Energy saving potentials in historic buildings' renovations: to which extent is the heating demand limit value (SIA 380/1) reachable and at which costs?

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Abstract. The renovation of historic buildings is essential to meet the Swiss objectives for energy consumption in 2050. These buildings offer a great saving potential, however, the heritage preservation has to be considered in the renovation scenarios. While essential for the historic conservation, this consideration restricts the renovation possibilities to achieve the heating demand requirements according to the SIA 380/1 standard. This study introduces a framework for identifying the suitable historic buildings' renovation schemes considering life cycle costs, energy and life cycle environmental impacts. With a case study, the feasibility of achieving the energy performance SIA 380/1 standard is then discussed.

Keywords. Historic building, Energy Efficient Renovation, Life Cycle Assessment, Life Cycle Cost

1. Introduction

The reduction of energy consumption in the existing building stock is a crucial element of the Swiss Energy Strategy 2050 since it accounts for more than 44% of the final energy use in Switzerland [1]. Breaking down the existing residential building stock into two parts, there are about 32% of residential buildings built before 1945 [2]. These buildings, identified as historic buildings in the RIBuild Horizon 2020 European project [3], present a substantial useful energy consumption estimated at about 115 kWh/(m^2.an) for MFH and 130 kWh/(m^2.an) for SFH which represents 31% of the total demand of the residential building stock [4]. Among the historic buildings, some of them present an architectural value and a degree of protection defined at the cantonal level (in particular exterior façade protection) leading to a more difficult process for energy-related refurbishment. As for the other non-historic buildings, they are currently not enough renovated [5,6,7]. The energy-related renovation of historic buildings is indeed a complex process aiming at the preservation of the architectural value of the external façade while improving the building energy consumption. Thereby, in many cases, to improve the building thermal envelope, interior insulation is preferred to preserve the exterior façade.

There are several possibilities of insulation systems, thicknesses and implementation leading to different energy saving potentials. In general, a compromise is made between the insulation system types (e.g., vapour-tight, capillary active…) and the applied thicknesses in order to avoid excessive condensation risks on the interior surface area [8]. Hence, the insulation thickness can limit the thermal performances of the renovated historic buildings because of the condensation risks.

In Switzerland, building renovation has to fulfill standard energy performances. Two approaches exist: the so-called "punctual approach" (each renovated building element has to be at least equal to fixed U-values) and the "general approach" comparing the building specific heating demand with the SIA 380/1 limit values after renovation [9]. The punctual approach, while in principle feasible, might not enable fulfilling the energy efficiency objectives of the building stock defined in the Swiss Energy Strategy 2050 if not all the envelope is renovated. Conversely, the general approach appears to be in line with the long-term Swiss objectives but is difficult to achieve for historic buildings because of the heritage preservation needs.

It is difficult to fulfil the requirements in terms of both hygrothermal risks, energy performances, environmental impacts and renovation costs because they deal with contradictory interests. This study presents, through the case study of a historic building, a general framework to identify the most appropriate scenarios for the refurbishment. This work aims also to discuss different indicators to characterize the feasibility of an historic building retrofitting in term of life cycle cost, energy and life cycle environmental impact.

2. Materials and methods

2.1. Method for assessing the possible renovation scenarios

The developed approach aims to identify the optimal renovation scenario in terms of 1- Life Cycle Cost (LCC) calculated with the Net Present Value (NPV) at 3% actualisation rate and 2- Life Cycle Assessment (LCA) based on greenhouse gas emissions (GHGe) and non-renewable primary energy (NRE) indicators. Both LCA and LCC take into account the investment, operational and replacement costs. The chosen reference study period is 60 years.

The first methodological step relies on the calculation of the space heat energy needs according to the Swiss SIA 380/1 standard [9]. The building, in its state before renovation, is modelled and the energy needs are calculated according to the SIA 380/1 assumptions (e.g. climate, interior temperature).

Then, the renovation scenarios are characterized. In this step, the building elements are merged into so called "renovation categories" in order to reduce the number of potential scenarios. The renovation categories are defined according to the building elements characteristics to get a homogeneous classification. For example, if different external wall's elements have the same renovation scenarios, they are merged in a single "renovation category".

Once these categories are defined, different renovation levels are set, characterized by specific punctual U-values (in $W/m^2.K$), from a low insulation level to a high insulation level. The levels represent realistic renovation solutions of the building elements according to the historic building initial state. It also takes into consideration the legal requirements for the insulation levels, in particular the U-value limit for punctual calculations of building elements in Switzerland (see SIA 380/1:2016 [9]).

Based on the renovation categories and the insulation levels, a full factorial experiment is performed, i.e., the energy needs (Q_h) are calculated considering all the possible permutations. Thus, the energy for space heat is calculated for all possible renovation scenarios. Based on these results, the GHGe, NRE and LCC indicators are then calculated. For each of the renovation categories and insulation levels set, specific costs and environmental impacts are defined and the overall LCC and LCA are estimated for all the renovation scenarios. Finally, the renovation scenarios are then assessed according to these indicators (and the space heat energy need) in order to discuss and identify the most suitable one.

2.2. Historic building case study

The case study was selected according to the eRen project [10] which identifies typical reference buildings for different construction periods. This building is considered representative of historic multi-family houses (MFH) in Switzerland. It was built in 1910 in the city centre of Lausanne (CH) and is part of a group of four adjacent buildings. As shown in Figure 1, it is made of five regular stories containing each four apartments, with three additional apartments just below the mansard roof. The building has an energy reference area (ERA) of 1563 m² and is not insulated. The external walls are made of limestone masonry (50 to 60 cm), visible on the ground floor and covered with a mineral coat on higher floors. They are responsible for around 57 % of the thermal losses of the building [11].

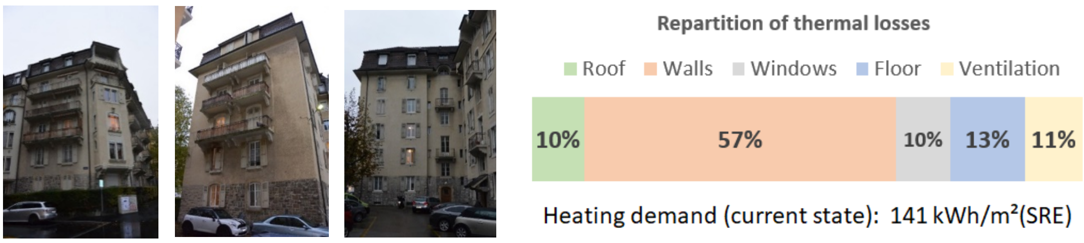

Figure 1. View of the historic building "eRen-02" (east, west and south-oriented facades)

The building "renovation categories" have been defined according to the energy distributed by element in Figure 1. The external walls have been divided into two parts i.e., the ground floor for which the stones are visible and the other floors for which the walls are covered with an external rendering.
The insulation levels and associated costs have then been defined. Table 1 presents the U-values and costs for different levels of renovation. The levels for the external walls were adjusted to match U-values close to SIA 380/1 renovation punctual thresholds (≤ 0.25 W/m².K), SIA 180 (≤ 0.40 W/m².K) as well as the Minergie renovation model 5 (≤ 1.1 W/m².K) [12]. In order to reach these objectives, internal Multipor insulation (capillary active material) and external aerogel rendering are used. For the bottom floor and ceiling, the levels were also defined taking into account the requirement of the SIA 380/1 punctual thresholds for renovation projects (0.25 W/m².K) as well as the minimum values for different Minergie renovation models (0.17 to 0.30 W/m².K). Rockwool is applied below the ground floor, using different thicknesses to reach the aforementioned U-values. Cellulose fibre is blown between the wooden beams of the ceiling and additional rockwool is used above the wooden beams. The standard level for the windows is compliant with the SIA380/1 punctual target value (1.0 W/m².K), which can be reached using triple glazing combined with a PVC frame. Other solutions including more efficient types of glazing were considered in order to achieve "advanced" and "extreme" levels.

Table 1. Considered U-values for the different elements.

	U-value configurations [W/(m².K)] & Investment costs [CHF/m²]								
Element	Current	Low		Standard		Advanced		Extreme	
	U-Value	U-Value	Costs	U-Value	Costs	U-Value	Costs	U-Value	Costs
Windows	1.30	1.10	429	1.00	687	0.90	764	0.80	840
External wall (ground floor)	1.55	0.52	118	0.35	130	0.30	136	0.26	142
External wall (upper levels)	1.60	1.02	100	0.39	130	0.34	230	0.24	470
Ceiling	0.98	0.30	105	0.25	100	0.20	119	0.17	126
Bottom floor	1.35	0.30	101	0.25	115	0.20	122	0.17	138

Renovation costs were obtained through different sources. They include quotations from practitioners [10], average data from CECB [13] and referential values from OFS [14]. The optimal insulation thickness tool developed in the ECO-Reno project was finally used to adjust the cost variation of the insulation layer to the corresponding U-value [15]. A gas boiler is considered to supply heat. The energy costs for space heat were estimated at a fixed rate of 0.15CHF/kWh during the building life cycle. The life cycle assessment data for renovation materials and energy carriers originates from KBOB list [16].

3. Results

The method was then applied to the case study according to the renovation categories and insulation levels described in Table 1. The initial energy simulation, i.e, the space heat energy need of the building in its actual state is 508 MJ/m$^2_{ERA}$ per year.

Based on the renovation categories classification and the insulation levels defined in Table 1, the full factorial experiment is then used to calculate the space heat energy need of the possible renovation scenarios. For the full factorial experiment, 3'125 renovation scenarios have been assessed. The energy need for space heat is ranging from 127 to 430 MJ/(m$^2_{ERA}$.an) According to the Swiss SIA 380/1, considering the global limit for space heat after renovation (considering the global renovation), $Q_{h\ lim,}$ is 139 MJ/(m$^2_{ERA}$.an). Thus, 4% of the renovation scenarios (126) enable to fulfil the legal requirements.

Then, based on the specific costs detailed in Table 1, the Net Present Value (NPV) has been calculated for all scenarios (see figure 2).

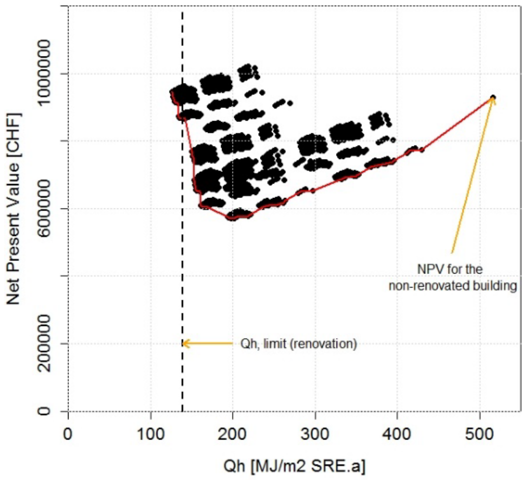

Figure 2. NPV of the renovation scenarios as a function of the space heat energy demand (Qh)

The bottom boundary of the NPV as a function of the space heat energy demand (red line) shows that there is a set of renovation scenarios that are found to be optimal (82 among the 3'125 scenarios). However, only 10 of them are found to fulfil the global requirement on the heating limit regarding a renovated building (left part of the dashed line on the figure 2). These scenarios, while fulfilling this limit, show significant higher NPV than scenarios with a higher heating demand.

From the graphic, the red line can be divided into three parts. The first part (from the Q_h of the non-renovated building to Q_h = 201.5 MJ/(m$^2_{ERA}$.an) being the heating demand with the lowest NPV, i.e., 570'554 CHF), the NPV is reduced when the building Q_h is reduced. By performing a linear regression on this segment, it is found that for each saved MJ/m$^2_{ERA}$ per year the NPV is reduced by 1'142 CHF.

In the second segment (Q_h ranging from 162 to 201.5 MJ/m$^2_{ERA}$.an); the Q_h still decreases but the NPV now slightly increases (from 570'554 CHF to 606'397 CHF). By assuming a linear regression on this segment, it is found that for each saved MJ/m$^2_{ERA}$ per year, the NPV is increased by 905 CHF.

In the third segment, the Q_h is still reducing but, the NPV now strongly increases. Still by assuming a linear trend, it is estimated that for each saved MJ/m$^2_{ERA}$ per year, the NPV is increased by 4'995 CHF. Finally, the scenario having the closest energy demand to the $Q_{h,\ lim}$ (SIA 380/1) has a NPV of 867'182CHF. Thus, to save 23 MJ/m$^2_{ERA}$ per year, the additional NPV is 260'785 CHF.

The environmental impacts have then been calculated, for the primary non-renewable energy (NRE) and the greenhouse gas emissions (GHGe) indicators. Only the GHGe results as presented in figure 3 (left) as both indicators are strongly correlated and present the same trend i.e., they are only driven by the energy needs (Q_h) per year. When the Q_h decreases, the two GHGe and primary NRE indicators decrease accordingly. Thus, in general, it appears that reducing the energy need will lead to the minimization of the environmental impacts. However, two parallel lines are observed for both indicators. The upper line corresponds to the scenario for which aerogel material has been used for the façade. This material shows a significantly higher environmental impact than the other considered insulation materials. In addition, the scenarios fulfilling the $Q_{h, lim}$ criteria systematically require the use of aerogel, which lead to overall higher environmental impacts. Conversely, the lower environmental impacts are obtained for an energy demand of 150 MJ/(m^2_{ERA}.an) which is found to be 8% above to the legal requirements. Finally, the GHGe indicator is now presented as a function of the NPV in figure 3 (right). Again, both LCA indicators are strongly correlated which lead to similar trends. So only the GHGe results are reported. From figure 3 (right), it first appears that in any cases, a renovation will greatly reduce the environmental impacts expressed in GHGe compared to the current building state. Then, most importantly, the GHGe show a plateau from 600’000 to about 800’000 CHF. This mean that the environmental impacts would remain in a close range in between these two values (between 17 to 18 t $CO_{2\ eq}$/y and 285 to 315 GJp/y). Thus, by choosing the appropriate renovation scenario from a LCA point of view could also lead to 200’000 CHF of savings. Finally, considering the lower bound of the scatterplot (red line), the highest NPV of the renovation scenario does not lead to the lowest GHG emissions.

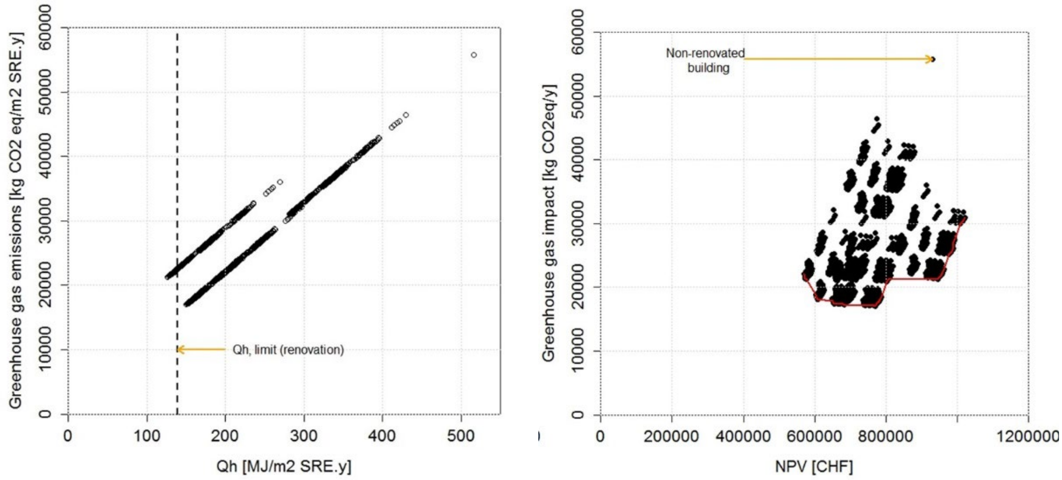

Figure 3. GHGe as a function of the Q_h (left) and as a function of the NPV of the renovation scenarios

4. Discussion

Based on a representative case study, the method has shown its interest regarding the renovation strategies definition of historic buildings. It appears that achieving the $Q_{h, lim}$ is possible only in few scenarios relying on substantial investment costs not compensated by the energy savings. In addition, using aerogel implies higher GHGe and primary NRE than renovation scenarios exceeding the $Q_{h, lim}$.

For the considered case study, the NPV is first decreasing (compared to the non-renovated scenario) until a Q_h, which is 45% higher to the legal limit. Then the NPV slightly increases until a Q_h being 17% higher the $Q_{h, lim}$. Finally, the NPV strongly increases in order to reach the legal limit. The additional cost to reach the $Q_{h, lim}$ compared to the scenario being 17% higher is found to be excessive (NPV increased by 43%) compared to the environmental and energy savings. This increase of cost could be used for renovating another historic building where the specific cost of saved energy would be lower.

The GHGe and NRE indicators have shown a strong dependency on the building energy need. This result is coherent since the insulation thickness is relatively limited and does not play any role in the building LCA results. However, the use of aerogel in order to reach the $Q_{h, lim}$ appears to increase the environmental impact compared to solutions with energy needs higher than $Q_{h, lim}$. Thereby, achieving the $Q_{h, lim}$ leads to higher overall GHGe and primary NRE indicators.

Thus, it appears that the $Q_{h, lim}$ criterion could be balanced, for historic buildings, with other considerations such as the marginal cost of saved energy and the environmental impacts expressed as GHGe and primary NRE. Indeed, when they are considered as a function of the NPV, their minimum is observed for reasonable and sustainable costs while the corresponding Q_h values are higher than the $Q_{h,}$

$_{lim}$. The most appropriate scenario for the historic building renovation (and the specific case study considered here) is thus a trade-off between life cycle cost, life cycle primary NRE and GHGe and direct heating needs. This optimization aspect should be considered for historic building renovation strategies.

In practice, for the historic building to be renovated, the public bodies, in charge to validate the renovation project, can provide exceptions to the $Q_{h, lim}$ criterion. However, it could be valuable and necessary to develop specific procedures and comprehensive methods, in order to increase the share of renovation for historic buildings. By considering the aspects presented in this study, the renovation share of historic buildings could be greatly increased and the cost of saved energy could be lowered if the $Q_{h, lim}$ would not be the major criterion for authorizing the building renovation. Indeed, in the specific case study presented above, a renovation strategy having a Q_h close to 120% of the $Q_{h, lim}$ would lead to about 43% of cost reduction that could then be used for the renovation of other historic buildings.

5. Conclusion

The historic buildings have a large potential for energy savings since they are almost not insulated. However, because of architectural protection, it is not possible to consider external insulation. The interior insulation is thus the only solution to insulate the façade. On the other hand, because of hygrothermal risks and interior space reduction, the insulation thickness is limited. Thus, the building performances exceed the legal energy requirements. This study has developed a method to help in assessing and later identifying the most suitable renovation scenario for historic buildings. Based on a full factorial experiment, a set of energy, life cycle cost and LCA indicators can be calculated for all scenarios. These indicators can then help in the decision making process. From the case study, it has been shown that achieving the $Q_{h, lim}$ criterion can lead to excessive costs without minimizing the environmental impacts. Renovations scenarios with higher Q_h than the $Q_{h, lim}$ have lower environmental impacts and are found to be economically competitive. Indeed, in practice, planners can claim some exceptions in terms of $Q_{h, lim}$ if the renovation scenarios cannot fulfil the $Q_{h, lim}$. Here, the study confirms this situation by showing also a high marginal cost of the energy savings in the zone between $Q_{h, lim}$ and 120% of the $Q_{h, lim}$. Further studies are now needed to confirm these results on other historic buildings.

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