Energy retrofit and conservation of built heritage using multi-objective optimization: demonstration on a medieval building

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Abstract

Energy retrofit of historic buildings is a complex activity, which requires a multidisciplinary approach. Interventions should limit energy consumption, consider users' comfort and preserve cultural and aesthetic values. While the impacts of interventions on energy performance and comfort can be quantified in advance using simulation software, conservation aspects are less tangible. In this paper, we propose a method to identify retrofit strategies that are optimal from an energy, comfort and conservation point of view. The first step is to choose a set of interventions and conservation aspects to consider. This requires a multidisciplinary team of experts. Next, quantitative metrics for assessing energy performance, comfort and conservation are defined. Through a multi-objective optimization, the combinations of interventions that yield the best tradeoffs among these objectives are found. We demonstrate the method on a calibrated EnergyPlus model of the "*Waaghaus*" (weigh house), a medieval building in Bolzano located in the north of Italy. The aim is to transform this currently vacant building into a cultural center. We considered the following interventions: external and internal envelope insulation with varying materials and thicknesses, airtightness improvements, replacement of windows and summer ventilation availability. Conservation aspects taken into account were visual, physical and spatial impact of the interventions on the building's heritage significance. We selected the hourly sum of all sensible and latent ideal loads for heating and cooling over a year as energy performance metric. All internal loads were modelled according to the planned future use of the building. We assigned a score to each intervention equal to the number of conservation aspects met. The yearly average of the absolute values of the predicted mean vote was used as a proxy for comfort. We performed the multi-objective optimization with the C code NSGA-II, which implements a genetic algorithm based on non-dominated sorting. As a result, we obtained solutions with an absolute mean PMV of 0.5, an annual ideal load for heating and cooling of 20 kWh/m^2 and a good level of conservation.

1. Introduction

The European building sector has a consistent number of historic buildings that can significantly affect the urban settlement. A substantial share of the European stock is older than 50 years with many buildings in use today that are hundreds of years old (European Commission, 2006). The potential for saving energy and reducing CO_2 emissions in existing buildings is high. For this reason, the European Commission has decided to develop a specific legislative framework in order to cut CO_2 emissions (Directives 2002/91/CE and 2010/31/UE), to increase the share of renewable sources (Directive 2009/28/CE) and to enhance the energy performance of existing buildings (Directive 2012/27/UE) by 2020. Many of these measures also affect the cultural heritage buildings that consume lots of energy (Mazzarella, 2014, De Santoli, 2014). Improving the energy efficiency and comfort in historic buildings, while simultaneously preserving and promoting the value and the historical character, is viable only by balancing the requirements of cultural protection, indoor comfort and energy efficiency. Only in this way is it possible to minimize the aesthetic, physical and visual impact of the energy efficiency measures on the conservation aspects (European Projects

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3ENCULT, EFFESUS, Sechurba, New4Old, Co2olBricks).

This work presents a method for optimizing retrofit solutions for historic buildings in order to improve their energy performance and internal comfort, and to preserve their cultural value.

For this purpose we developed a methodology based on the following steps:

- selection of a general set of energy retrofit for historic buildings, considering conservation aspects, energy performance and comfort;
- evaluation of the conservation impact on each retrofit measure;
- quantification of energy consumption and comfort using a dynamic simulation model;
- definition of the combinations of interventions that yield the best tradeoffs between these objectives, through a multi-objective optimization.

This method has been applied to the "*Waaghaus*" (German for "weigh house"), a medieval building located in the historic center of Bolzano, a city in the north of Italy. It represents a typical historic Tyrolean building, 4 with floors and basement in stone and a wooden roof. It is one of the case studies of the FP7 European project 3ENCULT (Efficient Energy for EU Cultural Heritage). This allowed us to conduct a series of diagnostic and energy modelling activities in order to acquire a deeper knowledge of the energy performance of the building. In particular, a calibrated EnergyPlus model has been realized to quantify the energy consumptions in detail with the objective to define the most appropriate interventions. With this model, a multi-objective optimization has been carried out using the genetic algorithm NSGA-II in order to identify the optimal solutions as regards energy consumption, compatibility with conservation and comfort.

2. Methodology

2.1 The case study

The "*Waaghaus*" was built at the end of the twelfth century and formed part of the first nucleus of the city centre. Until 1780, the building accommodated the *Fronwaage*, an officially calibrated public set of scales. Afterwards it was used for commercial and residential purposes. By the 1990s, the house was no longer in use.

The "*Waaghaus*" has all floors and the cellar built in masonry composed of natural stone with lime mortar joints. Exterior walls have a thickness of about 60 to 80 cm. Except for the basement, the stonework on both sides of the walls is mostly covered with historic lime plaster, and in parts with wall paintings and frescoes that should be preserved. Most of the original windows were replaced by box-type windows in the 1950s/60s (U_g=5.8 W/m^{2}K; U_w=2.7 W/m^{2}K) that are now heavily damaged and dirty. The building has a saddle roof with wooden rafters and casing, a roofing cardboard (bitumen) on the wooden casing, and above it a tile cladding. In its current state, it is partially insulated with 8 cm of mineral wool between the rafters covered with gypsum plasterboard.

Fig. 1 The Waaghaus in Bolzano (© Florian Berger/EURAC)

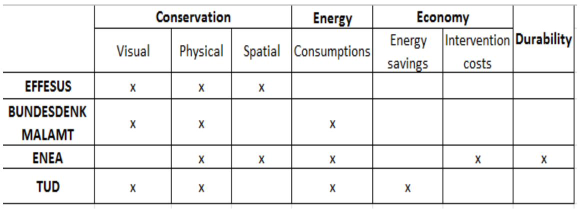
2.2 Selection of the retrofit interventions

The retrofit solutions considered are commonly used for historic buildings to balance conservation aspects, comfort, and energy performance (Changeworks, 2008; English Heritage, 2008; SPAB, 2014). We focused mainly on passive solutions for the building envelope. The interventions encompass: airtightness improvements, exterior walls insulation, whole window or pane replacement, roof insulation, and the installation of a mechanical cooling system. We did not consider floor and ceiling insulation due to the technical difficulties in applying it to vaults and decorated ceilings. For the exterior walls and the roof, we considered both exterior and interior insulation applied either to all surfaces or only to surfaces without any historic significance (surfaces without frescos or visible parts of historic value).

For the external insulation, we chose between permeable (rock wool λ=0.038 W/mK; expanded cork λ=0.043 W/mK) and impermeable (calcium silicate λ=0.076 W/mK) materials, with thicknesses from 10 to 20 cm. For the interior insulation, we chose between natural (rock wool λ=0.038 W/mK; expanded cork λ=0.043 W/mK) and artificial materials (aerogel λ=0.013 W/mK; capillary active insulation λ=0.031 W/mK; calcium silicate λ=0.076 W/mK), with thicknesses from 3 to 10 cm (1 cm of aerogel). To improve the performance of the roof, we considered 20 cm of rock wool or cork insulation on the outside and 10 cm of one of the above mentioned insulation materials on the inside. Two interventions were considered for the windows: pane replacements with low-e glass (U_g=2.126; τ_v=0.81; g=0.79) and full window replacements with triple-glazed units (U_g=0.57; τ_v =0.68; g=0.56). Both interventions were accompanied by airtightness improvements of the whole building (0.3 modelled air changes per hour). In addition, we optimized the natural ventilation air change rates and the minimum temperature difference between the inside and the outside for which natural ventilation was active, in order to investigate if comfort could be reached also without a mechanical cooling system. The air change rates ranged from 0.5 to 10 h^{-1} and the temperature differences from 1 to 5 K.

2.3 Quantifying the impact of each intervention on conservation aspects

A number of studies deal with the conciliation of energy and conservation related aspects in historic building retrofits. In the EFFESUS Project (Eriksson, Hermann, Hrabovszky-horváth, & Rodwell, 2014) the intervention impact on conservation has been divided into visual, physical and spatial impact. "Visual impact" (V) refers to the alteration of the aesthetic appearance of the building; "physical impact" (P) refers to the conservation of the original materials, and "spatial impact" (S) refers to the retention of the original shapes and dimensions. The impact of the most common energy retrofit measures on each envelope component (exterior wall, interior wall, roof, etc.) was analyzed from a conservation point of view. The Austrian Bundesdenkmalamt (Bundesdenkmalamt, 2011) presented the visual and physical impact of many types of energy retrofit, coupled with qualitative indications for energy efficiency. The Italian ENEA (Boriani, Giambruno, & Garzulino, 2011) also presented indications for physical and spatial impact on conservation, energy savings, costs and durability of the retrofit interventions. All these works can be thought of as qualitative guidelines for the energy refurbishment of historic buildings. Finally, a study conducted by the Technische Universität Dresden - TUD (Grunewald, Will, & Pohl, 2010) presented more quantitative results on the compatibility of energy saving measures with conservation. Table III summarizes the most important aspects taken into account by these works.



	Conservation			Energy	Economy		Durability
	Visual	Physical	Spatial	Consumptions	Energy savings	Intervention costs	
EFFESUS	x	x	x				
BUNDESDENKMALAMT	x	x		x			
ENEA		x	x	x		x	x
TUD	x	x		x	x		

Table III Results from a literature review on the impact of energy retrofit measures on the conservation of historic buildings

We decided to start from the EFFESUS approach ((Eriksson, Hermann, Hrabovszky-horváth, & Rodwell, 2014), analyzing the visual, physical and spatial impact of different energy retrofit measures on the conservation of each building component and distinguishing between exterior (roof, exterior and interior surfaces of the exterior wall, windows) and interior (ceilings, internal walls) components.

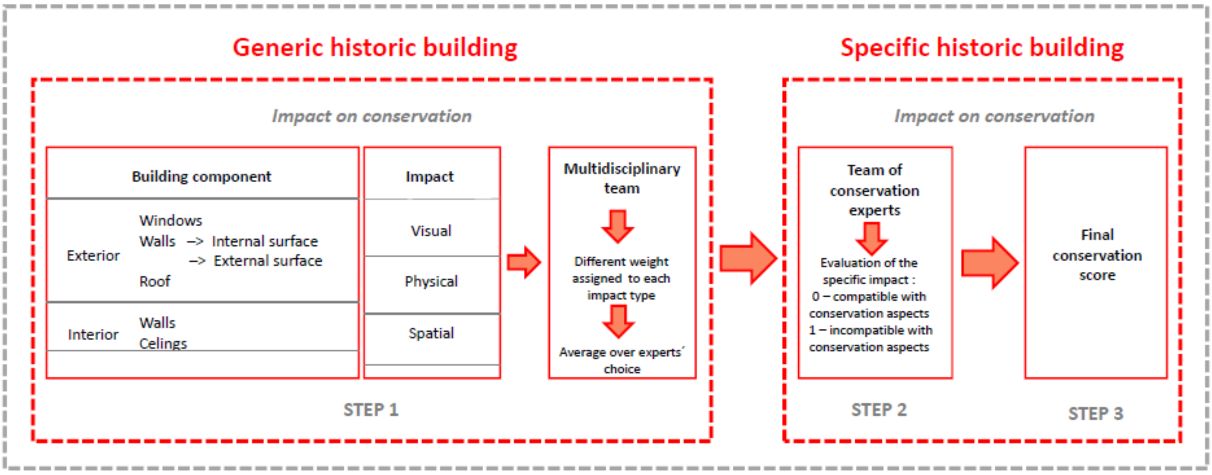


Fig. 2 – Steps to define the impact of retrofit measures on conservation

Three steps were performed to assign a conservation score to each type of impact and each type of retrofit. As a first step, a multidisciplinary team of technicians and conservation experts assigned different weights to each impact type (V, P, S) and for each considered building component. We then calculated the average of the experts' choices to take them into account in equal measure. The results of this first step are independent from the specific case study and can be applied to historic buildings in general.

As a second step, a team of conservation experts evaluated for each type of impact and each considered building component whether a retrofit intervention was compatible with conservation or not. The evaluation could thus be 0 (incompatible) or 1 (compatible). In this phase the specific characteristics of the case study (in our case the "*Waaghaus*") are taken into account.

The final conservation score for each retrofit intervention was calculated as the sum of the zeros and ones obtained in the second step. This means that each type of impact and building component was given equal importance. The highest conservation score (no retrofit) was 24, the lowest (all interventions) was 8. The overall methodology is sketched in Fig. 2.

2.4 Quantification of energy consumption and comfort

In order to estimate the hourly ideal heating and cooling load and the comfort, we modelled the Waaghaus in EnergyPlus 7.2 dividing the building into 29 thermal zones. To obtain reliable results, the model was calibrated to indoor air temperatures monitored in representative zones.

In accordance with the plan to transform the building into a museum after the refurbishment, we considered all thermal zones as occupied and therefore air-conditioned except for the basement and the wings on the top floor. We modelled the internal gains as per ASHRAE Fundamentals (ASHRAE, 2009): 145 W/person (75 sensible heat; 70 latent heat), 14 m^2 occupied space per person (own estimation); 11.84 W/m^2 for lighting (57% radiant sensible heat); no other equipment; all gains active from 10:00 until 18:00. The heating system was set up with unlimited power and the cooling system as well in case the retrofit measures included the installation of a mechanical cooling system.

Setpoint and setback in winter (from 15 October to 15 April) were 20 and 16°C, respectively. The setpoint in summer (from 15 June to 15 September) was 26°C.

Overheating was prevented with an external shading system that was activated if the solar horizontal radiation exceeded 400 W/m^2. The outdoor conditions were taken from the Typical Meteorological Year (TMY) file for Bolzano available on the Meteonorm website (http://meteonorm.com).

2.5 Multi-objective optimization

Multi-objective optimization of energy models with the purpose to find optimal tradeoffs between energy savings and costs is quite in use (Chantrelle et al., 2011; Hamdy, Hasan, & Siren, 2011; Murray, Walsh, Kelliher, & O'Sullivan, 2014). In this work, we propose to consider within this framework also the compatibility with conservation.

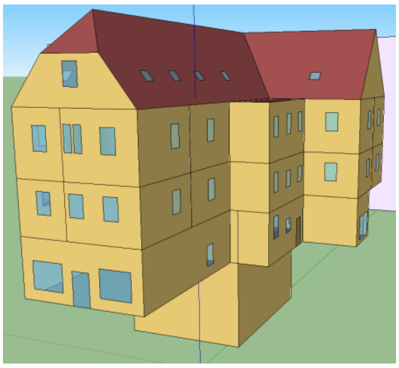


Fig. 3 – Geometry model of the *Waaghaus*

To perform an optimization simultaneously taking into account energy performance, comfort and conservation, we used the NSGA-II algorithm (Deb, Member, Pratap, Agarwal, & Meyarivan, 2002). NSGA-II is a genetic algorithm that performs a non-dominated sorting of the retrofit solutions, keeping those with the highest rank in the pool. To avoid crowding, optimal solutions which are distant from other optimal solutions are preferred. Within the pool, tournament selection, crossover and mutation operations are performed. Further, *elitism* is used to prevent the loss of optimal solutions once they have been found.

We minimized (maximized in case of the conservation score) the following objective functions:

- total annual sensible and latent ideal heating and cooling load;
- comfort, expressed as mean absolute Predicted Mean Vote (PMV) during the occupation hours, averaged over all thermal zones weighted by zone volume;
- conservation score, computed as explained in Section 2.3.

We simulated 20 generations of an evolving set consisting of 300 retrofit solutions.

3. Results and discussion

3.1 Check on the number of generations

In order to check that the number of simulated generations was necessary and sufficient, we plotted the non-dominated retrofit solution sets up to the 10th and 15th generation (Figs. 4 and 5). Fig. 6 shows the final non-dominated solutions.

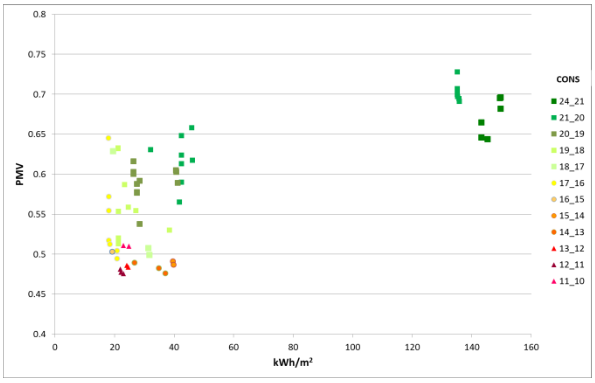


Fig. 4 – Non-dominated retrofit solutions up to the 10th generation

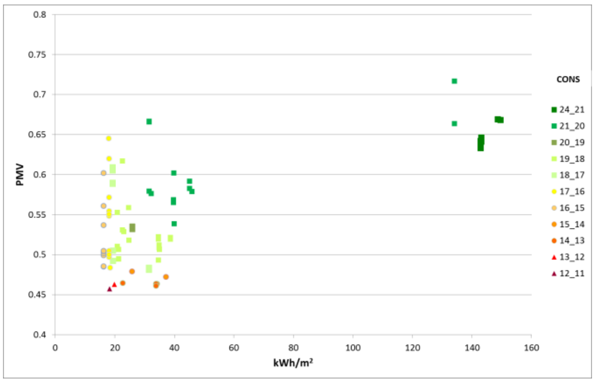


Fig. 5 – Non-dominated retrofit solutions up to the 15th generation

One expects that the number of dominated solutions is higher in the first generations and gets progressively lower thereafter. A solution is said to be dominated by another solution if the latter is better with respect to all objective functions than the former. Further, solutions should gradually move towards the theoretical Pareto front (which is the theoretical surface composed of all globally optimal solutions) and spread on it. Finally, solution sets should change less and less over time except for sporadic and random wiggling motions induced by the mutation operator. Judging from Figs. 4 to 6, the 20th generation seems to us a reasonable milestone in reaching these objectives, although one could arguably obtain improvements by simulating more generations.

3.2 Discussion on the optimal retrofit solutions

81 optimal (non-dominated) retrofit solutions were identified (Fig. 6). As all these solutions are optimal, an improvement of one performance target (energy, comfort, or conservation) is always associated with a deterioration of another performance target. Nevertheless, there can be better or worse solutions, in the sense that a slight deterioration of one target could lead to big improvements in other targets.

The retrofit solutions decompose into two clusters. The cluster on the right in Fig. 6 contains all the retrofit solutions without any intervention related to the airtightness or the windows. Whole window or pane replacements were always associated with comprehensive airtightness improvements at building level, which explains why there is such a big difference in ideal load and comfort between the two clusters.

No airtightness or fenestration provisions. The annual ideal heating and cooling load for retrofit solutions without any intervention on the airtightness or the windows is high (between 130 and 150 kWh/m^2) and the discomfort as well (mean absolute PMV above 0.63), especially because of the high infiltration rate caused by the numerous cracks in the external wall and damaged windows, but the conservation score is of course excellent. *Airtightness provisions and replacement of windowpanes.* Solutions where only the windowpanes were replaced are located on the left cluster, with ideal loads between 19 and 46 kWh/m^2, mean absolute PMVs ranging from 0.46 to 0.68, and conservation scores between 13 and 21. If insulation was applied only to surfaces without any historic value, ideal loads and mean absolute PMV were at least 40 kWh/m^2 and 0.52, respectively. These targets and a conservation score of 20 were reached by insulating the parts of the façade and the roof without any historic value from the outside with 20 cm expanded cork. Practically the same performance was obtained with rock wool. This is not surprising as both materials have comparable thermal properties and a lower thermal conductivity than calcium silicate. Insulating both the façade and the roof from the inside with 3 cm of capillary active material or rock wool increased the ideal load by 5 kWh/m^2 compared to insulating from the outside. The lowest mean absolute PMV was 0.58. A higher comfort could be attributed to some extent to an increase in the natural ventilation rate, which varied between 2 and 10 h^{-1}. The minimum temperature difference between the inside and the outside for which natural ventilation was active ranged between 1.0 and 2.6 K.

Airtightness provisions and replacement of windows. Focusing only on retrofits where surfaces with historic value were preserved, little could be gained in terms of energy savings and comfort by replacing the whole windows instead of the windowpanes. This indicates that other factors such as infiltration play a major role. Further, the glass to wall ratio of the building is only 10%.

Façade insulation. We concentrate on retrofit solutions in which airtightness provisions were taken and all surfaces with historic value were preserved. Both external and internal insulation solutions were identified.

Façade insulation from the outside. In case of external insulation, total ideal load, mean absolute PMV and conservation score varied between 37 and 40 kWh/m^2, 0.52 and 0.64, and 19 and 20, respectively. A façade insulation with 10 or 20 cm rock wool applied from the outside was the preferred choice. The roof could be insulated from the outside or from the inside with rock wool or expanded cork. Mechanical cooling was switched off in all cases. Instead, cooling was provided by natural ventilation. The lower mean absolute PMVs were obtained with air change rates varying between 7 and 10 h^{-1}.

Façade insulation from the inside. Retrofits performed with 3 cm rock wool or the capillary active insulation were fairly competitive with the external insulation solutions insofar as ideal loads of 45 kWh/m^2 along with mean absolute PMVs of 0.58 could be reached. The conservation score was 21.

Insulation of surfaces with historic value. In order to understand what could be gained in terms of load reduction or comfort increase, we considered also retrofit solutions in which all surfaces were insulated, independent of their historic value. In case of the Waaghaus, surfaces with historic value take up about 25% of the total available façade surface for insulation. We would like to stress that these retrofits are unacceptable, as they would definitely spoil the heritage value of the building. A solution with low ideal load and mean absolute PMV (16 kWh/m^2 and 0.49, respectively) was given by insulating façade and roof from the outside with 20 cm rock wool. In addition, windows were replaced. Although during the heating season the ideal heating system was switched on during opening hours, visitors of the museum were cold (PMV lower than -0.5) approximately 40% of the time because of the low radiant temperature in the morning. This issue can be resolved by switching the heating system on a couple of hours before the museum opens. Outside the heating season, in case mechanical cooling was switched off, visitors were hot (PMV higher than 0.5) only about 20% of the time thanks to the high natural ventilation rate (9 h^{-1}). The conservation score of this solution was 16. Good tradeoffs for all the three performance targets are highlighted in Fig.6 (black circle).

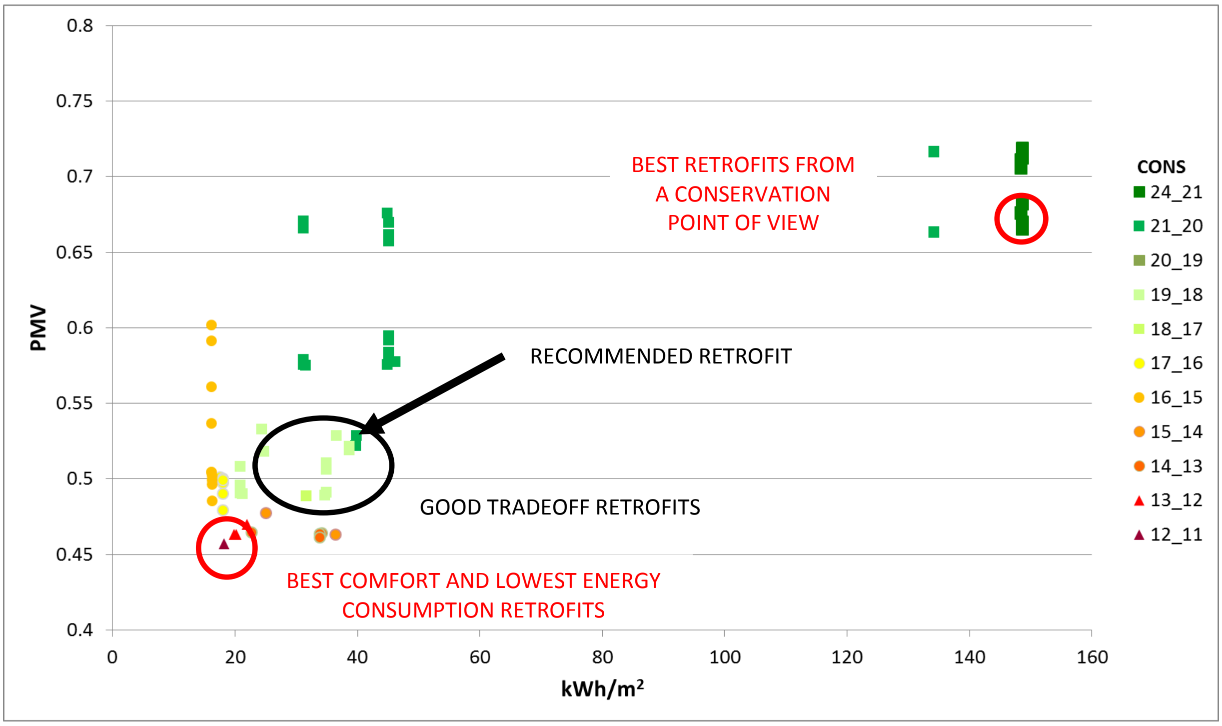


Fig. 6 – Optimal retrofit solutions up to the 20th generation

4. Conclusion

In this paper, we have presented a methodology aimed at identifying retrofits for historic buildings which are optimal in terms of three performance targets: potential energy savings, comfort, and conservation. An important step has been to assign a conservation score to each intervention, based on the opinion of technicians and conservation experts. The best trade-off retrofit solutions have been computed performing a multi-objective optimization. We have discussed different interventions and have quantified their impact on the performance targets.

Within the limitations of this study, we recommend a retrofit with an annual ideal heating and cooling load of 40 kWh/m^2, a mean absolute PMV of 0.52 and a conservation score of 20 out of a maximum of 24 (cf. Fig. 6). In this solution, the façade and the roof are insulated from the outside with 20 cm rock wool and 20 cm expanded cork, respectively. To reduce infiltration and further enhance the thermal performance of the façade, the building is made airtight and the windowpanes are replaced. Finally, no mechanical cooling system is provided. Instead, natural ventilation is maximized in terms of duration and air changes per hour.

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Legislative framework

DIRETTIVA 2002/91/CE DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 16 dicembre 2002 sul rendimento energetico nell'edilizia.

DIRETTIVA 2010/31/UE DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 19 maggio 2010 sulla prestazione energetica nell’edilizia (rifusione).

DIRETTIVA 2009/28/CE DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 23 aprile 2009 sulla promozione dell’uso dell’energia da fonti rinnovabili, recante modifica e successiva abrogazione delle direttive 2001/77/CE e 2003/30/CE.

DIRETTIVA 2012/27/UE DEL PARLAMENTO EUROPEO E DEL CONSIGLIO del 25 ottobre 2012 sull'efficienza energetica, che modifica le direttive 2009/125/CE e 2010/30/UE e abroga le direttive 2004/8/CE e 2006/32/CE.