysis and modeling of the San Vito alla Rivera church, a XIV century building that was damaged during 2009 L’Aquila earthquake, suffering a partial collapse of the façade and of the roof. The latter was selected for a complete restoration that could improve its thermal performance while maintaining, as much as possible, the original structure. Several elements of the roof were collected in situ in order to measure, in laboratory, its thermophysical properties applying standard techniques and alternative methods based on infrared thermography. The accurate characterization of the materials was the starting point for the estimation of the environmental impact of the retrofit aimed to reach a defined thermal transmittance. A model of the building was created with TRNSYS software to calculate the energy consumption before and after the intervention. A Life Cycle Assessment (LCA) analysis was conducted on different insulation materials to determine the one with the lowest impact.

1. Introduction

The energy efficiency policies, both at an European and national level, are stressing the impact of buildings on the overall energy consumption. Economical and legislative actions are promoted to increase the energy savings of newly built and existing edifices. Historical and listed buildings are a wide part of the Italian building stock both in terms of quantity and value [1]. Frequently these edifices are residential or host institutional or commercial activities, hence they are required to comply with the current standards on energy performance, thermal comfort and safety, even if they were planned and built without these goals [2]. At the same time, especially in the case of listed buildings, they are subject to strict codes that strongly limit even small modifications to the original building structure. A further challenge is that usually few information are available on the design and material specification of these buildings and, even if data are present, the effect of aging on the structure must be taken into account. Nowadays several historical buildings must undergo a refurbishment process in order to comply with the energy performance prescribed by European and Italian standards and codes. The knowledge of the building condition is a primary necessity in order to plan an adequate retrofit strategy. For this reason, on-site surveys and laboratory testing should be performed before any other analysis. When
dealing with cultural heritage, the diagnostic instruments that are non-invasive and non-destructive are preferred or even mandatory. From this standpoint, infrared thermography [3] (IRT) is a well-established technique for the survey of buildings and the measurement of material properties [4, 5]. The data obtained from the survey should be utilized for the creation of a mathematical model of the building, where the availability of real data should significantly increase the accuracy and the reliability of the model itself. The model is necessary to compare the impact of different retrofit solutions both in terms of applicability and expected impact of the proposed measures. After the comparison of different solutions, only the most effective ones should be implemented and their impact should be measured. The complete process, summarized in figure 1, suggests that different and complex tasks should be completed by researchers and technicians with various and complementary skills.

![Figure 1. Workflow of the retrofit process of a historical building](image)

This study is focused on the first part of the retrofit process. In this framework, the goal of the work is underlining the limits and possibilities of the application of Life Cycle Analysis (LCA) during the modeling and evaluation of energy savings phases. This method has been applied more and more frequently as a planning tool for new buildings, however it is not commonly chosen for building retrofit and in particular for the renovation of historical buildings. In Italy the LCA method is not mandatory, therefore it has been applied only in few cases (e.g. planning competitions) and only under direct request of the customer [6, 7]. The stock of Italian historical and listed buildings that needs retrofit interventions would benefit from the application of LCA, as it would lead to the use of materials with a lower environmental impact. The main barriers to the diffusion of LCA for historical building retrofit are the lack of a standardized approach and the difficulty of obtaining accurate data about the manufacturing processes and the material properties of construction elements.

2. Building evaluation

2.1. On-site survey

The building studied in this work is the San Vito alla Rivera church, located inside the historical city center of L’Aquila (Italy). This church dates back to the 14th century and was damaged by the 2009 earthquake, suffering a partial collapse of the roof and the façade, as shown in figure 2. The on-site survey on the building started with a thermographic campaign that was aimed to identify hidden structural elements and to investigate the thermal behavior of the building. The experiment were repeated in summer and winter conditions with the use of advanced scanning techniques. Other measurements were performed with video endoscopy and temperature sensors. The roof was the thinnest and most damaged element, therefore it was easier to identify it as the primary component that should be retrofitted.

2.2. Laboratory testing – Thermal diffusivity

Few material samples were collected from the remains of ceiling tiles and from walls. The most important material parameters from a thermal standpoint are thermal conductivity ($\lambda$) and thermal diffusivity ($\alpha$), defined in equation (1) as:

$$\alpha = \frac{\lambda}{\rho c_p}$$
where $\lambda$ is the thermal conductivity (W m$^{-1}$ K$^{-1}$), $\rho$ is the volumic mass (kg m$^{-3}$) and $c$ is the specific heat (J kg$^{-1}$ K$^{-1}$). Conductivity is related to the building behavior in steady state conditions while diffusivity influences the dynamic performance of the building. Several techniques based on infrared thermography are available to measure the thermal diffusivity of materials and have been applied in the literature [8]. In this work firstly a transmission method was used [9], were one side of the sample was heated with a pulse produced with a 1000 W lamp and the temperature increase was measured with the thermal camera on the opposite side. A different measurement was carried on in a reflection scheme, where the specimen was heated with a laser on a localized spot and the temperature increase and distribution was measured with the thermal camera on the same side. This technique, with an adequate setup, could be transferred from the laboratory to the on-site survey. The third method is derived from the classical Ängstrom method that applies two thermoelectric devices to create a sinusoidal heating on one end of the specimen while the thermal camera measures the propagating thermal wave along it. These techniques and the analysis of results are described in details in [10] and the final results are resumed in table 1.

### Table 1. Comparison of thermal diffusivity measurements obtained with different procedures

| Method               | $\alpha$ [m$^2$ s$^{-1}$] average value | $\alpha$ [m$^2$ s$^{-1}$] standard deviation |
|----------------------|----------------------------------------|---------------------------------------------|
| Transmission method  | 4.96 E-07                              | ± 2.01 E-08 (-4%)                           |
| Reflection method    | 5.07 E-07                              | ± 9.85 E-08 (± 19.4%)                       |
| Wave method          | 4.67 E-07                              | ± 3.80 E-08 (± 8.1%)                        |

2.3. Laboratory testing – Thermal conductivity

For small samples of construction materials, thermal conductivity could be measured directly on the specimen sandwiched between two thermoelectric modules that generate a heat flux through it, with an infrared camera monitoring the temperature gradient [11]. In this work also specific heat (with differential scanning calorimetry) and volumic mass were measured, making possible to derive the conductivity value from the diffusivity, as shown in table 2.

### Table 2. Comparison of thermal conductivity measurements obtained with different procedures

| Method                        | $\lambda$ [W m$^{-1}$ K$^{-1}$] average value | $\lambda$ [W m$^{-1}$ K$^{-1}$] standard deviation |
|-------------------------------|-----------------------------------------------|--------------------------------------------------|
| Direct measurement            | 0.76                                          | ± 0.01 (± 1%)                                    |
| Indirect (transmission method)| 0.64                                          | ± 0.06 (± 9.3%)                                  |
| Indirect (reflection method)  | 0.66                                          | ± 0.16 (± 24.7%)                                 |
| Indirect (wave method)        | 0.61                                          | ± 0.08 (± 13.4%)                                 |

3. Mathematical modeling

3.1. Building simulation

Several simulation strategies are available to model the thermal behavior of a building. In this work the San Vito church was studied with the commercial software TRNSYS version 16 [12].
software was chosen for the easy and reliable implementation and comparison of different energy savings measures. The creation of the model was based on a geometrical model, with respect to the sizes and orientations of walls, and on the measured thermal properties of the walls. When data could not be obtained directly, typical values derived from the literature were used. The TRNSYS software was used to determine hourly values of heating demand over one year of simulation. The weather data for the city of L’Aquila were selected from the standard weather libraries. The first simulation was performed to determine a baseline, with the hypothesis of a retrofit aimed to restore the building exactly as it was before the earthquake. Then the impact of energy saving measures was assessed. Usually the first retrofit option is the complete insulation of the external walls but in this case aesthetical and practical reasons discouraged this solution. From a structural standpoint the first element that should be retrofitted was the ceiling, where an insulating layer could be added inside the existing stratigraphy and the estimated thermal transmittance value was higher than 3 W m⁻² K⁻¹ [13]. A realistic goal was reaching a transmittance equal to 0.3 W m⁻² K⁻¹, value suggested by the current standards on energy efficiency. The second option was the replacement of the existing windows (single pane, metal frame) with new efficient glazing systems (triple pane, wooden frame) that could decrease the windows thermal transmittance to a value close to the one of the walls (around 1.3 W m⁻² K⁻¹). The replacement of windows has also a positive effect on building leakage. An estimation based on literature values led to quantify the decrease in thermal leakages equal to 25%. With the combination of both energy savings measures, the yearly energy demand was lower than 40%, going from the baseline value of 65000 kWh to the post-retrofit value of 38000 kWh. More simulations were performed with a parametric thickness of the insulation material on the roof, combining the energy output with the LCA method as described in the next chapter.

3.2. LCA method

The LCA method [14] was applied in two successive steps with different goals. Initially, three different insulating materials were compared to determine the one with the lowest impact. A multiple search conducted on the ECOshopping database of insulation materials [15] and on the EcoInvent 2.2 database [16, 17] led to group all the materials in three different categories. For each category one material was chosen on the basis of an estimated on-site availability. The first group was made by traditional material with very good thermal properties and low cost, and the selected material was extruded polystyrene (XPS). The second group was made by natural materials with good thermal properties and high cost, and the selected material was cork. The last group was made by intermediate thermal properties and cost, and the selected material was wood wool. The material properties are described in the next table, including the quantity needed to reach the target thermal transmittance of the renovated wall equal to 0.3 W m⁻² K⁻¹.

| Material   | Thickness [cm] | Volumic mass [kg m⁻³] | Thermal conductivity [W m⁻¹ K⁻¹] | Quantity [kg m⁻²] |
|------------|----------------|------------------------|----------------------------------|-------------------|
| Cork       | 11.6           | 120                    | 0.039                            | 13.9              |
| XPS        | 10.4           | 35                     | 0.034                            | 3.6               |
| Wood wool  | 26.9           | 400                    | 0.090                            | 107.6             |

The software used for the LCA calculation was SimaPro 7.3 [18]. The study considered the impact due to transportation from the manufacturer to the building site and also the impact of the end-of-life disposal of the materials. The available solutions for the end-of-life are various, including recycling; this work considered the material will be incinerated after use.
The LCA study could be conducted with different methodologies. The results shown in the next figures 2-5 were respectively obtained with five methods: IMPACT 2002+ v2.11, EDIP 2003 v1.04, EPS 2000 v2.07, Re.Ci.Pe. Endpoint (E) v1.09 / Europe ReCiPe E/A, and IPCC 2007 GWP 100a v1.02 [19,20,21]. All methods have different impact categories and different weighting factors. The obtained results are represented in figures 2-6 as environmental damage indexes.

**Figure 2.** Comparison based on IMPACT 2002+ method.

**Figure 3.** Comparison based on EDIP 2003 method
Figure 4. Comparison based on EPS 2000 method.

Figure 5. Comparison based on Re.Ci.Pe method.

Figure 6. Comparison based on IPCC method.
The comparison between materials is not straightforward, as different methods give different results. Moreover, the evaluation should rely only on relative comparison between materials analyzed with the same methods, as the absolute values cannot be compared between different methods. The best material for the majority of methods was Extruded Polystyrene (on the third column) while EDIP 2003 and IPCC gave different indications. For the EDIP method, the high impact is due to the category “Ozone depletion” that represents the 96.8% of the total impact. This is caused by the use of CFC-113, a foaming agent with a very high atmospheric lifetime, during the production process. Also for the IPCC method, the greatest part (81.7%) of the environmental damage is due to the presence of foaming agents, in this case HFC-134a, and to Carbon dioxide.

After the choice of XPS as the insulating material for the roof, several parametric simulations were made in TRNSYS software. The thickness of the insulating layer was changed from 0 to 35 cm with a step of 5 cm. The obtained annual energy consumptions were integrated with further LCA analysis, in order to determine if there was an optimum thickness with respect to energy consumption and material impact. The results obtained with five different LCA methods are shown in the next figures 7-11.

**Figure 7.** Comparison of different insulation thicknesses with the IMPACT 2002+ method

**Figure 8.** Comparison of different insulation thicknesses with the EDIP 2003 method
Figure 9. Comparison of different insulation thicknesses with the EPS 2000 method

Figure 10. Comparison of different insulation thicknesses with the Re.Ci.Pe. method

Figure 11. Comparison of different insulation thicknesses with the IPCC method
The effect of insulation is always positive, as even the thinner insulation is always better than the case without insulation, but an excess of insulation could be detrimental. Each method shows that the reduction of energy consumption, obtained increasing the insulation thickness, is counterbalanced by the increase of the environmental impact. Therefore an optimum thickness value could be identified and it is generally located between 5 and 15 cm. This result is shown in figure 12, where the parametric results for all the methods are reported.

![Figure 12](image)

**Figure 12.** The comparison of different insulation thicknesses with all methods allows to identify the optimum thickness value.

### 4. Conclusions

The study of a historical building aimed to an energy retrofit is a complex task, that should be arranged in multiple steps. The preliminary operations should be focused on the evaluation of the current state of building, from an energetic and structural point of view, gathering data with on-site surveys. In these phase the use of non-destructive evaluation techniques (e.g. infrared thermography) is always advisable and, in some cases, mandatory. This work showed how IRT could be successfully applied to characterize the main thermal parameters of a construction material.

The measured data are the basis or the benchmark value of building mathematical models that are necessary to evaluate the impact of different energy savings measures. In this case, for energetic and structural reasons, the best energy saving measure was the insulation of the roof. The combination of energy simulation and LCA to compare different insulating material and find the best solution is driven to a holistic approach, that should be considered when dealing with a multi-criterion optimization. The benefits of the insulation with respect to the baseline standard are as clear as the damages due to an excess of insulation. The results showed that different LCA methods find an optimum insulation thickness in the range between 5 and 15 cm, that contains the value of 10.4 cm that is suggested by the energy savings standards.

Future work on this building may regard the final part of the retrofit process, including the evaluation of the energy savings obtained with the implemented energy measures, or a more in-depth analysis of other possible energy saving strategies. More work should focus also on the transfer of different data types between each phase of the process, with the aim of integrating different sources into a single streamlined procedure.
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