Optimization of building envelope components based on life cycle environmental impacts and costs

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Keywords: refurbishment, life cycle assessment, life cycle cost, optimization, insulation

Abstract. Recent national and international building regulations on the energy performance of buildings focus mainly on the reduction of operational energy. This can be achieved by increasing the energy efficiency of the building, installing highly efficient building service systems and applying renewable energy sources. However, these measures have a price in terms of investment costs, and also in terms of environmental impacts.

The life-cycle of building materials, building constructions or whole buildings 'from cradle to grave' can be assessed using the method of Life Cycle Assessment (LCA) and Life Cycle Cost analysis (LCC). These tools take into account not only the heating energy saving due to additional insulation, but also the embodied environmental impacts and costs of the investment.

In this paper, the optimum thickness of various insulation materials, including natural and recycled materials is examined considering three main environmental indicators and global costs. The analysis is performed for a typical Hungarian single-family house subject to retrofit.

1. Introduction

The goal of the European Union is to drastically cut its domestic greenhouse gas emissions by 80% by 2050 compared to 1990 levels [1]. Since the building sector has been identified as one of the key sectors for cost-efficient savings, at least 88-91% reduction is necessary here to reach these ambitious targets [1]. This can only be achieved if the energy consumption of both the existing building stock and new buildings is reduced, and the share of renewable energy sources is increased in the energy supply. As the construction rate of new buildings has sharply fallen recently, the refurbishment of existing buildings has acquired especial importance.

By applying energy efficiency measures in existing buildings, drastic space heating energy reductions are feasible. However, the manufacturing, transport and installation of materials, as well as their maintenance and replacement require energy and causes emissions. With larger insulation thickness, the space heating energy use and associated costs decrease, but the embodied energy and the investment costs increase. The goal of this paper is to analyse the effect of additional insulation of building elements on the whole life cycle, and to find the optimum thickness for various material types. These results can also be used to assist architects in designing refurbishment scenarios and material manufacturers to define possible directions of product development.

The results of the paper are based on a student assignment performed in the course Environmental friendly constructions at the Department of Architectural Engineering at the Budapest University of Technology and Economics in 2013.

2. Methodology

Case study building. As a case study building, a typical Hungarian detached house situated in Vác was chosen, which was built in large volumes between the 1950s and the 1970s (Fig. 1). The characteristics and composition of the original building elements are summarised in Table 1. The original windows have already been replaced by double-glazed insulating windows. Space heating is supplied by a non-modulating atmospheric gas boiler and radiators, and the hot water by an electric boiler.

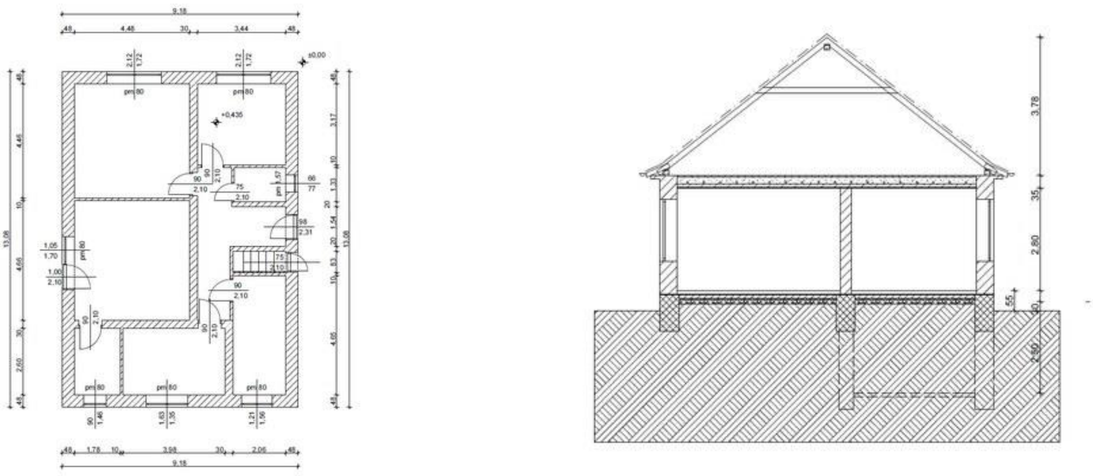

Fig. 1. Ground floor plan and section of the examined house [2]

Table 1. Composition of the building elements

Building element	**Thickness (m)**
Wall (U = 0.74 W/m^{2}K)	
Cement plaster	0.015
Concrete blocks	0.380
Perlite plaster	0.070
Attic slab (U = 1.09 W/m^{2}K)	
Cement plaster	0.015
Prefabricated floor trays (’Horcsik floor’)	0.065
Concrete	0.030
Sludge	0.200

Considered energy saving measures. Additional insulation was applied on the external wall and the attic slab. In every case, only one measure was considered, i.e. either wall or attic slab insulation and not their combination. Only the insulation thicknesses available on the market were taken into account, and necessary supplementary materials, such as fixing, plaster, wooden planks and OSB were included as well. The analysed measures are summarised in Table 2.

Table 2. Selected insulation measures.

Element	**Material**	**Additional materials**	**Comment**
Wall	expanded polystyrene (EPS) with graphite	glue, fixing, glass fibre net, thin plastering	the environmental data of EPS were used
Wall	reed plate	fixing, 2 cm cement plaster	the environmental data of straw were used
Wall	straw bale	wooden frame, fixing, 3 cm adobe plaster, iron net, 0.5 cm lime plaster	
Attic slab	cellulose blown-in	wooden frame, 9 mm OSB on top	
Attic slab	mineral wool (step-resistant)	vapour barrier foil, 9 mm OSB on top	
Attic slab	rigid polyurethane (PUR)	12 mm OSB on top	

Calculation of the energy demand. The energy demand was calculated according to the Hungarian Government Decree on the energy performance of buildings [3] with the help of the Belső Udvar E-

P-LCC-LCA software [4]. Thermal bridge effect caused by fixing of the additional insulation and wooden elements was taken into account wherever necessary. Vapour calculations were also performed to avoid the risk of interstitial condensation. The space and water heating demand was calculated for every option, considering the efficiency and losses of the building systems.

Life cycle costs. The global costs were calculated according to the European Directive 244/2012/EU [5]. Global costs correspond to ‘life cycle costs’ (LCC), i.e. in this case the investment cost of the refurbishment and the sum of annual costs for every year (energy costs, maintenance, replacements, etc.), all expressed as Net Present Value referring to the starting year. The following parameters were taken into account:

- calculation period: 30 years,
- discount rate, excluding inflation 4%,
- long-term energy price escalation: 2% for electricity and 2.8% for natural gas.

The investment cost of additional insulation and supplementary materials, including the price of material and labour, were taken from cost databases [6], manufacturer data and quotes. The operational costs, including space and water heating, were calculated with a price of 0.167 EUR/kWh for electricity and 0.053 EUR/kWh for natural gas including taxes.

Life cycle assessment. For the calculation of the environmental impacts, the method of life cycle assessment (LCA) was applied, following the norms ISO 14040 and ISO 14044. The functional unit was a residential building over a 30-year period in Hungary. In LCA, normally a longer period is considered, but here this time span was chosen in line with the LCC calculations.

High-quality environmental data from the Swiss ecoinvent 2.0 database was used, with certain modifications to account for the Hungarian circumstances where necessary [7]. Three impact categories were considered:

- non-renewable cumulative energy demand (CED, n.r.) [MJ]
- global warming potential (GWP100a, CML 2001) [kg CO_2-eq]
- acidification potential (AP, CML 2001) [kg SO_2-eq]

3. Results

Fig. 2-5 show the LCA and LCC results. In general, the values are decreasing with increasing insulation thickness. As expected, generally the first few centimeters of insulation result in a significant reduction of both global costs and environmental impacts. Depending on the insulation type and the analysed indicator, after a certain thickness the curve flattens. It is possible to perform a mathematical optimization with computerized algorithms as explained in [8, 9], but in this paper we used a simplified approach and defined the ‘optimum’ thickness as the minimum point of the curve in the predefined thickness range.

Fig. 2 shows that there is a significant difference in the global cost of the insulation of the attic slab and the insulation of the walls (excluding the straw insulation). While the optimal global cost of wall insulations is about 12.4 M HUF at a thickness of 13 cm, that of cellulose on slab is about 11.2 M HUF at 18 cm, and that of rockwool on slab is about 12 M HUF at 8 cm. This means that the insulation of the slab is more cost-efficient than the insulation of the walls.

The “PUR on slab” curve has a jump between 7 and 8 cm. The reason for this is that above 7 cm another type of PUR product is available on the market, which has a higher unit price.

The straw-bale wall insulation has substantially different values. This is due to the fact that its investment cost is significantly lower, and the common thicknesses are significantly higher than for the other measures. This measure shows the best results from the point of view of global costs without a minimum point in the analysed thickness range.

It is remarkable, that for EPS the 2 cm thickness has higher global cost than the original state. The reason is that the costs of the supplementary materials (glue, fixing, plastering, etc.) correspond to a higher investment cost than the savings from the insulation.

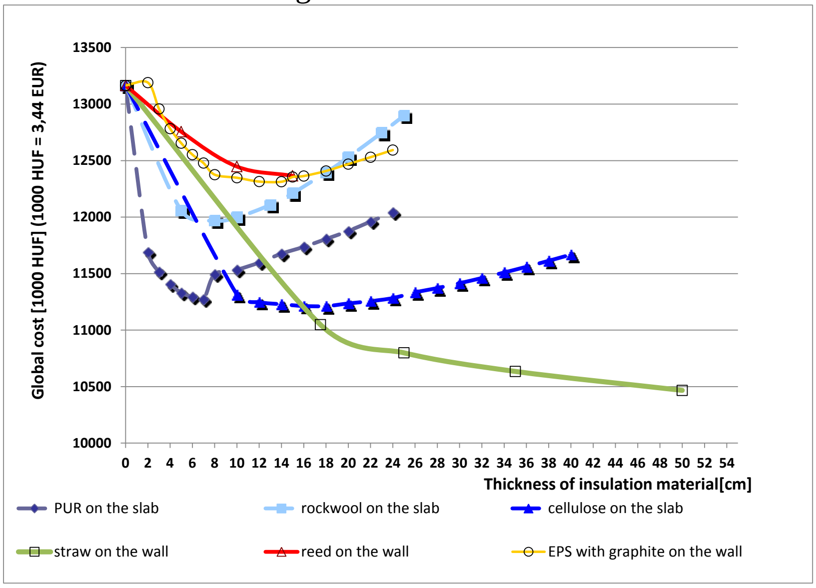

Fig. 2. Global cost of the measures taking account 30 years lifespan [HUF]

Fig. 3 shows that in every case the insulation of the slab has a lower cumulative energy demand than the insulation of the wall. Hence the insulation of the slab is always more efficient than the insulation of the walls: with the same amount of material we can achieve a higher energy reduction or the same energy reduction can be achieved with less building material.

It is interesting to see that reed insulation, which is a natural material, has higher values than for example EPS. The reason for this is that operational impacts are dominant for this indicator. As the heat conductivity of reed is almost 1.5 times higher than that of EPS, in spite of its lower embodied energy the total cumulative energy demand will be higher.

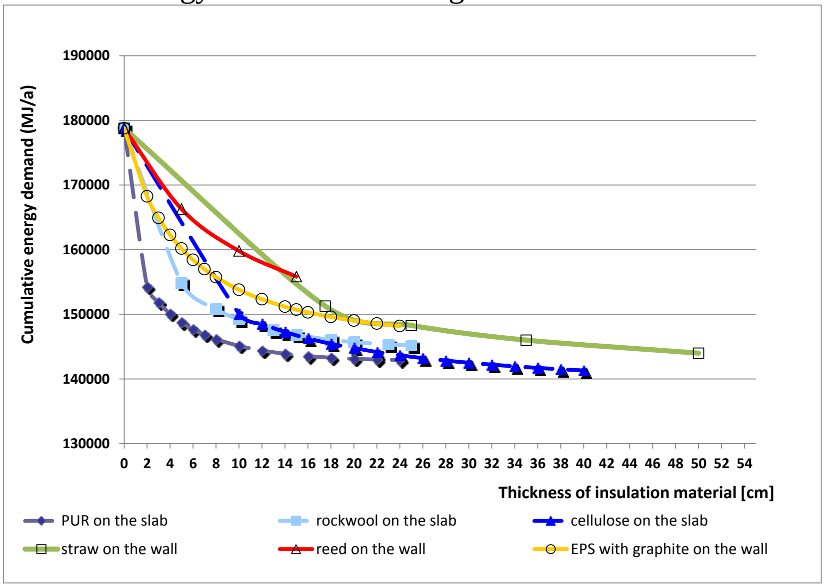

Fig. 3: Cumulative energy demand of the measures per year [MJ/a]

Fig. 4 shows that the cumulative energy demand and the global warming potential correlate well. The curves have the same character as in Fig. 3.

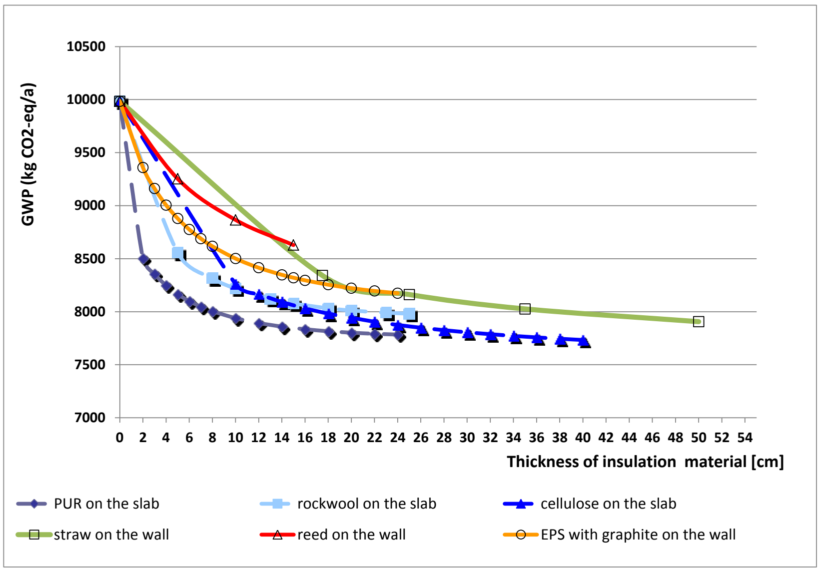

Fig. 4. Global warming potential of the measures per year [kg CO_2-eq/a]

The acidification potential of natural and recycled insulation materials has a different character than industrial materials (Fig. 5). In the examined range of insulation thicknesses, the acidification potential of natural materials monotonically decreases. The curve has a minimum point for industrial products. This means that there is a limit in the use of these materials, and when this threshold is exceeded, there is no environmental advantage of the additional thickness.

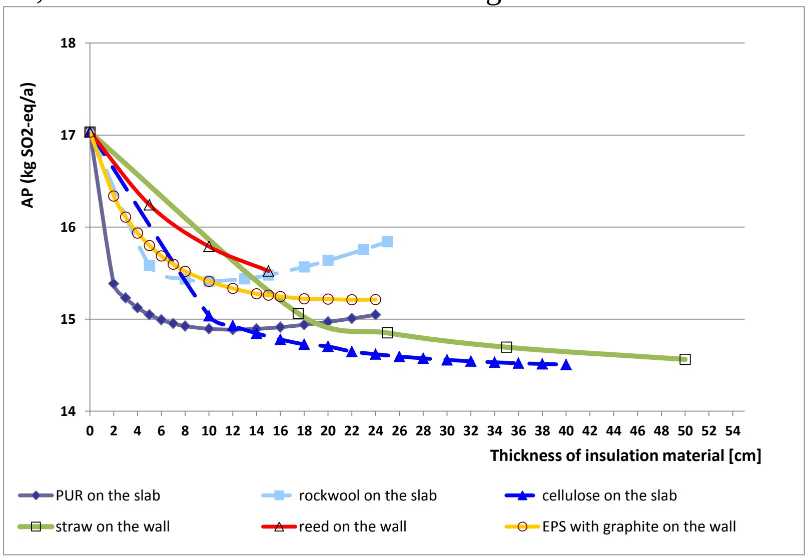

Fig. 5. Acidification potential of the measures per year [kg SO_2-eq/a]

4. Conclusions

This paper analysed the global costs and environmental impacts of various additional insulation measures. According to the results, the insulation of the attic slab is generally more effective than the insulation of the external wall regarding both economic and environmental aspects in the examined building situation.

In the present Hungarian circumstances, from an economic point of view the optimum thickness of industrial materials is around 15 cm for wall insulation and around 12 cm for slab insulation. The optimum for natural materials was at higher thicknesses, namely at approx. 50 cm for straw bale wall insulation and at 20 cm for cellulose slab insulation.

For the cumulative energy demand and global warming, no optimum points could be found in the analysed range, i.e. larger insulation thicknesses were also worthwhile. As the operation phase of buildings has a significant effect on the environmental impacts, it is important to use insulation materials with a high thermal resistance.

From the point of view of acidification potential, there is a limit in the use of industrial materials, and when this threshold is crossed, there is no environmental advantage of the additional thickness. In the case study, this threshold was at 25 cm for wall and at 15 cm for slab insulation.

These results are valid for the specific case study building, with the given building elements and assumptions. However, since there are about 800,000 - 1 million buildings in Hungary with similar geometry and building constructions [10], the results have a more general scope and hence can assist architects and engineers in designing refurbishment scenarios.

Further research is needed to analyse the combinations of retrofit measures, and to study the impact of the building geometry and the properties of the original building elements on the results.

This paper proved that LCA and LCC are useful for optimizing the building design. It is not enough to consider the production or the use phase of a building alone, the whole life cycle must be taken into account. The choice of the retrofit measures can be justified based on life cycle thinking. These methods can also be useful for building material manufacturers in product development.

Acknowledgements

The work is supported by the TÁMOP-4.2.2.A-11/1/KONV-2012-0041 project. The project is co-financed by the European Union and the European Social Fund.

We would like to thank the selected students of the group for their high-quality work: Olivér Czoboly, Marcell Futó, Dénes Glavatity, Szilvia Hinkel, Eszter Váraljai and Réka Nagy.

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