Stepwise renovation of buildings: what to refurbish first to minimize life-cycle carbon emissions?

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Abstract. To tackle the upcoming renovation wave, this work evaluates renovation strategies with a life cycle GHG emissions perspective and includes time and sequencing in the decision-making process. A case study is used to conduct a full life cycle assessment of renovation strategies in line with the Swiss normative context. Improvements in the operational energy consumption are evaluated with an energy model using the software Lesosai and considering the normative limits from the SIA 380/1. GHG emissions are calculated using the Swiss KBOB data inventory and in line with the SIA 2032 methodology. The renovation measures are then examined individually with the carbon payback time indicator and strategies with cumulative emissions over time in contrast to carbon budgets. Results show that the sequence of the refurbishment steps can increase or decrease cumulative GHG emissions of ca. 30% over the lifetime of the building. Changing a fossil-fuel based heating system is the most impactful measure and must happen as soon as possible. Switching to decarbonized heating systems reduces the carbon effectiveness of subsequent renovation measures but poses the question of energy availability. Fully renovating a building but delaying the change of heating system by only 7 years can compromise the achievement of the carbon targets.

1. Introduction

In Switzerland, 23.9% of CO_2 emissions are due to the operation of buildings and the existing building stock is responsible for 44.4% of total energy consumption [1]. Renovating the existing building stock is a key strategy to reduce greenhouse gas emissions (GHG) from, commonly, energy-inefficient and fossil-fuels dependent buildings. In October 2020 the European commission presented its renovation wave strategy as part of the European Green Deal with the main objectives to at least double the annual energy renovation rate of buildings by 2030 and to foster deep renovation [2]. In Switzerland numerous financial and regulatory tools are in place to reduce emissions from the building stock. A CO_2 tax [3] is operational since 2008 to incentivize the reduction of fossil-fuels consumption. Also, a Building Programme [4] is available and aims at promoting the energy renovation of building envelopes and the renewable and optimized use of energies by providing economic incentives. Finally, the cantons are required to enact laws and regulations to reduce emissions from existing and new buildings. For example, most cantons implemented heating needs limitations and minimal percentages of renewables when changing heating system in residential buildings (such as 20% in Fribourg). In the latest review report (period 2016 to 2020), the Swiss Federal Office of Energy reported a decrease in operational CO_2

emissions of ca. 20% partially due to milder climate conditions but also due to the reduction measures [5]. It must be noted at this point that the policy framework in place only focuses on energy efficiency and reduction of energy consumption (and related emissions) but materials (and related emissions) are not mentioned even though they represent ca.30% of the Swiss building related emissions [6]. Deep energy renovations imply an elevated share of refurbished elements (ex: roof, technical systems, facades, etc.) in the building. Studies highlight the importance to have a life cycle perspective on emissions for such renovations. If renovation rate is increased without looking at embodied emissions, cumulative national emissions will increase until 2050 [7]. Adding fossil derived insulation when the heating system is decarbonized has a negative effect on life cycle emissions [8]. In the context of the IEA-EBC Annex 56 [9,10] a methodology is proposed for cost effective, energy, and carbon emission optimization in building renovation. The methodology integrates a life cycle perspective with an environmental Life Cycle Assessment (LCA) methodology next to a Life Cycle Cost assessment. The LCA methodology is used to quantify the embodied carbon emissions due to the manufacturing, replacement and end-of-life (e.g., disposal or recycling) of construction materials and building integrated technical systems added during a building renovation [11]. A supplementary study to the annex 56 methodology evaluated the importance of embodied carbon in decision making of renovation in relation to cost and energy saving [12] and concluded that embodied emissions decrease the potential benefits of renovation measures but do not affect the overall ranking of the strategies. Furthermore, the increasing pressure of climate change is translating into challenging climate targets and GHG reduction pathways [13], this affects also buildings and construction activities that will have to adapt practices to conform with limited carbon budgets to achieve the climate goals [14]. Finally, deep energy renovations are often conducted in a stepwise manner over a couple of years to, mainly, reduce or dilute the high investment costs. However, the impact of the sequencing of such refurbishments on emissions is not discussed in the literature.

2. Methodology

The environmental evaluation of the renovation measures is conducted in three subsequent steps. First, the current state of the building is analyzed and modeled in the simulation software to validate the model with current consumption patterns. Secondly, renovation measures are modelled in separate steps to identify the potential energy gains and material investment of each measure. Lastly, life cycle GHG emissions are reported, and efficiency and effectiveness of measures and their sequencing are extracted with selected indicators.

2.1. *Thermal model and Life Cycle Assessment*

Lesosai 2020.0 is used in this study to conduct static energy simulations of the initial case study and of all subsequent renovation measure. The simulation is conducted in accordance with Swiss Norm SIA 380/1:2016 and only heating needs are evaluated in kWh/m^2(energy reference area). Renovation measures are evaluated with a life cycle assessment approach. Construction phase (A4 and A5 according to standard EN 15978) is neglected. In the use stage (B), only heating needs in B6 (operational energy use) and B4 (replacements) are accounted for. Impact assessment method is IPCC 2013 and climate change is the impact category chosen with GWP100 as indicator and kgCO$_{2eq}$ as unit. Impact factors for production and end-of-life of construction materials and supply of energy are taken from the KBOB 2009/1: 2022 database. In accordance with Swiss standards (SIA2032), the time frame is set to 60 years as it is considered that a renovation starts a new life cycle. The amortization periods of construction elements are taken from the annex C of the SIA 2032. These periods define the rate of replacements (phase B4) of the materials during the time frame. Finally, residual values (non-amortized emissions) from works preceding the start of the renovation are taken into account.

2.2. *Efficiency and effectiveness of renovation measures*

Renovation measures are evaluated under three main aspects. First, efficiency of renovation steps is assessed towards the achievement of the SIA 380/1 norm (heating demand) and SIA 2040 recommendations (embodied and operational emissions). Secondly, ratios between invested carbon emissions (embodied) and annual operational carbon savings are calculated for each measure individually. This carbon payback time indicator has been proven to help compare the effectiveness of renovation measures [15]. Lastly, emissions of renovation strategies are plotted over the time frame in a cumulative way and compared with limited budgets to determine the effectiveness of the strategies. Cumulative carbon budgets are extracted from a recent study [14] translating the national strategy to specific building targets until 2050.This final step is necessary to better understand the trade-offs of the implemented measures as well as identifying the role of time in the decision-making process.

3. Case Study

A case study is used to exemplify the methodology and represent concrete results. The chosen building is a multi-family residential house with 24 units distributed over 8 floors and an energy reference area (ERA) of 3’021m^2. The building was built in 1971 and some punctual renovation works were conducted in the early 2000’s. The building is located in Fribourg, Switzerland and is part of a typical residential neighborhood of the 60s-70s. The external walls are composed of load-bearing concrete walls, 5cm of external insulation, and prefabricated concrete panels in the façade. The building is heated by an oil boiler and the distribution is through radiators without thermostatic valves. In 2005, the building underwent a first renovation cycle with the remake and insulation of the flat roof (10cm of XPS) and the addition of peripheral insulation to the façade (12cm of EPS). Windows have not been replaced and thermal bridges haven’t been solved yet.

Figure 1: Photo of the case study

3.1. Renovation measures

The case study illustrates adapted measures for energy-efficient building renovation. The main goal is to achieve the legal requirements (SIA 380/1:2016) with a global performance perspective but detailed by single measures to understand the effective impact of each one. The planning and ordering of the renovation measures is done according to the easiness of implementation while the building is in use. The order considers the obsolescence and the lifetime of the components and hierarchize the interventions over time. In a first step, measures for the energy renovation that are easily implementable and have low impact on the users have been identified (M0 to M4 in **Table 1**). In the second cycle, the complete insulation of the envelope is prioritized, allowing also the intervention on the numerous thermal bridges and the redefinition of the building character (M5 to M8).

Table 1. Renovation measures applied to the case study

No.	Name	*Detail*	Year
M0	Change of heating system	Connection to a district heating at 80% renewables	2023
M1	Thermostatic valves	Thermostatic valves are added to radiators	2023
M1’	Entrance door and ERA	Sliding door replaced and reduced ERA on ground floor	2023
M2	Slab above non-heated	U-value- from 1,97 W/m^{2}K to 0,26 W/m^{2}K. glass wool	2023
M3	Walls against non-heated	U-value from >2 to 0,2 W/m^{2}K – calc. silicate and mineral wool	2023
M4	Windows and shading boxes	Original windows replaced with triple glazing.	2023
M5	Insulation of external façade	U-value from 0,28 to 0,68W/m^{2}K to 0,2W/m^{2}K - rockwool	2030
M6	Thermal bridges (balconies)	Slabs of balconies are insulated	2030
M7	Insulation of roof	U-value from 0,44W/m^{2}K to 0,15W/m^{2}K - cellular glass	2030
M8	Dual flow ventilation	Dual flow ventilation with heat recovery	2030

4. Results

4.1. Efficiency and effectiveness of renovation measures

Figure 2 shows the heating needs Qh according to the norm SIA 380/1:2016 (left scale) as well as the reduction of GHG emissions (operational, embodied, and nonamortized) in contrast to the SIA 2040 recommendations (right scale) for each step of the renovation. The distinct colours and letters assigned to the heating needs refer to the Swiss cantonal energy certificate of buildings (CECB) energy classes. A new insulation of the façade (M5) is necessary to reach the legal limits of energy performance (Q_h,limit). A higher performance is achievable by implementing a dual-flow ventilation with heat-recovery (M8) but this measure will involve a heavy renovation of the living spaces. It is noticeable that reaching carbon targets (SIA 2040, GHG limit) is not directly coupled with reaching current energy standards – carbon target is reached with M0 and waiting for the amortization time of the first cycle to end. While changing the energy carrier (M0) from fossil to renewable drastically reduces life cycle emissions, further measures down the line tend to transfer emissions from operation to embodied.

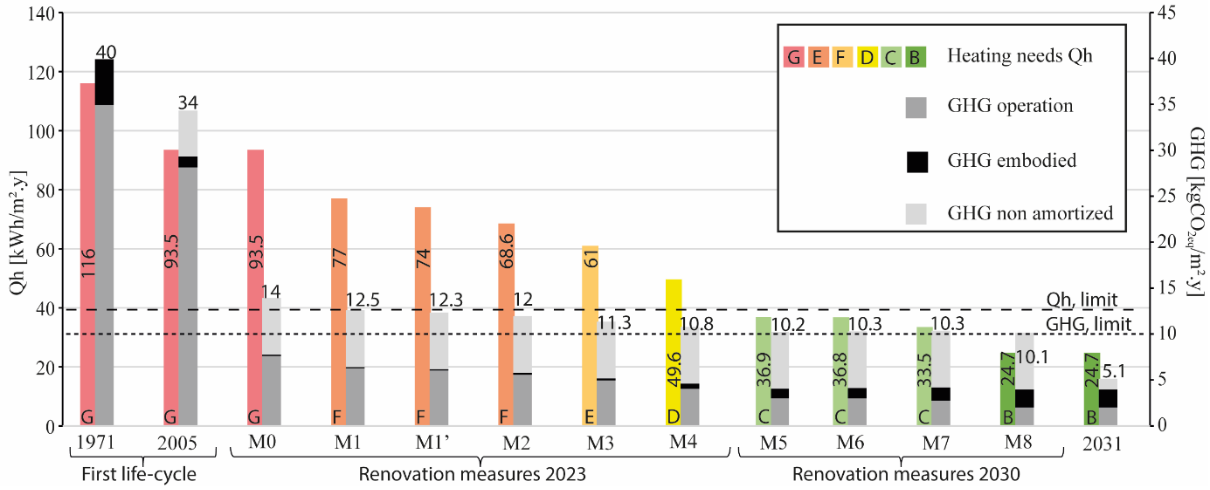

Figure 2. Benchmark of renovation measures with heating needs limits (SIA 380/1), building energy performance certificate (CECB), and GHG emissions targets (SIA 2040)

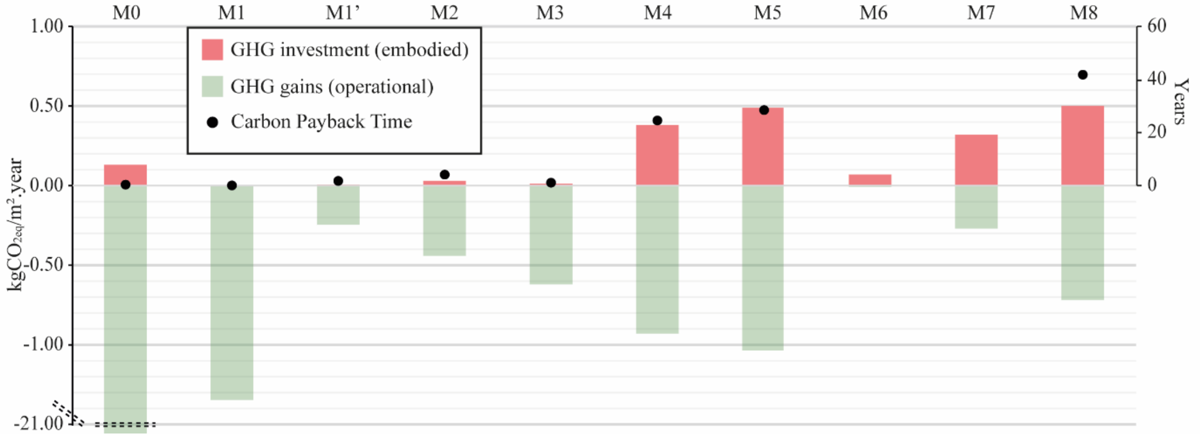

Figure 3. Efficiency of renovation measures. Operational GHG emissions savings versus embodied GHG emissions investment (left scale) and carbon payback time (right scale).

Figure 3 presents the operational gains (negative bars) of each measure in contrast to the embodied investment (positive bars) and the carbon payback time limited to 60 years (time frame). M0, changing the heating energy supply, is undoubtfully an effective measure in terms of carbon payback time. The carbon savings, generated by switching from a fossil fuel source to a more renewable one, are largely higher than the embodied carbon investment required. The strategy described in section3.1. prioritizing interventions that are easily implemented and have a minimal impact on the users (M0 to M3), is also reflected in the carbon effectiveness results where the embodied carbon investment is generally low and relevant operational savings are observed. The new insulation of the envelope (M4 to M7) includes more important interventions and therefore also require a more substantial investment of embodied carbon. M6 does not show any substantial operational saving but is essential for other health aspects of the internal comfort of the building. M7 would require lowering the embodied investment to be effective.

4.2. *Impact of ordering on cumulative GHG emissions*

Cumulative emissions over the life cycle of the building are a powerful indicator to identify effective emissions released in the atmosphere and to compare strategies to carbon budgets over time. The reference line represents the current consumption with heating oil until the end of the time period. **Figure 4** a,b, and c show the effects of four temporal renovation strategies (coloured lines) in relation to the heating system considered. The intersection of the strategies lines with the reference heating line indicates the effectiveness (carbon payback time) of the strategy. It is immediately noticeable that the more decarbonized the heating system (**Figure 4**c) the less effective it is to apply any renovation measure. It also always paybacks, on the long term, to apply all the measures in the beginning. Finally, delaying the change of heating in the renovation process can affect the results drastically and compromise, in certain conditions (**Figure 4**b), the achievement of the carbon budgets.

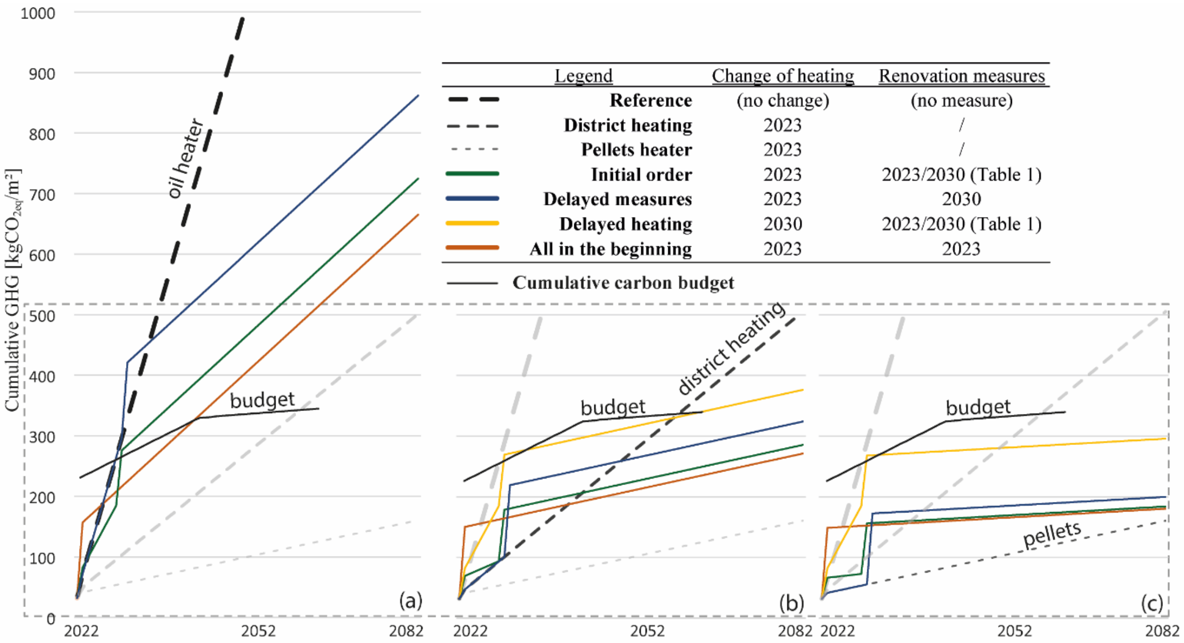

Figure 4. Cumulative emissions over the time frame of the study for four renovation strategies. (a) with an oil-based heating system, (b) switching to a district heating at 80% renewables, and (c) switching to a pellets-based heating system

5. Conclusions and discussion

The main objective of this contribution was to evaluate the efficiency and effectiveness of renovation measures with a life cycle GHG emissions approach and over time. The study was limited to the impact category climate change, but other categories and indicators could highlight potential further pollution transfers not depicted in this work. From a purely normative perspective, achieving the required heating needs requires important interventions such as the insulation of the thermal envelope. This result is decoupled from achieving the recommended carbon targets but coupled with higher embodied emissions investments. These measures require a deeper evaluation of the choice of materials (low carbon) to become effective in terms of carbon payback time. Not surprisingly, switching from fossil fuel systems to renewable energies is the most efficient and effective measure in the short and long term. Switching to low carbon energy carriers (ex. Pellets) drastically reduce the effectiveness of following renovation measures. As shown in **Figure 4**c, renovation measures are not effective (higher cumulative emissions) when compared to the simple switch of heating system. Although, from a carbon perspective, it is evident that switching to renewables must be the first step of a renovation, this opens a variety of questions related to the dimensioning of a new heating system if subsequent renovation measures are carried out and, most importantly, if no further measures are applied, how will the supply of energy keep up with the high energy demand. To tackle this question a promising methodology has been recently proposed by the Low Energy Transformation Initiative (LETI) named "Split carbon factor method" [16]. This method suggests that energy needs can only "use" decarbonized energy factors if below a certain threshold. Above which a fossil fuelled grid must be considered to account for the difficulties to fully decarbonize the grid if demand keeps increasing. Finally, renovation strategies are not always relevant from a carbon perspective, but other constraints and needs must be considered like comfort, aesthetics, building physics, health aspects (thermal bridges, condensation, mould), and other obsolescence (safety aspect, fire and noise protection, harmful substances, etc.). Further reflections on the building typology, use, and potential of densification could also increase the value of the renovation works. In conclusion, renovations are only valid if they consider the lifetime of the elements, they preserve the existing qualities and create new ones. Renovations must, therefore, be considered as an optimization process in a sustainability perspective that includes embodied and operational emissions and time frame of interventions. A roadmap illustrating the impact of the measures gives the owner a viable idea of the necessary works and investments. Stepwise interventions enable the renovations to be technically and economically viable while ensuring the achievement of the overall climate targets.

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