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What is the optimal robust environmental and cost-effective solution for building renovation? Not the usual one

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ABSTRACT

Buildings are responsible for a large share of CO_2 emissions in the world. Building renovation is crucial to decrease the environmental impact and meet the United Nations climate action goals. However, due to buildings' long service lives, there are many uncertainties that might cause a deviation in the results of a predicted retrofit outcome. In this paper, we determine climate-friendly and cost-effective renovation scenarios for two typical buildings with low and high energy performance in Switzerland using a methodology of robust optmization. First, we create an integrated model for life cycle assessment (LCA) and life cycle cost analysis (LCCA). Second, we define possible renovation measures and possible levels of renovation. Third, we identify and describe the uncertain parameters related to the production, replacement and dismantling of building elements as well as the operational energy use in LCCA and LCA. Afterwards, we carry out a robust multi-objective optimization to identify optimal renovation solutions. The results show that the replacement of the heating system in the building retrofit process is crucial to decrease the environmental impact. They also show that for a building with already good energy performance, the investments are not paid off by the operational savings. The optimal solution for the building with low energy performance includes the building envelope renovation in combination with the heating system replacement. For both buildings, the optimal robust cost-effective and climate-friendly solution is different from the deep renovation practice promoted to decrease the energy consumption of a building.

1. Introduction

The building sector has more than doubled its greenhouse gas emissions (GHG) since 1978 resulting in 25% of global emissions [1,2]. To decrease the amount of emissions, new regulations regarding energy-efficiency in buildings have been proposed regarding new constructions. However, it has been shown that 35% of the buildings in European Union are more than 50 years old and 75% of the building stock is energy inefficient [3]. By the year 2019, the renovation rate of the existing building stock was estimated to be merely 1% per year, which cannot ensure the climate neutrality of buildings by 2050 [4]. The objective of the European Union is to at least double the current renovation rate by 2030, which is planned to be done through deep energy renovation strategies [5].

To evaluate the cost and environmental performance of a building renovation scenario, life cycle cost analysis (LCCA) and life cycle assessment (LCA) are commonly used [6,7]. During the analysis of LCCA and LCA, the whole building life cycle is examined. Due to a long life of a building, many sources of uncertainties can be identified in the analyses. Such uncertainties include the ones related to the time when the analysis is performed, such as the embodied emissions, investment cost, energy price, and those related to the future – climate change, prospective electricity and energy mixes, replacement time of the materials, and occupancy behaviour. The combined effect of these uncertainties may lead to significant deviation from the expected outcome of LCCA and LCA. To model the uncertainties and quantify their effect, uncertainty quantification may be used [8]. Many techniques currently exist and several studies using different methodologies have been performed for uncertainty quantification in LCCA [9,10] or LCA [11,12]. In these studies, it was concluded that uncertainty quantification is needed to increase the reliability of the cost and envi-

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ronmental assessment. In previous research, we have integrated the LCA and LCCA for a building renovation and performed the uncertainty analysis using surrogate modelling [13].

To identify the most cost-effective and at the same time climate-friendly solution while accounting for uncertainties, robust and multi-objective optimization techniques may be used. A robust design is one for which the effects of uncertainties at the optimal solution are kept minimal. The idea was formalized in the context of design optimization by Genichi Taguchi [14]. While there is currently a lot of research done on the optimal renovation solutions in a deterministic context, there is a lack of studies performing robust optimization under uncertainty for integrated LCA and LCCA. Several studies have tackled this problem very recently [15,16]. In both studies, Monte Carlo simulation is used to perform the analysis of uncertainties. It has been shown that Monte Carlo simulation is the most used method for uncertainty quantification in LCA studies [17]. This can be explained by the easy applicability and straightforward procedure of the Monte Carlo simulation. However, Monte Carlo simulation is also very much time consuming and may not be appropriate for a decision making tool, where the user wants a quick and robust solution for his energy-related renovation context.

Multi-objective optimization, on the other hand, is a process of finding a solution, which would be optimal for two or more objectives. Because these objectives are often conflicting, it is usually impossible to find a unique optimal solution. Instead, a set of equivalent optimal solutions, known as Pareto set, is sought after. The Pareto front is the image of this set in the objective space. Various techniques have been developed to aproximately identify the Pareto front. Specifically, in building simulation, genetic algorithms are often considered. A genetic algorithm is based on the theory of the survival of the fittest point [18]. It starts from a random selection of the design points and follows a sequence of generations, where the best solutions for the objective function(s) in the current generation are found and further reproduced to achieve the optimal solution [19]. Recently, there were several studies performing the multi-objective genetic algorithm (MOGA) for integrated assessment of LCA [20] or integrated assessment of LCCA and LCA [21,22]. In particular, the non-dominated sorting genetic algorithm II (NSGA-II) [23] is often used in the field of the built environment for optimizing thermal comfort [24], minimization of overall costs and environmental impacts of a single building [25,26] or multi-building scale [27]. Another study was identified using NSGA-III for the identification of robust refurbishment scenario [28].

The common obstacle of NSGA-II is the computational cost that it requires. To reach convergence, the objective function needs indeed to be evaluated repeatedly. This is even more demanding when the objective function involves propagating uncertainties through an expensive-to-evaluate computational model as it is the case in this paper. To leverage this prohibitive computational cost, surrogate models can be used. A surrogate model is an inexpensive approximation of the original, computationally demanding model. Surrogate models have shown themselves as a proven solution for design optimization issues. In a recent study, artificial neural networks were used for the optimization of building renovation scenarios [29,30]. An overview of the methodologies is summarized at Schuëller and Jensen [31].In this study, we perform a multi-objective and robust optimization design for LCCA and LCA to identify robust renovation solutions. To do that, we combine the use of NSGA-II and Gaussian process regression a.k.a. Kriging [32,33] as a surrogate modeling tool. The optimization problem is formulated by considering quantiles of the objective functions as measure of robustness. The implementation in this paper follows the methodology of robust multi-objective optimization proposed by Moustapha et al. [34].

The goal of this study is to develop a method in order to identify robust cost-effective and climate-friendly renovation solution for building renovation in Switzerland. We identify the uncertain parameters critical for the analyses of LCCA and LCA and possible renovation solutions and perform multi-objective robust optimization for two residential buildings with different construction period and architectural period located in Switzerland. These buildings are representative of buildings in the construction period where renovation are the most needed.

2. Methodology

The methodology of the paper is presented in Fig. 1.

First, the deterministic model is established using simplified LCA and LCCA procedures. Then, renovation scenarios are defined consisting of the envelope renovation and heating system replacement. This is followed by the parameters description in a probabilistic context. Afterwards, multi-objective robust optimization is performed considering two objective functions related to the overall cost and GHG emissions over the building lifetime. Finally, the optimal solutions are compared in a probabilistic context. Each step is described in detail below.

2.1. Deterministic model

The first step of the methodology is to define the deterministic simulation model. The model consists of a simplified LCA and LCCA. The detailed procedure of the integrated assessment is

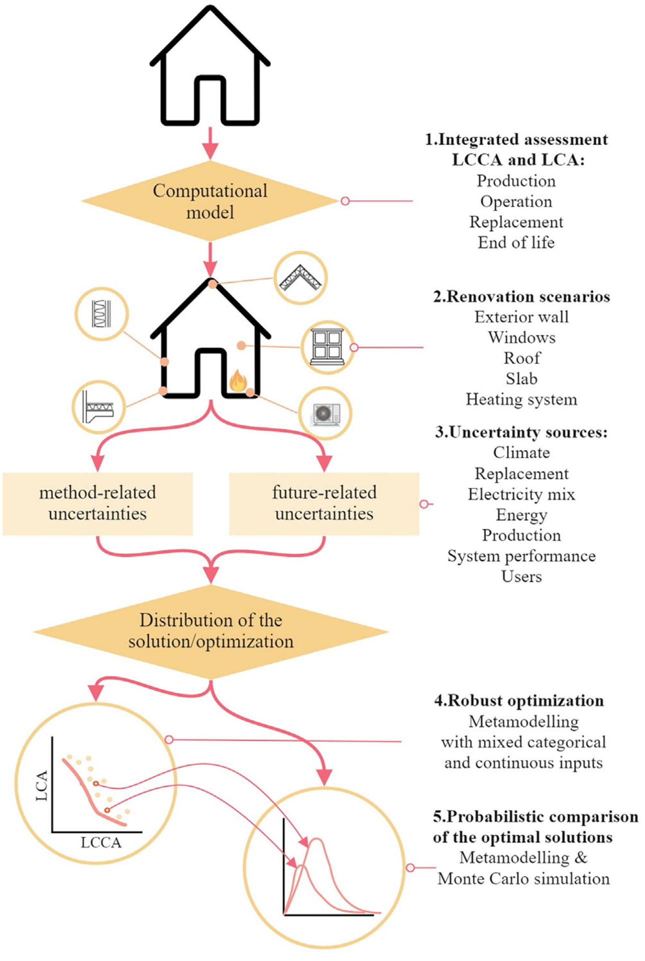

Fig. 1. Methodology of the paper.

described in [13]. A brief summary is provided here. The system boundaries for the analyses are production (A1-A3), energy demand in the operation (B6), replacement (B4) and end-of-life (C3-C4) modules according to the standard for assessing the environmental performance of buildings (SN EN 15978) [35]. Global warming potential (GWP) is used as an indicator for climate change based on IPCC characterisation factors and used in this study [36]. For LCCA, Swiss Francs (CHF) are used as an indicator. The functional unit refers to the building use over its lifetime. The lifetime of a building is considered to be 60 years according to Swiss standard SIA 2032 [37]. The calculation of the energy demand in the operational stage includes a quasi-static monthly heating demand analysis according to SIA 380/1 [38]. In the heating demand analysis, a standard energy balance equation is used, including transmission losses, ventilation losses, internal gains and solar gains. Monthly solar irradiation for different orientations is used for the solar gains and monthly projected values for the dry bulb temperatures according to different representative concentration pathways (RCPs) are introduced. Simplified thermal bridges in terms of percentage of a heat loss are used as well as the thermal mass in terms of heat storage capacity per energy reference area. Depending on the type of occupation, such parameters like occupants' heat gains, area per person, operating temperature and air flow are adapted according to SIA 380/1 [38]. The details of the analysis can be found in Galimshina et al [13]. The model was created with the use of python programming language.

2.2. Building representativeness and renovation scenarios

In this study, the buildings were chosen to represent the highest share of the building stock in Switzerland, with the closest match to typical representative buildings on a given construction period. Buildings are taken from eRen database which contains 15 building models representative of the residential building stock for multifamily houses in Western Switzerland [39]. The buildings were defined based on the professional building stock, technical guide and inventory analysis of buildings in Geneva Canton and cover from 72 to 89% of the overall dwellings number in Switzerland according to the Federal Statistical Office of Switzerland [39]. The eRen buildings were also compared to the building archetypes, which were identified in a recent separate study based on Swiss Cantonal Building Energy Certificates [40] and it was confirmed by the authors of this work that eRen buildings represent credible archetype for Swiss building stock.

Once the buildings are identified and the model described, renovation scenarios are defined. They shall fulfil the current heating demand requirements set according to SIA 380/1 [38]. First, the renovation categories are defined according to the building elements characteristics to achieve a homogeneous classification. Once the categories are determined, different renovation levels are defined. The insulation thickness ranges from the minimum level of the local code acceptance to an extreme solution with high insulation thickness. Details on the envelope renovation can be seen in Favre et al. [41]. The envelope renovation solutions are combined with three types of heating systems – gas boiler, wood pellets boiler and an air-to-water heat pump. When considering replacing an existing boiler with an air-to-water heat pump, the lower flow temperature difference is assumed for all the scenarios. Depending on the renovation scenario, the heat distribution system replacement is also considered.

2.3. Probabilistic model

Once the deterministic model is created and renovation scenarios are defined, a probabilistic model is constructed. Several categories of uncertain parameters are defined: climate change, operational costs and environmental impacts, service lives of building materials, embodied environmental impacts and investment cost, system performance and user-oriented parameters. In this section, we present the modelling of these parameters.

2.3.1. Climate change

Three climate projections have been distinguished by the National Centre for Climate Services (NCCS) in Switzerland and described as representative concentration pathways (RCP). Three RCPs are selected – RCP 2.6, RCP 4.5, and RCP 8.5. The number represents the radiative forcing (RF) in W/m^2 reached by the end of the century. The RCPs represent the scenarios from the continuous unabated emissions (RCP 8.5) to the strong reduction of GHG emissions during the early 21st century and compliance with 2 °C scenario (RCP 2.6). In Switzerland, the projections are analysed based on five regions: Northeastern Switzerland, Western Switzerland, Southern Switzerland, Western Swiss Alps and Eastern Swiss Alps. The climate projections for each emissions scenario for different regions are created as a set of models based on the recent EURO-CORDEX ensemble of regional climate simulations (RCM) [42]. For each RCP, we are thus provided with hundreds of realizations of temperature pathways following different models. Using *Principal Component Analysis (PCA),* these data are reduced into a few meaningful components that represent the observed variability in temperature time-series. By statistically identifying the underlying distributions of these components, we are able to resample new time-series with the same stochastic content as the data originally provided. These resampled time-series are eventually used as input parameters in the LCCA and LCC models to account for the effect of climate change. Further details of this climate change uncertainty application on a building scale can be seen in Galimshina et al. [43].

2.3.2. Operational costs and GHG emissions

This group represents the uncertain parameters associated with the building operation. Such parameters include the costs and emissions associated with the energy and electricity mixes, and nominal discount rate to take into account the future price changes in the overall cost analysis. Data for the energy costs and GHG emission factors are taken from the Swiss database KBOB [44], which is based on the Ecoinvent v2 and compared with other sources such as WWF (World Wide Fund for Nature): "*Heizungsvergleich* Excel Tool" [45] and house owners association in Switzerland [46]. The uncertainty for the data is defined based on the variations within the available sources. Regarding economic parameters such as discount and inflation rates, the recommendation of a local Swiss standard SIA 480:2016 as well as current inflation rate from Federal Statistical Office of Switzerland were taken into account [47,48].

Regarding the electricity mix, several scenarios have been developed based on the Swiss energy strategy 2050 [49]. The main idea of this strategy is the gradual phase out of nuclear energy and increase of the application of renewable sources of energy. Three scenarios are developed based on the data collected from various sources [49–51]. The data is afterwards processed and merged into a trendline for the CO_2 intensity of the future electricity mix in Switzerland. The electricity mix is analysed using monthly values to account for seasonal difference of carbon intensity. The resulting scenarios for the environmental impacts and costs can be seen in the supplementary information.

2.3.3. Service life of building materials

It has been shown that the material replacement corresponds to a high share of the total GHG emissions and to a considerable share of uncertainty in the overall result [52]. The difficulty for quantification of such influence is the quality of the database which is often scarce [53]. In this paper, the service life of building materials is taken from the Duree database [54] where data for service life of 100 building elements have been collected from various literature sources and countries. The use of such database was implemented in recent studies looking specifically at influence of building element service life on LCA uncertainties [55].

2.3.4. Embodied emissions and investment cost

The embodied emissions related to the material production have high uncertainty due to varying system boundaries and assumptions for the methodological choices as well as the comparability of the results from different studies [56]. In this paper, the data for embodied emissions was taken from the Swiss database KBOB as well as more recent versions of Ecoinvent [44,57]. The uncertainty for the embodied emissions is assumed to be ± 30% according to the detailed studies on LCA results [56,58].

Investment costs for the construction materials and heating systems are taken from the data provided by the Swiss database *Bauteilkatalog*, the WWF (World Wide Fund for Nature): "*Heizungsvergleich* Excel Tool", and CRB database for the construction components costs [45,59,60]. The uncertainty on the values are taken as suggested by SIA 480:2016 [47].

2.3.5. System performance

Parameters for the system performance include efficiencies of the heating systems, material degradation and uncertainty on the existing state of a building and thermal bridges of the renovated building. The efficiencies of the new and old heating systems are taken from the European Commission directorate-general for energy and the Swiss company Viessmann [61,62]. The existing state of a building is analysed and degradation is applied depending on the year of the construction using the existing literature [63]. Thermal bridges are calculated using the model described in Section 2.1.

2.3.6. User-oriented parameters

Parameters associated with the user behaviour are represented by the operating temperature inside the building, time of the occupation and the ventilation rate. Different dynamics have been established regarding the effect of the occupants on the overall energy performance [64,65]. This variation can be explained by the uncertainty on the modelling of the occupancy behaviour. It has been shown that the operational temperature inside the building is one of the most important exogenous parameters in LCA while considering the quasi static energy simulation [66]. In this study, we use a variation of 20 °C to 23 °C in the operating temperature, 0.7–1 m^3h/m^2 in airflow and 8–16 h/day as occupation time as suggested by a recent study [67]. This is done in order to account for high variations of the parameters, and thus avoid the underestimation of their variability.

2.4. Multi-objective robust optimization under uncertainties

This section represents the methodology we use to find the optimal and robust solution for building renovation considering the uncertain parameters and the model described above.

Two quantities of interest (QoI) are to be optimized, namely the total costs and the greenhouse gas emissions over the entire building life cycle. Following an extensive literature review and expert knowledge, we have identified more than forty potential parameters affecting these two quantities. We quantitatively identified the most influential parameters using Sobol' sensitivity analysis [68]. This allowed us to reduce the dimension of the problem to 20 parameters, as presented in the supplementary information. Some of these parameters, namely the exogenous ones, are assumed random and modelled following the probabilistic distributions presented in the previous section. The design parameters, on the other hand, are deterministic and are shown in Tables 2 and 3. They identify possible renovation choices and are therefore modelled as categorical variables.

To account for the randomness in the input parameters, and therefore in the corresponding QoI, we resort to robust optimization. The goal is to find an optimal solution, which shows little sensitivity to the variability in the inputs. Various measures of robustness have been proposed in the literature [69,70]. The most popular ones are the mean and standard deviation or a combination thereof. In this work, we consider conservative quantiles as a measure of robustness. Such a measure can be seen as a combination into a single metric of the mean m and standard deviation s in the form $m + ks$, where k is a positive factor controlling the degree of robustness of the solution. However, we do not need to rely on approximations of these statistical moments in our case. Instead, we estimate the quantiles using crude Monde Carlo simulation [71]. *In fine*, the multi-objective robust optimization problem consists in minimizing the 90th percentile of the total costs and greenhouse gas emissions for various choices of the design parameters. This is carried out using the non-dominated sorting genetic algorithm II (NSGA-II), a widely-used state-of-the-art multi-objective optimization algorithm [23]. This algorithm is particularly suitable as it can be easily adapted to handle mixed continuous-categorical variables encountered in the problem we are solving. However, its main drawback is its computational cost as it requires repeated evaluations of the objective functions, herein quantiles of the two QoIs. On top of that, the quantiles for any combination of design parameters are evaluated by propagating the uncertainties in the input through the computational model described in Section 2.1 using crude Monte Carlo simulation. The compound cost of both uncertainty propagation and objective functions evaluations makes the cost of the entire optimization process prohibitive.

To alleviate the burden of the analysis, surrogate modelling is considered, more specifically Gaussian process modelling also known as Kriging. Kriging is a popular technique where the function to approximate is assumed to be a realization of a Gaussian process [32,33]. The surrogate model is calibrated by statistical learning over a limited set of evaluations of the original model, known as the experimental design. The size of the latter is usually relatively small, i.e. in the order of tens or a few hundreds of samples. Once a surrogate is calibrated and built, it can be evaluated millions of time in a relatively short period of time, i.e., in the order of the second. This allows us then to perform NSGA-II by replacing the original model with the built surrogate. The validity of the ensuing results highly depends on the accuracy of the surrogate model. In this work, the latter is built adaptively by controlling its local accuracy throughout the optimization, hence allowing us to ensure the quality of the identified Pareto front. Detailed developments related to the methodology of robust optimization are proposed by Moustapha et al. [34].

2.5. Probabilistic comparison of the optimal solutions

Once the optimal and robust solutions are identified, the probabilistic assessment of each solution is performed. In this assessment, we compare the optimal solutions for three heating systems and solutions without envelope renovation. This is done to evaluate the overall costs and GHG emissions with the possibility of the heating system replacement under the same energy performance of a building.

The 90th percentiles of the response distribution together with the first and third quartiles are used for the results representation.

3. Case study

The methodology described above is applied on two residential buildings with different energy performance, construction period and architectural period. The buildings are taken from the eRen project which gathers representative buildings for different construction periods [39]. The two buildings chosen represent the construction period with the highest amount of buildings in Switzerland. This would cover about 36% of the buildings built before 2000.

The basic details of these buildings are described in Table 1. The uncertain parameters, value range and distribution are presented in Supplementary information.

The proposed renovation solutions for both buildings are presented in Tables 2–3. These solutions are later used for optimization. The associated costs and environmental impacts can be seen in supplementary information.

4. Results

On Fig. 2, the Pareto fronts representing the optimal solutions for three different heating systems are shown. The results in the Pareto front represent the robust optimal solutions for the 90th percentile. The red points on the Pareto front represent the median solutions. The resulting renovation solutions for the medians are shown in Tables 4–5. As it can be seen in Fig. 2, the trend is similar for both buildings. It can be clearly noticed that optimal solutions with existing gas boiler have the highest overall GHG emissions in most of the cases. The lowest GHG emissions are achieved with a wood pellets boiler while the lowest costs are achieved with an

Table 1
Basic description of buildings used as case studies.

	Building 1	Building 2
Location and context of the building	Western Switzerland, urban contiguous multifamily building in an urban area* [72]	Western Switzerland, detached multifamily building in a small center in a rural area* [72]
Year of construction	1911	1972
Energy performance (heating) [kWh/m^2, a]	141	90
Energy reference area [m^2]	2445	1446
Walls construction	Limestone masonry, not insulated	Double brick wall
Slabs construction	Hollow core clay slabs	Reinforced concrete
Windows construction	Double glazing, PVC frame	Double glazing with low-E layer, PVC frame

*: The ARE Swiss classification of municipalities can be grouped in three types according to [73]: Urban including (1) Large center, (2) Secondary center of large center; Suburban including (3) Belt of large center, (4) Medium center, (5) Belt of medium center and Rural including: (6) Small center, (7) Sub-urban rural commune, (8) Rural commune, (9) Touristical commune.

Table 2
Proposed renovation scenarios for a building with lower energy performance (Building 1).

Insulation systems' configurations	Renovation scenarios for the building envelope				
Categories	Current	Low	Standard	Advanced	Extreme
Windows	Wooden frame (U_f = 1.65) with double glazing (U_f = 1.1)	PVC frame (U_f of 0.94) with double glazing (U_g = 1.1)	PVC frame (U_f of 0.94) with triple glazing (U_g = 0.7)	PVC frame (U_f of 0.94) with triple glazing (U_g = 0.6)	PVC frame (U_f of 0.94) with triple glazing (U_g = 0.5)
External wall (ground floor)	Uninsulated	Multipor 4 cm	Multipor 8 cm	Multipor 10 cm	Multipor 12 cm
External wall (upper levels)	Uninsulated	Hagatherm 2 cm	Multipor 8 cm	Hagatherm 2 cm Multipor 8 cm	Aerogel 4 cm Multipor 9 cm
Ceiling (against attic)	Uninsulated	Cellulose fibre 13 cm	Cellulose fibre 16.5 cm	Cellulose fibre 21 cm + rock wool 1.5 cm	Cellulose fibre 21 cm + rock wool 4 cm
Floor (against cellars)	Uninsulated	Rock wool 8 cm	Rock wool 11 cm	Rock wool 14.5 cm	Rock wool 17.5 cm

Table 3
Proposed renovation scenarios for a building with higher energy performance (Building 2).

Insulation systems' configurations	Renovation scenarios for the building envelope				
Categories	Current	Low	Standard	Advanced	Extreme
Windows	Wooden frame (U_f = 2) with double glazing (U_g = 1.1)	Wooden frame (U_f = 1.24) with double glazing (U_g = 1.1)	Wooden frame (U_f = 1.24) with triple glazing (U_g = 0.6)	PVC frame (U_f = 0.94) with triple glazing (U_g = 0.6)	PVC frame (U_f = 0.94) with triple glazing (U_g = 0.5)
External walls, storeys	Uninsulated	4.2 cm wood fibre	9.4 cm wood fibre	21.9 cm wood fibre	38 cm wood fibre
External walls, shop	Uninsulated	10.3 cm cellular glass	14.8 cm cellular glass	25.4 cm cellular glass	38.7 cm cellular glass
Storeboxes	Uninsulated	1.8 cm glasswool	3.8 cm glasswool	7 cm glasswool	12.7 cm glasswool
Int. walls ag. cellar	Uninsulated	7.8 cm rockwool	10.1 cm rockwool	16.7 cm rockwool	23.8 cm rockwool
Ceiling	Uninsulated	6.8 cm glasswool	9.8 cm glasswool	16.1 cm glasswool	23 cm glasswool
Floor (against cellars)	Uninsulated	6.9 cm rockwool	10.2 cm rockwool	17.1 cm rockwool	24.5 cm rockwool

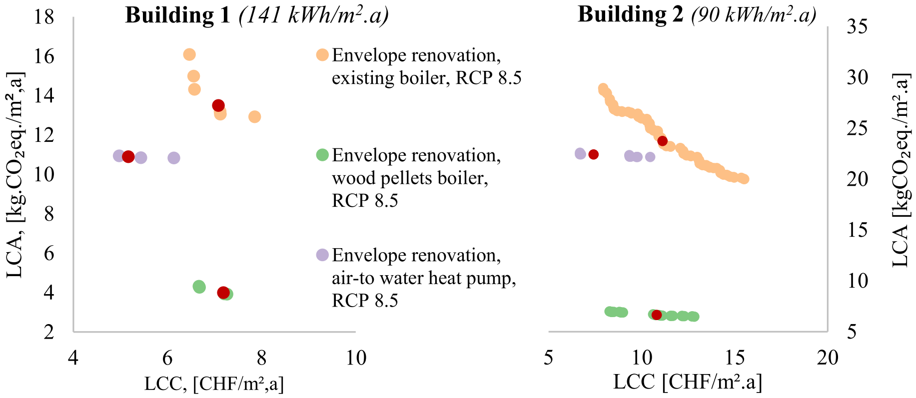

Fig. 2. Pareto front for both case studies with different heating systems.

Table 4
Optimal solutions for the building with lower energy performance (Building 1).

Optimal solutions, RCP 85	Window	Wall	Wall ground floor	Ceiling	Slab (against cellars)
Wood pellets	Current	Hagatherm 2 cm Multipor 8 cm	Multipor 12 cm	Cellulose fibre 21 cm + rock wool 1.5 cm	Rock wool 11 cm
Heat pump , COP 3.0	Current	Hagatherm 2 cm Multipor 8 cm	Multipor 12 cm	Cellulose fibre 16.5 cm	Rock wool 11 cm
Gas boiler	Current	Multipor 8 cm	Aerogel 4 cm Multipor 9 cm	Cellulose fibre 13 cm	Rock wool 14.5 cm
Deterministic	PVC frame (U_f of 0.94) with triple glazing (U_g = 0.6)	Hagatherm 2 cm	Multipor 8 cm	Cellulose fibre 21 cm + rock wool 1.5 cm	Rock wool 17.5 cm

Table 5
Optimal solutions for the building with higher energy performance (Building 2).

Optimal solutions RCP 8.5	Windows	Exterior walls residential	Storeboxes	Exterior walls shop	Int. walls against cellar	Ceiling	Slab against cellars
Wood pellets	Current	4.2 cm wood fibre	7 cm glasswool	38.7 cm cellular glass	7.8 cm rockwool	Current	10.2 cm rockwool
Heat pump COP 3.5	Current	Current	12.7 cm glasswool	10.3 cm cellular glass	10.1 cm rockwool	16.1 cm glasswool	6.9 cm rockwool
Gas boiler	Current	9.4 cm wood fibre	7 cm glasswool	Current	10.1 cm rockwool	23 cm glasswool	10.2 cm rockwool
Deterministic solution	Triple glazing (Ug = 0.6)	9.4 cm wood fibre	Current	38.7 cm cellular glass	16.7 cm rockwool	16.1 cm glasswool	6.9 cm rockwool

air-to-water heat pump. The solutions for other climate change scenarios can be seen in Supplementary information.

The Figs. 3–4 represent the comparison of the median solutions for all the examined heating systems and two case studies. We also present the solutions with only heating system replacement to compare the results. The dashed line shows the target for the Swiss buildings concerning renovation in CO_{2eq} and includes the embodied and operational GHG emissions [74]. The results of the sensitivity analysis to filter non-influential parameters for both buildings can be seen in the Supplementary information.

The non-renovated building is far from reaching the SIA 2040 target value. It can also be noticed that the solution with only envelope intervention does not reach the target. For a building with lower energy performance (Fig. 3), every intervention saves both GHG emissions and costs in the overall life cycle. For a building with higher energy performance (case of Building 2), it is clear that every intervention still decreases overall GHG emissions, however, there is no cost benefit in renovating the building and the non-renovation solution has the lowest cost.

It is also worth mentioning that the uncertainty for both LCA and LCC for the existing non-renovated building is the highest. The uncertainty decreases with any intervention done, which can be explained by the biggest share of the uncertainties coming from the future operation of the building.

5. Discussion

The results show that the key parameter for minimizing both LCC and GHG emissions in the energy-related renovation process is the heating system. The most optimal and robust solution for both buildings in terms of LCA is the wood pellets boiler with the envelope renovation. However, once considering LCC, the heat pump shows the best performance in terms of costs. These results also comply with a recent study performed on assessment of different renovation scenarios including different heating systems [75]. However, the corresponding GHG emissions of a heat pump are higher than for the wood pellets boiler. One explanation for this is the lower flow temperatures needed to operate the heat pump, which leads to either low efficiency of a heat pump or the need of distribution system replacement to maintain high COP. The replacement of the heat distribution system, mainly radiators in the older building, is carbon intensive in case of the use of ordinary steel radiators. Another solution for heat distribution system might be wall clay heating panels. It has been shown that this solution

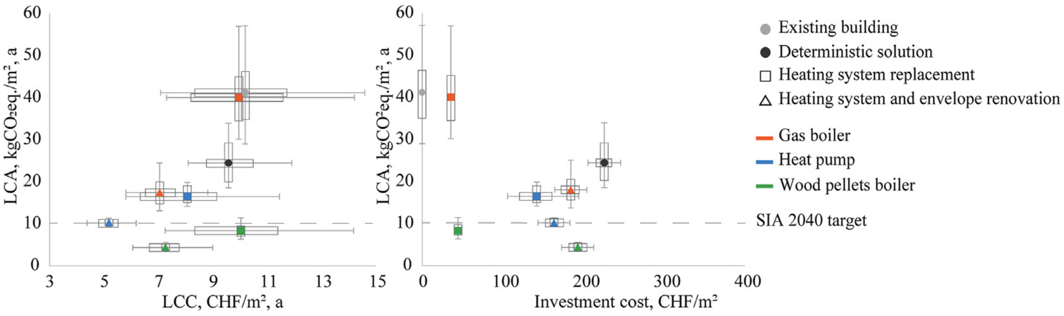

Fig. 3. Comparison of the solutions for the building with lower energy performance (Building 1). The box plot represents the 1st and 3rd quartile, upper and lower whiskers represent 95th and 5th percentiles, the mean value is shown in a symbol.

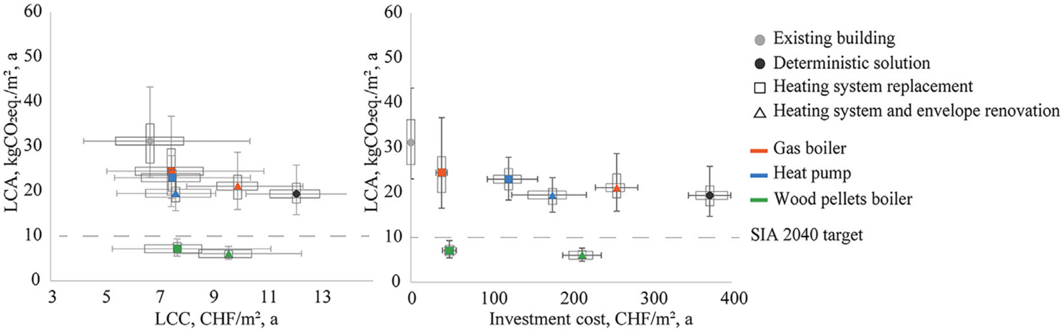

Fig. 4. Comparison of the solutions for the building with higher energy performance (Building 2). The box plot represents the 1st and 3rd quartile, upper and lower whiskers represent 95th and 5th percentiles, the mean value is shown in a symbol.

shows lower GHG emissions and overall costs [76]. One more solution that can be used is the conversion of existing radiators into ventilation radiators.

It is interesting to note that all the optimal solutions for the selected case studies include keeping the existing windows regardless of the heating system type or the energy performance of an existing building. This can be explained by the high price and embodied impact produced by the windows, which do not pay off during the operational savings. For a building with higher energy performance, it can also be explained by the fact that installed buildings before renovation already have quite low U-value. In general, the results show that in a building with higher energy performance, the investments done for the building renovation do not pay off the operational savings. This can be explained by the low energy price for fossil fuels, which in turn explains the problem of the low renovation rate. However, as the results show, the envelope renovation makes sense regarding the building with lower energy performance. For all the investigated heating systems, the optimal solutions do not prescribe deep renovation. This can be explained by the further warming in Switzerland and therefore decrease in the heating demand. Current results can be generalized to the construction periods of the selected buildings, which represent about 36% of building before 2000.

It is worth noting that, according to the results of the study, the replacement of the heating system alone has lower overall GHG emissions compared to a solely envelope renovation. This can be explained by the low carbon intensity value for wood pellets. The solutions with wood pellets also show the highest robustness compare to other solutions. This can be explained by the fact that there are more uncertainties associated with future building operation than with production of the materials.

The study shows that the wooden boiler has a big potential for reducing the GHG emissions in a building renovation process. The question that might be raised in this regard is the availability of the resources to satisfy the demand for the Swiss building stock. We have analyzed the demand based on the Federal statistical office and the supply based on the recent report for the biomass potential as the energy source for Switzerland [77,78]. Based on this study, the total current amount of energy supplied by the oil and gas is around 43,640 GWh/year. There is a clear decrease of the amount of new oil boilers installed during recent years however, a considerable amount is still used in older buildings (See Fig. 5). The amount of gas boilers is significantly lower, however, the distribution is not the same and there is no clear decline in recent years. According to the mentioned report, the overall theoretical potential to use wood for heating is around 25,100 GWh/year and sustainable potential is 2500 GWh/year, which respectively corresponds to around 57% and 7.5% of the current need. Sustainable potential here means the theoretical potential after excluding ecological, economic, legal and political constraints. This potential includes the forest wood, waste wood, industrial residues and

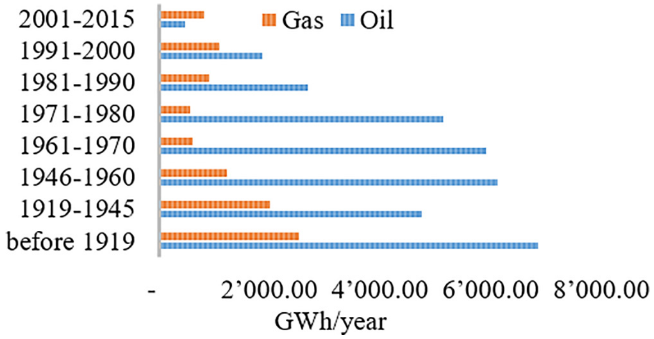

Fig. 5. Distribution of oil and gas boilers for the construction periods in Switzerland.

landscape maintenance. It can be clearly seen that the solution presented in this paper is optimal on a building level but cannot be scaled up. Thus heating demand reduction is still relevant on the bigger scale.

In this work, we show that deep renovation is neither cost effective nor climate-friendly considering future uncertainties. Instead, the results show that the replacement of the heating system by wood pellets boiler has the highest impact on the overall LCA results and allows achieving the local standard for the CO_2 emissions target [74]. Similar results were previously shown in other research [79,80]. However, it is important to note that the optimal solution with wood pellets does not show a high degree of applicability on a bigger scale due to the limited resource availability of wood in Switzerland. Moreover, considering social justice, such solution does not reduce the energy bill for the residents. It has been shown previously that there is a relationship between the fuel and monetary poverty, which happens due to either inability of residents to pay the energy bill or the high percentage of income that is spent on the energy bill [81]. It is therefore clear that energy-efficient measures provide stable solution to the fuel poverty. However, considering in particular the Swiss context, the overall energy bill has a small share of the expenses compared to other living costs.

Another important aspect to consider is the thermal comfort. During this study, optimal solutions were also analysed in terms of the simplified analysis of overheating hours according to ISO 52016-1 [82]. The results were combined with other metrics and can be seen in the Fig. 6. As it can be seen, the amount of overheating hours increases with the increase in the insulation thickness considering conventional building insulation materials. This can be explained by the future climate in Switzerland that is characterized by the further temperature increase and anthropogenic warming will be about three times larger by the end of the century relative to today in a scenario without mitigation (RCP 8.5) [83].

Our study shows that a solution with a common insulation level is decreasing the robustness. However, this study is limited to conventional construction materials. The possibility of using bio-based materials that combine the decrease in energy consumption and carbon storage still needs to be explored. It has been shown that only fast growing materials show the potential for Carbon Capture and Storage [84]. Further studies should be conducted with consideration of bio-based materials to see if a robust renovation solution could also be compatible with resource availability and social justice requirements.

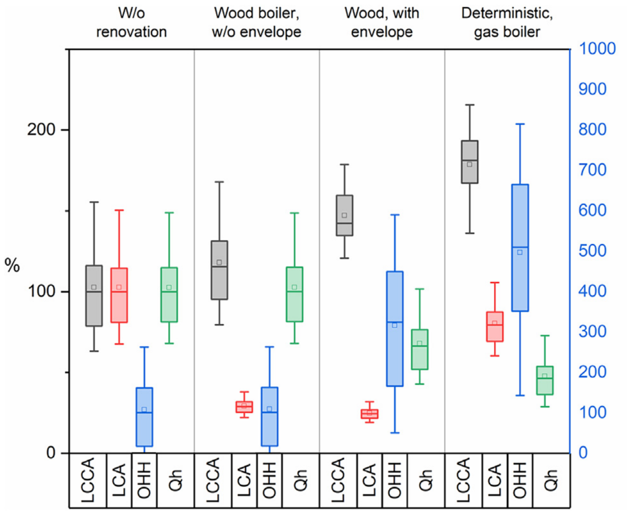

Fig. 6. Simplified analysis of overheating hours for a case study with higher energy performance and comparison with other metrics of the analysis. Result for the most optimal solution (in this case wood) is compared to the wood boiler solution without envelope renovation, as well as non-renovated building and deterministic solution, details can be seen in the Table 5. The scale is relative in percentage to the mean value of the scenario with no renovation applied. Scale on the left represents the LCA, LCCA and heating demand (Qh), while scale on the right represents the overheating hours.

5.1. Limitations

The range of some parameters used for this study might be found too large. The reason for this is to be able to cover "the worst case scenario" in the case where the amount of information is limited. The distributions and range are defined based on the literature review, existing data or expert opinion. Defined data might be updated further, which can have an influence on the distribution and overall results as the analysis is sensitive to the distributions of the input parameters.

In this study, we use simplified the quasi-steady heating demand calculation. The use of dynamic hourly analysis could provide results with higher precision. The difference between the monthly and hourly analyses might be justified by the large amount of uncertain parameters used in this study and the large range of uncertainty for these parameters.

For the LCA, in this study we use only global warming potential (GWP) as an indicator. This is explained by the fact that the building stock is mainly affecting the climate change and building renovation is a priority for the CO_2 reduction. However, taking into account a broader range of indicators could provide a bigger picture for the overall analysis.

Another limitation of this study is just three selected energy sources such as gas, wood pellets and heat pump without considering district heating. This can be explained by the clear carbon intensity values for the selected heating sources, and district heating carbon intensity value provided by gas or wood pellets would be similar to the one for individual boilersHowever, taking into account a bigger range of energy sources would provide a better understanding of the outcomes of this study.

6. Conclusion

In this work, a new methodology for the identification of robust climate-friendly and cost-effective renovation solutions was created. The methodology includes the description of uncertain parameters and possible renovation solutions for the envelope as well as different heating systems. The uncertain parameters include the ones related to the production of the materials and those related to the future building operation, such as climate change, future material replacement and electricity mix, occupancy behavior. To decrease the computational cost of the uncertainty quantification, surrogate modelling using the Kriging technique was used, and the optimization under uncertainty was performed afterwards on a surrogate model using the NSGA-II algorithm. Two case studies were applied to evaluate the applicability of the methodology.

The results of the study differ between the building with higher heating demand and lower heating demand. For a building with lower heating demand, the most robust and optimal solution is the heating system replacement to a wood pellets boiler. For a building with higher heating demand, the envelope of a building needs to be renovated with the application of either a heat pump or a wood pellets boiler. Overall, the results show that the heating system is an important retrofit measure that needs to be taken into account as it helps to drastically decrease the amount of GHG emissions during the building life cycle. The proposed solution is different from the usual one when deep renovation strategy is proposed without necessarily changing the heating source.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.111329.

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