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BIO-BASED MATERIALS AS A ROBUST AND OPTIMAL SOLUTION FOR BUILDING RENOVATION

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Abstract
Building energy renovation is urgent in order to lower green house gas (GHG) emissions and achieve carbon neutrality by 2050. Building energy renovation can be achieved by more efficient thermal insulation and replacing the fossil heating system in a building. Currently, conventional building insulation materials dominate the market. However, to drastically reduce GHG emissions, bio-based materials are a valuable asset. These can be applied not only to reduce the operational energy but also to temporarily store carbon in the building stock. To evaluate the environmental and cost performance of such insulation, life cycle cost analysis (LCCA) and environmental life cycle assessment (LCA) can be used. However, as buildings are long lasting systems, many parameters in these analyses are uncertain. Such parameters include the future climate, future inflation rates, point in time when materials are replaced, future energy policies, and so on. In this paper, we apply bio-based insulation materials for building renovation and define the optimal solution for building energy-related renovation using a novel methodology, which combines non-dominated sorting genetic algorithm (NSGA-II) with surrogate modeling. We use materials such as straw, hemp, and wood fibre along with conventional materials such as EPS. At the same time, we account for the uncertainties associated with these materials' production and replacement as well as those associated with the future building operation. In this analysis, we also include the carbon storage calculation. The results show that bio-based materials provide a robust solution for building renovation and have high potential to store carbon in building components in comparison with conventional insulation materials. The results also show that to achieve the highest GHG emissions reduction, building energy-efficient measures should be combined with the replacement of the existing fossil heating system. The approach presented here allows the identification of the robust and optimal building renovation solution performed with bio-based materials and the comparison of such renovation with conventional materials.

1. INTRODUCTION

In 2019, a European Green Deal was initiated, the aim of which is to be climate neutral by 2050. 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 [1]. Therefore, building renovation plays a key role in greenhouse gas (GHG) emissions reduction and achieving the goal of climate neutrality. Building retrofit can be achieved by applying thermal insulation to lower operational heating demand. Currently, conventional materials are being used for this purpose due to their high thermal properties and low cost. However, such common materials as extruded polystyrene foam (EPS) are very carbon intensive and are not biodegradable. Currently, there is a lot of research going on in the field of bio-based materials, that are regenerative and have high potential to reduce carbon in the overall building lifecycle [2]–[4]. Moreover, such materials have the capability to store carbon in the building. It has been show that fast growing materials such as straw, hemp and flax have higher potential to store more carbon due to the fast regrow, or rotation, period [2].

To evaluate the potential of such materials, common assessment as life cycle assessment (LCA) and life cycle cost analysis (LCCA) can be used. The main advantage of such analyses is that the whole life cycle of a building is examined. Such analyses are commonly integrated to identify the environmentally-friendly and, at the same time, cost-effective solution. However, a big drawback of such analyses when applied to buildings is a long service life, typically 60 years when applied to Swiss regulations [5]. During such period, many uncertainties might affect the result of the analyses, which makes them unreliable for further interpretation. Such uncertainties include the future climate, heating cost and environmental impacts, future energy mix, policies and so on. It has been shown that while comparing two products, the effects of these uncertainties might be higher than the intrinsic difference between the two products in a deterministic context [6]. Therefore, uncertainty quantification is an important step in LCA and LCCA. Uncertainty quantification aims at identifying such parameters and modelling their overall effect on the model output. Uncertainty quantification can be used when comparing two building retrofit scenarios or it can be combined with optimization techniques to identify a robust optimal renovation solution. Several techniques have been proposed for robust optimization in LCA and LCCA [7], [8]. In this work we use the non-dominated sorted genetic algorithm (NSGA-II) combined with surrogate modelling, a methology proposed in Moustapha et al. [9]. The goal of this work is to identify the most robust solution for climate-friendly and cost-effective renovation using bio-based materials, combined with the heating system replacements.

2. METHODOLOGY

The methodology of the analysis is described as follows. First, we create an integrated simplified assessment of LCCA and LCA, which includes the stages of production, operation, replacement and end of life, in case of LCCA, a stage of repair as a percentage of the investment cost is also implemented. The operational stage includes simplified heating demand analysis based on a local SIA 380/1 standard [10]. The functional unit of the analysis refers to the building operation over its lifetime. The indicators for the analyses are the global warming potential expressed in kgCO2eq. and overall costs expressed in Swiss Francs. The details for the analysis can be found at Galimshina et al. [11].

Afterwards, renovation scenarios are defined. In this paper, renovation scenarios are composed of the biobased materials for thermal insulation, such as straw, hemp, wood fibre and hempcrete and heating system replacement. EPS insulation is also used as an additional solution to compare the bio-based solution to the conventional one. The data for environmental impacts and costs is presented in Table 1. In this paper, carbon storage analysis is included in calculation and a dynamic methodology is used following the procedure of Guest et al. [12].

Table 1. Data for environmental impacts, costs and carbon storage of the insulation materials for renovation.

Material	GWP fossil, kg CO_2eq/kg	Carbon content, %	Biomass content, %	Density, kg/m^3	Rotation period	Cost CHF/m3
Wood fibre	0.46	50.0	100.0	50	20	650
Hempcrete, 8 cm	0.288	45.0	64.0	600	1	480
Hemp mat, 3 cm	0.622	45.7	100.0	37	1	640
Straw, 48 cm	0.09	44.3	100.0	105	1	104
Straw, 20 cm	0.09	44.3	100.0	105	1	86
Straw, 70 cm	0.09	44.3	100.0	105	1	115
EPS, 5 cm	7.64	0	0	30	-	500

Afterwards, we define and describe the uncertainties associated with all the stages of integrated LCCA and LCA. The uncertainties related to operational costs and environmental impacts, production of the materials, users and service lives of the materials are included in the calculations. The details for the parameters' description can be found in Galimshina et al. [11]. Climate change under uncertainties was also integrated as an additional parameter [13].

Once the integrated assessment is developed, renovation scenarios are defined and uncertain parameters are described, we perform multi-objective robust optimization under uncertainties. The quantities of interest in this study are the total cost and overall environmental impacts over the building life cycle. In this study, the combined use of NSGA-II and Kriging or Gaussian process regression as a surrogate tool is applied. The implementation of this procedure is proposed by Moustapha et al. [9]. Once the optimal solutions are identified, the results are compared with each other in a probabilistic context.

The methodology described above was applied for a case study of a typical building from the 1970s located in Switzerland. The basic properties of this building are presented in Table 2. From the solutions presented in Table 1, all range of insulation materials are applied to the exterior surfaces and ceiling, however, only EPS and hempcrete are applied for the surfaces facing underground construction for the sake of moisture safety.

Table 2. Basic description of a case study.

Location and context of the building	Western Switzerland, detached multifamily building
Year of construction	1972
Energy performance (heating) [kWh/m^2,a]	90
Energy reference area [m^2]	1446
Walls construction	Double brick wall
Slabs construction	Reinforced concrete
Windows construction	Double glazing with low-E layer, PVC frame

3. RESULTS

The optimal solutions for the considered case study are presented in Table 3. The solutions are afterwards compared to each other probabilistically in terms of LCCA and LCA. The results can be seen in the Figures 1 and 2.

Table 3. Optimal solutions for considered case study. Conventional solution is added for the comparison.

Component / Heating type	**Exterior wall**	**Int. walls ag. cellar**	**Ceiling**	**Floor (against cellars)**	**Windows**
Gas	18 cm hemp mat	10 cm EPS	18 cm hemp mat	20 cm EPS	Not included
Wood	20 cm straw	15 cm EPS	70 cm straw	15 cm EPS	Not included
Heat pump	70 cm straw	10 cm EPS	22 cm hemp mat	10 cm EPS	Not included
Conventional solution	18cm rock wool	16 cm XPS	20 cm mineral wool	-	Triple glazing, PVC frame

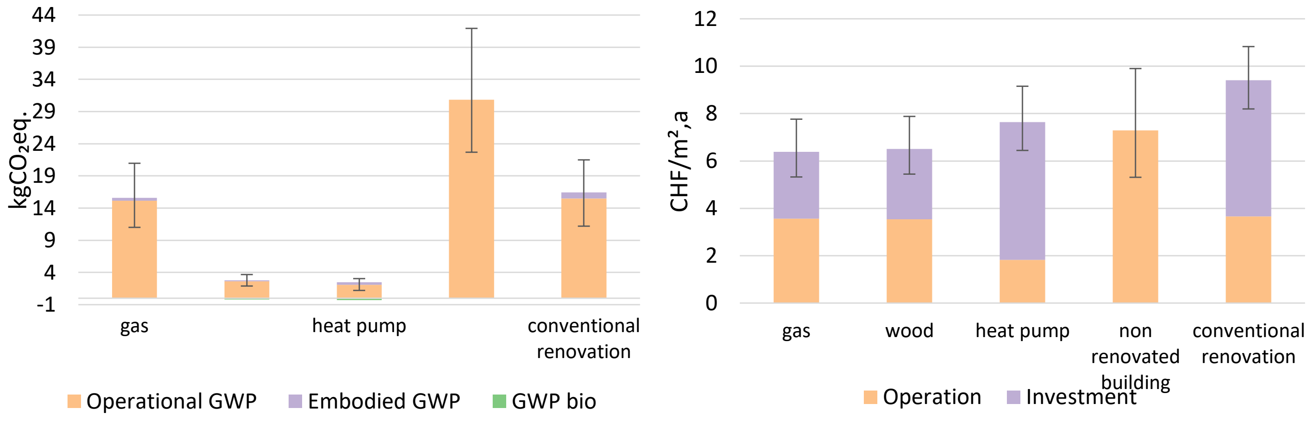

Figure 1 and 2. LCA and LCCA results of the proposed solutions.

As it can be seen from the Table 3, the optimal solution for gas boiler has the lowest amount of insulation compared to the wood pellets boiler or a heat pump. It can be noticed that for both heat pump and wood pellets solutions, the exterior surfaces include the maximum amount of straw insulation of 70 cm.

The error bars in Figures 1 and 2 represent the 10th and 90th percentiles. It can be seen from the figures that the highest environmental impact corresponds the non renovated building while the highest cost is the conventional renovation solution. Regarding the lowest environmental impact, the solution with wood or heat pump is the most beneficial one, while the lowest cost solution represents the gas boiler with the least amount of insulation in comparison with other solutions.

It can be noted that embodied impact has a small share in the overall emissions while the investment costs have a substantial part in the overall costs. It can also be noted that carbon storage has a low impact in the analysis overall and can only be visible once the low carbon heating solution is installed.

4. CONCLUSIONS

In a previous study [14], it was identified that considering conventional materials, robust renovation is comprised of the heating system replacement and a small amount of insulation on the facades while keeping the existing windows. In contrast, the results of this study show that using bio-based materials provide an opposite solution to the conventional renovation and the optimal solution applies a thicker insulation on the facades. This can be explained by the low carbon bio-based materials and the carbon storage. However, the results show that the heating system is the most crucial parameter for renovation also in this study and replacing the gas boiler by a heat pump or a wood pellets boiler provides five times less overall GHG emissions.

Regarding the cost analysis, it can be seen that a gas boiler with the minimal insulation thickness provides the lowest cost. This can be explained by the low cost for gas and high investment cost for insulation materials. The conventional solution shows the highest cost, which can be explained by the very high cost for windows, which is included in this scenario.

Regarding the environmental assessment, in opposite to LCCA, the optimal solution is to apply the biggest amount of bio-based insulation on the facades and change the heating system to wood pellets or a heat pump. In this case, the carbon storage of the insulation materials can also be visible in the results because of the low overall GHG emissions due to the change of the heating system. Overall, it can be seen that the carbon storage has a low impact on the analysis.

This study proposes a methodology for robust optimization under uncertainties using bio-based materials and the carbon storage potential. We define the uncertainties associated with all the stages of the building life cycle and optimize using a novel methodology, which combines NSGA-II analsyis with surrogate modeling. The results show that the highest impact for the analysis has the heating system replacement, which is a heat pump or a wood pellets boiler. The best performing solution in both quantities of interest is the replacement of the heating system in combination with thick bio-based thermal insulation on the exterior surfaces.

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