454: Ecological optimisation of thermal insulation

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Abstract

New legislation, most notably the EU Energy Performance of Buildings Directive (EPBD) has brought more stringent requirements on the operational energy consumption of buildings. However, the energy and emissions corresponding to the construction and maintenance of buildings are often significant as well.

The life-cycle of building materials, building constructions or whole buildings "from cradle to grave" can be evaluated using the method of life cycle assessment (LCA). LCA is a tool for measuring the environmental performance of products, such as building materials, building constructions or whole buildings.

Measures like the change of windows or additional insulation of the envelope aim at the reduction of operational energy, but at the same time result in an increase of embodied energy for production and maintenance. Future amendments to the Building Regulations are expected to further cut energy and CO_2 emissions, and approach the level of passive houses in 5-10 years.

This paper describes a methodology developed for the environmental analysis of residential buildings. The use of the methodology is presented and demonstrated for single-family houses and typical building systems in Hungary. The contribution of the life cycle phases is determined and the effect of increased thermal performance is analysed. The paper analyses whether thermal insulation has ecological limitations for conventional homes. The optimum point of thermal insulation is sought in an example.

Keywords: life cycle assessment, cumulative energy demand, thermal insulation

1. Introduction

Decisions made by architects in the present can influence the economy, society, the townscape but also the energy and ecological scene for a century or more. It is a well-known fact that about 40 percent of the annual gross energy consumption – and the corresponding emissions – are connected to buildings in Europe [1].

Several studies have shown that the use phase is dominant in the life of buildings. However, as the energy to heat our buildings has decreased in the last decades due to the increased thermal performance, the energy used for construction has gained in importance. Since the lifetime of buildings is typically 50-100 years, energy needed for regular maintenance and replacement of elements is also significant.

Buildings contribute not only to the depletion of energy sources, but also to other environmental problems, such as climate change or acidification. A complex environmental evaluation and optimisation should cover the whole life cycle of buildings and look at a range of different environmental impact categories. Environmental Life Cycle Assessment (LCA) is a method fulfilling these requirements. LCA quantifies the environmental impacts related to a product through all stages of its life, “from cradle to grave”. Life cycle approaches avoid problem-shifting from one life cycle stage to another, from one geographic area to another, and from one environmental medium to another.

This paper describes a methodology developed for analysing the life cycle environmental impacts caused by residential buildings. The results are derived not only from a few case studies, but from the analysis of a large building sample. The goal was to compare different building systems and the contribution of life cycle phases to the total impacts. The effect of increased thermal performance is shown and, as an example for using LCA for building optimisation, the life cycle optimum thickness of wall insulation is sought.

2. Methodology

The life cycle environmental impacts were calculated for six building categories, four building systems and ten environmental indicators using a randomly generated building sample of 1,000 buildings per category. The results were analysed with the help of mathematical statistics and the expected value, standard deviation and confidence intervals were calculated in each case.

The functional unit was a residential building over a 50-year period in Hungary.

The results were presented for 1 year and 1 m^2 net heated floor area, on three levels:

- the building envelope, i.e. building materials and building-related building services (heating energy demand covering transmission losses minus solar gains);

- the building envelope and the other elements (internal slabs, walls, cellar etc.), i.e. all building-related components;
- the building and the user-related building services (heating energy covering ventilation losses minus internal gains, domestic hot water production and lighting).

2.1 The database

As data quality is crucial in LCA, the available databases were evaluated. We decided to use the Swiss ecoinvent database, which contains high-quality inventory data of more than 2,500 products and services [2]. The ecoinvent data is used by more than 40 countries and is included in the leading LCA software tools. Since the data source is primarily the Swiss and German industry, certain modifications were necessary for building materials produced primarily in Hungary. The composition of the Swiss and the Hungarian electricity mix and the source of the natural gas differs significantly, hence these modules were changed. For products missing from the database new datasets were developed based on the material composition.

2.2 The building sample

An algorithm was worked out for the random generation of a large building sample. The building sample is not based on statistical data, but covers the population of the “technically feasible” buildings. For this, the parameters describing the building geometry and the realistic ranges of these parameters were determined based on functional and architectural considerations. The parameters were floor area, the number of storeys, the perimeter to floor area ratio, the fraction of the building envelope adjacent to neighbouring heated buildings, the window ratio and frame factor and the density of partition walls in the layout. Six building categories were analysed: one and two-storey single-family houses, one and two-storey low-rise high density housing, low and medium-high multi-family houses.

Based on the geometric parameters the area of the building elements and the surface to volume ratio ($\Sigma A/V$) describing the dimensions and compactness of buildings were calculated. We developed an Excel-based tool for the analysis.

In the base scenario, the buildings were built with an unheated cellar and unheated attic, the window ratio was 10-30 % of the façade area, 10 % of the windows faced North, 30-30-30 % South, East and West, respectively, and the windows were partly sunlit. The effect of parameters was evaluated with sensitivity analysis.

2.3 Building systems and building services

For the analysis, we have chosen four building systems typical for new buildings in Hungary and complying with the current energy regulation.

Insulating brick system: with specially designed porous hollow clay bricks that reduce heat flow. These walls can just fulfil the new national energy performance requirements without additional insulation (U=0,41 W/m^{2}K for 38 cm blocks). The brick density is between 600-800 kg/m^3, depending on the number and arrangement of the voids. The system includes partition walls, lintels, beams, girders etc. made of burnt clay.

Brickwork with external insulation: clay bricks with a density of 1200-1400 kg/m^3 are suitable from an energy point of view as external wall only if an insulation layer is added.

Autoclaved aerated concrete system: AAC is a lightweight material of low heat conductivity. The current Hungarian thermal requirements for external walls can be fulfilled with single-layer AAC walls of 30 cm. The aerated concrete system includes load-bearing and partition walls, lintels and reinforced wall or roof boards.

Timber stud system: wall panels consist of solid timber studs with a usual spacing of 60-80 cm connected with top and bottom plates. The spaces are filled with mineral wool insulation. The thermal bridge effect of the wooden studs can be decreased by applying an additional insulation layer with battens perpendicular to the studs. Due to the composition of the elements, larger insulation thickness is typical than in masonry systems (e.g. for walls U=0,22 W/m^{2}K).

The same building service systems typical for new buildings in Hungary were chosen in the study for all building systems. For heating and domestic hot water production a low temperature modulating gas boiler was considered, with radiators and indirectly heated hot water storage tank. This is also the reference system defined in the Hungarian regulation [3]. Mechanical ventilation is not common in residential buildings in Hungary. No mechanical cooling was taken into account.

2.4 Life cycle phases

The life cycle of buildings was divided into four phases:

Production includes acquiring raw materials, manufacturing and transporting building products to the site and erecting the building. Based on the geometric data, the weight of materials was calculated and then connected with the ecoinvent modules.

Maintenance means small repairs and changing the building elements at the end of their useful life, this includes the production of the new elements. The useful life of the elements was estimated based on literature sources. Three maintenance scenarios were applied: high, average and low maintenance requirement.

Operation is the energy demand for heating, domestic hot water and lighting. The annual heating energy demand was calculated based on the energy balance of the heating season. For the user-related components, a “standard user” was considered, as defined in the regulation [3]. The gross energy demand including the efficiency and losses of the systems was also calculated based on the decree. For the primary energy conversion factors we applied ecoinvent data.

Disposal includes the disposal of the old building materials in the maintenance phase and demolition of the building at the end of the effective life, separation, transport and processing of materials for reuse/ recycling/ incineration/ landfill and recultivation of the deposit site. A most probable end-of-life scenario was assumed for the elements.

All processes were taken into account together with their upstream processes, and where appropriate the provision of infrastructure (machinery, plant, roads) as well. For electricity consumption, for example, we considered not only the end-use but also the exploitation of fuels, their transport to the generation plant, the emissions at the generation plant, etc.

3. Results

The life cycle non-renewable cumulative energy demand (CED, n.r.) of different building systems is presented here for two-storey single family houses. Only the level of the building envelope is compared. (For further results see [4]). Next the influence of increased insulation thickness is analysed and the optimum of the insulation thickness is sought for the whole life cycle.

3.1 Comparison of building systems and contribution of life cycle phases

The expected value of the non-renewable cumulative energy demand of the building envelope is between 430 and 508 MJ/m^{2}a for the whole life cycle (*Figure 1*). The reference system for the comparison is the insulating brick system.

The differences in the CED values of the masonry systems are not significant. The CED of the AAC system is 93-96 %, that of the brick+insulation system is 93-99 % compared to the insulating brick, the reference system. The timber system has the lowest values, the CED is 85-89 % of the reference system. This is mostly due to the better thermal characteristics of the timber system.

The contribution of the four life cycle phases in the non-renewable cumulative energy demand is shown in the following *Figures*. Production is responsible for 14-20 %, maintenance for 6-13 %, heating for 68-77 % and the disposal phase for 1-2 % of the impacts related to the building envelope over the whole life cycle of 50 years.

The ratio of the life cycle phases is similar for the insulating brick and AAC systems. The production phase amounts to a slightly higher proportion in the case of the brick+insulation systems due to the higher material use, and also the maintenance phase due to the higher maintenance need of the external insulation system. In absolute values, compared to the reference system this means about 15 % higher CED in the production phase, and 10 % higher in the maintenance phase.

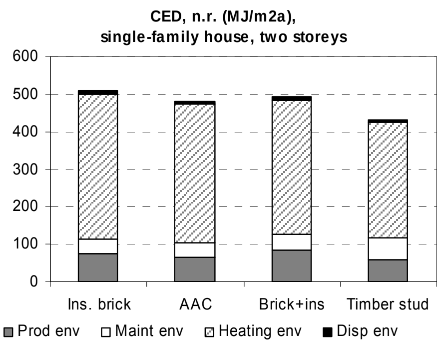

Figure 1: Contribution of life cycle phases in absolute values for different building sytems, CED, n.r. (MJ/m^{2}a), building envelope, two-storey single-family houses

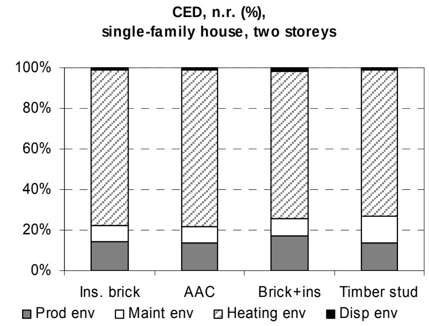

Figure 2: Contribution of life cycle phases in percentages for different building sytems, CED, n.r. (MJ/m^{2}a), building envelope, two-storey single-family houses

In case of the timber system, production corresponds to slightly lower proportional values than in the reference system, and about 20 % lower values in absolute terms. The maintenance need is significantly higher: in absolute values it is almost 50 % higher. The CED of the heating phase depends mostly on the thermal characteristics of the envelope. The average thermal transmittance of the timber buildings is much lower, hence the CED values are also lower: in absolute terms about 20 % lower than in the insulating brick system. Compared to the reference system, the heating demand is slightly lower in the AAC system due to the better U-values of the cellar and attic floors and also lower in the brick system due to the better insulation of the wall.

3.2 Increased thermal performance

Transmission losses and the corresponding energy demand can be reduced by improving the building envelope. The effect of increased insulation of the wall was tested on the brick+insulation system, since here an external insulation system was applied in the base system too.

If we increase the original insulation thickness of 8 cm to 14 cm, the CED of the envelope decreases by 12 %. This way the CED of the envelope becomes similar to the CED of the timber system (*Figure 3*). Compared to the timber system, the heating demand of the brick+insulation system with 14 cm wall insulation is lower due to the better utilisation of the solar gains, but the CED of the production phase is higher.

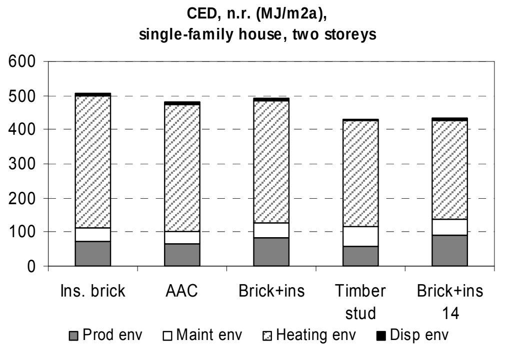

Figure 3: CED, n.r. (MJ/m^{2}a) of the building systems, two-storey single-family house

3.3 Optimum insulation thickness

As a next step, we analysed whether the insulation thickness has limitations from the point of view of energy rationalisation and whether there is an optimum point. By applying more insulation, the embodied energy of the building increases (production and maintenance), but the transmission losses and the heating demand decrease.

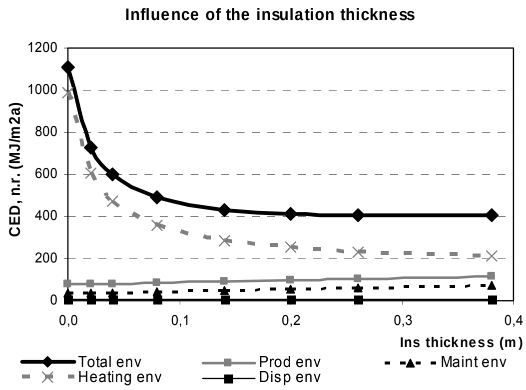

Figure 4: Influence of the insulation thickness on the CED, n.r. of the building envelope, two-storey single-family house, brick+insulation system

Figure 4 shows the CED of the building envelope as a function of the insulation thickness (thermal bridge effect was assumed to be 30 % of the transmission losses of the wall). If only heating is considered, the values decrease exponentially and the marginal benefits are decreasing. The production and maintenance values increase linearly. If we look at the total non-renewable cumulative energy demand, the tangent of the function approaches the horizontal around 20 cm. No more benefits can be realised by further increasing the insulation, we reach an optimum point.

3.4 Other impact categories

The previous sections showed the results for non-renewable cumulative energy demand. Life cycle assessment, however, normally applies several environmental categories for impact assessment. The results were analysed with three other methods: the CML-method (global warming potential, acidification, ozone depletion potential, photochemical oxidation, eutrophication), the eco-indicator 99 method and the cumulative exergy demand. These methods are internationally accepted and widely used, except for the exergy method which is relatively new in LCA.

Next, the relationship between the energy demand and other environmental indicators was analysed. For typical building systems and heating fuels, the non-renewable cumulative energy demand proved to be highly correlated with the global warming potential, the total eco-points in eco-indicator 99 and with the non-renewable cumulative exergy demand. The other impact categories showed some discrepancy. We applied normalisation to help the interpretation, i.e. calculated the magnitude of category results relative to a reference value (in this case the annual interventions in Western Europe). This proved that the relative significance of the other environmental indicators, such as acidification, ozone depletion, photochemical oxidation, eutrohication is far less than that of global warming. As a conclusion, non-renewable cumulative energy demand is a suitable screening indicator in the environmental assessment of buildings (with the given boundary conditions.)

4. Conclusions

The environmental impacts of buildings should be analysed for the whole life cycle. The methodology described in this paper is based on life cycle assessment and on the analysis of a large building sample. The examples shown demonstrate the usability of the methodology for building optimisation. Here, the impacts caused by typical new residential buildings in Hungary were determined and the ecological optimisation of wall insulation was shown. The methodology can be used in other climates, for other building systems and the evaluation of other energy efficiency measures.

5. Acknowledgements

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6. References

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