Life cycle environmental impacts of residential buildings

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1 INTRODUCTION

"The architect must be a prophet . . . a prophet in the true sense of the term . . . if he can't see at least ten years ahead don't call him an architect"

Frank Lloyd Wright

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* [EPBD, 2002].

The growing concern of professionals and the general public about the role of the building sector in energy use have led to national and international legislative measures. The latest significant effort, the European Directive 2002/91/EC on the energy performance of buildings (EPBD) and the related national regulations, aim at increasing the energy efficiency of buildings and indirectly the reduction of carbon dioxide emissions [EPBD 2002]. The Directive gives a general framework for the calculation of the integrated energy performance of buildings and lays down requirements on their energy certification. The integrated energy performance includes, among others, the energy use for heating, cooling, ventilation, hot water supply and lighting, all expressed in primary energy. The EPBD encompasses only the use phase of buildings, while the other phases of the life cycle, the production, transport of building materials and the construction, maintenance and end-of-life of buildings are completely neglected.

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.

The oil crisis in the 1970s made people realise that fossil fuels are not infinite resources and energy saving became a prominent issue. A search for alternative technologies using renewable energy sources started. The first standards and requirements on the thermal performance of buildings also came into force at that time. Today, climate change is the main focus of environmental initiatives and scientific debates, and it receives huge media and political attention. Many countries of the world have ratified the Kyoto protocol and undertook to reduce their aggregate emissions of greenhouse gases. The Kyoto Protocol is based on the recognition that even though scientifically it is hard to prove to what extent anthropogenic emissions contribute to global warming, the risk for mankind is so high that urgent global measurements are necessary.

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. At the same time, it has to be underlined that buildings can be evaluated from many aspects. The environmental performance is an important and still not widely used indicator, but it does not overrule or substitute other properties, for example statical, acoustic, thermal, vapour and fire characteristics or costs. The aim of the environmental evaluation is not to judge whether a building is "good" or "bad", but to provide information from another aspect, which completes the overall picture when deciding about building materials and fuels or optimising a building.

2 PROBLEM DEFINITION

The main goal of this study was to evaluate the life cycle environmental impacts related to residential buildings, with a main focus on new buildings and on the influence of the architectural design. From the study of the literature, databases and software tools for buildings, I identified the problems that this study had to address:

- *Developing a suitable life cycle inventory database*. As data quality is of vital importance for LCA, the choice of the database is crucial. Regional differences have to be reflected in the data, but as there is no database for Eastern Europe and Hungary, the suitability of a European database has to be analysed, data have to be adapted and country-specific data have to be defined, if necessary.
- *Considering the effect of building geometry*. In available life cycle assessment studies, the analysis is usually done for one or a few specific buildings or "type houses". The wider implication of these results is, however, questionable.
- *Determining the role of the building and the users*. The literature review showed that most of the studies had focused on the total operational energy demand and the total built-in energy of the building and attempted to optimise the building based on this information. Certain impacts are related to the building itself, but the user and the building service systems also have a significant influence. The final aim is obviously to minimise the total environmental impact of buildings as a whole. This can be realised through the tight collaboration of the architect and the building service engineer and with a conscious user behaviour. However, if we analyse the responsibility of the architect and the aim is the optimisation of the building itself, the predominantly building-related and the predominantly user-related components have to be separated.
- *Analysing the impacts related to the building envelope and to the other elements*. Certain building elements – such as the building envelope – directly influence the operational energy demand, while other elements, for example internal walls, floors or the foundation only have an indirect or no influence. The energetic performance is decisive for the building envelope. For other elements, other aspects such as functional, structural, acoustic and fire considerations are dominant. If the aim is the energetic optimisation of the building, it is primarily the building envelope which must be considered. However, the evaluation of the hotspots in the whole building obviously requires a full inventory.
- *Determining the contribution of the life cycle phases* for different building categories and building systems.
- *Providing a screening indicator for buildings*. LCA professionals use different impact assessment methods, with several environmental indicators. The results are often contradictory and difficult to interpret.
- *Analysing the effect of different parameters with a sensitivity analysis*.
- *Providing further aspects for the evaluation of retrofit.*
- *Recommending a new approach for building regulations to include all life cycle phases when evaluating the energy performance*.

The methodological questions emerging in the study are general, the numerical results refer to Hungary, new residential buildings built with typical construction and building service systems.

3 METHOD OF ANALYSIS

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 in every case the expected value, standard deviation and confidence intervals were calculated.

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, and on three levels:

- the building envelope, i.e. building materials and building-related building services;
- the building envelope and the other elements, i.e. all building-related components;
- the building and the user-related building services.

The database

As data quality is crucial in LCA, I evaluated the available databases and decided to use the Swiss ecoinvent database, which contains high-quality inventory data of more than 2,500 products and services. The ecoinvent data is used by more than 40 countries and is included in the leading LCA software tools. The ecoinvent Centre has more than 20 years of experience in LCI data compilation. Since the data source is primarily the Swiss and German industry, for building materials produced primarily in Hungary certain modifications were necessary. 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. (This work started in the framework of the OTKA Research Project T/F 046265.)

The cumulative exergy values were calculated with the help of eXoinvent, the software tool developed by De Meester and Dewulf.

I verified the ecoinvent data for brick by compiling data for brick in three Hungarian brick factories in the framework of a research contract with the Hungarian Brick Association. To my knowledge, this was the first inventory in the field of building materials.

The geometry

I worked out an algorithm 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, I determined the parameters describing the building geometry and the realistic ranges of these parameters based on functional and architectural considerations. The parameters were the 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. I analysed six building categories: 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 I calculated the area of the building elements and the surface to volume ratio ($\Sigma A/V$) describing the dimensions and compactness of buildings. I 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.

Building systems and building services

In the study, construction and building service systems were chosen which are typical for new buildings in Hungary and comply with the current energy regulation (insulating brick system, brickwork with external insulation, autoclaved aerated concrete system and timber stud system). Timber was only analysed in single-family houses. In buildings higher than four storeys a reinforced concrete loadbearing system with infill walls was assumed.

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 [TNM 7/2006]. Mechanical ventilation is not common in residential buildings in Hungary. No mechanical cooling was taken into account.

Life cycle phases

I divided the life cycle of buildings into four phases:

- Production: acquiring raw materials, manufacturing and transporting building products to the site and erecting the building. Based on the geometric data, I calculated the weight of materials and then connected it with the ecoinvent modules.
- Maintenance: 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: 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, I considered the "standard user", as defined in the [TNM 7/2006]. 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: 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. I assumed a most probable end-of-life scenario for the elements.

All processes were taken into account together with their upstream processes, where appropriate the provision of infrastructure (machinery, plant, roads) also. 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.

Impact assessment categories

For the impact assessment, we used four methods: the cumulative energy demand, the CML-method, 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. Indicators with a high degree of uncertainty were not considered. The indicators used in the study are summarised in *Table 1*.

Table 1: Impact assessment categories in this study

Cumulative energy demand:	**Eco-indicator 99:**
non-renewable cumulative energy demand	ecosystem quality
	human health
CML-method:	resource use
global warming potential, 100 a	
acidification, average European	**Cumulative exergy demand:**
ozone depletion potential, steady state	non-renewable cumulative exergy demand
photochemical oxidation, high NOx	
eutrophication, generic	

4 PRINCIPAL RESULTS

0.

The environmental impact of buildings must be analysed for the whole life cycle, including the life cycle phases production, maintenance, operation and disposal.

1.

Many international research projects have been focusing on the resource use and emissions related to the production of building materials and the construction of buildings.

I critically analysed and compared the methodologies for the environmental evaluation of buildings and data available in the literature and databases on the production of building materials. I adapted the most suitable European database to Hungarian conditions based on the electricity mix, natural gas module and transport distances and developed some new datasets. Considering that brick is the most common building material in walls in Hungary, I compiled data for brick in three Hungarian factories. I concluded that there are no significant differences between the Hungarian and the adapted European data, hence the developed database is suitable for use in Hungary.

2.

2a.

Based on architectural and functional considerations, I determined the realistic ranges of the parameters describing the geometry of the "technically feasible" buildings and their relationships. These parameters are the 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.

2b.

I developed an algorithm for the random generation of a large building sample based on the realistic ranges of the geometric parameters. I calculated the environmental impacts of buildings for six building categories, four building systems and ten environmental impact categories, based on 1,000 geometries per category. I analysed the results with the help of mathematical statistics, and calculated the expected value, standard deviation and confidence interval of the sample.

2c.

I proved with a chi-square test that the results follow a normal distribution and with the given parameter and sample size the central limit theorem is fulfilled.

3.

The operational energy demand of buildings includes many components which are not directly related to the building. The hot water demand, for example, is influenced by the number of users; the lighting mostly by the function of the room. From the components of the heating demand, the ventilation losses can be considered as building-related only if the air tightness of the building is poor, the joints are not appropriate or if a higher air change rate is necessary due to the release of harmful compounds from the internal surfaces. In airtight new buildings, ventilation losses are typically not building-related components as the necessary air change rate is determined by the number and activity of users.

3a.

I argued against the approaches which take into account non-building related components when optimising the environmental impacts of the architectural design. In order to focus on the building itself, I divided the operational impacts into predominantly building-related components, such as the heating demand covering the algebraic sum of the transmission losses of the envelope and the utilised fraction of the solar gains, and predominantly user-related components, such as the heating demand covering the algebraic sum of the ventilation losses and the internal gains; the domestic hot water demand and the lighting.

3b.

In one-storey buildings the building accounts for about 64 % and the user-related building systems for 36 % of the total non-renewable cumulative energy demand. In multi-family houses these ratios are appr. 50-50%. While the building-related specific heating energy demand decreases as the building size grows, the user-related components remain almost constant for the different building categories, hence their significance increases. This underlines the statement, that from the point of view of the optimisation of the building envelope, the results would be misleading, unless the user-related service systems are separated.

4.

4a.

I determined that production is responsible for 14-20 %, maintenance for 6-13 %, heating for 68-77 % and disposal for 1-2 % of the non-renewable cumulative energy demand related to the building envelope over a life cycle of 50 years.

4b.

The specific heating demand depends strongly on the surface-volume ratio, which is decreasing with increasing building dimensions. The ratio of walls adjacent to neighbouring heated buildings (adiabatic walls) also has a significant influence on the heating demand.

I proved that the specific non-renewable cumulative energy demand of the production and maintenance related to the building envelope is dependent on the surface to volume ratio, but the dependence is not as strong as in the case of heating. Compared to two-storey single-family houses, the specific total non-renewable cumulative energy demand related to the building envelope is 40 % lower for low multi-family houses and almost 50 % lower for medium-high multi-family houses. Due to the adiabatic walls, it is 17-22 % lower for terraced houses.

4c.

From the total building related impacts, building envelope is responsible for 80 % and the other building elements (internal walls, floors etc.) for 20 % of the specific non-renewable cumulative energy demand in single-family houses, and 70 % and 30 % in multi-family houses. As these other elements do not influence the operational energy demand, they should not be taken into account in the energetic optimisation of the building. However, these elements can be taken into account in a labelling system.

5.

The standardised methodology of life cycle assessment recommends the use of impact assessment categories instead of the evaluation of separate emissions. However, there are many impact categories and the results are usually difficult to interpret.

I analysed the relationship between the energy demand and other environmental indicators based on the analysis of the technically feasible buildings. I proved that energy demand is a suitable screening indicator in the environmental assessment of buildings. For typical building systems and heating fuels, energy is highly correlated with the global warming potential, the resource use in eco-indicator 99 and with the non-renewable cumulative exergy demand. When normalising, i.e. comparing the magnitude of the other indicator results to a reference value (the annual interventions in Western Europe), I demonstrated 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.

6.

The sensitivity of the results to different parameters was evaluated using my own calculation method and the same building sample as before.

6a.

In the base scenario, the building life was assumed to be 50 years, but the actual life of a building might be much longer. A longer life might change the results significantly. During the time period no major energy efficiency upgrade was assumed.

I showed that assuming a longer building life of 75 years decreases the yearly fraction of the non-renewable cumulative energy demand of the building envelope by 6-8 % in every building category and building system. Heating is responsible for 78-83 % of the impacts. If an even longer building life of 100 years is assumed, the yearly values do not decrease significantly any more. This is due to the increased maintenance requirements, since the impacts caused by the maintenance exceed the impacts caused by the construction in the long-run.

6b.

Increasing the thermal performance of the building envelope is a very efficient measure for the reduction of the transmission losses and the heating demand. However, by applying more insulation, the energy demand for production and maintenance increases.

I analysed whether the insulation of the building envelope has limitations from the point of view of energy rationalisation. I proved that the marginal benefits in the total non-renewable cumulative energy demand for the whole life cycle were insignificant after reaching an insulation thickness of 20 cm for a brick wall with expanded polystyrene insulation.

6c.

I proved that solar gains through transparent building elements can significantly reduce the heating energy demand. In average two-storey single-family houses, where the architectural freedom is usually not limited regarding the orientation and the arrangement of windows, solar gains correspond to a difference of ± 8 % (total shading or unlimited solar access) in the impacts related to the building envelope for the whole life cycle. With a favourable building orientation and good solar access, the reduction can reach 14 %.

These statements apply to winter conditions, but we must pay attention to the architectural details to avoid summer overheating.

6d.

I showed that in the operation phase, a considerable reduction of the environmental impacts can be achieved if renewable energy sources are applied. In average two-storey single-family houses in Hungary, the potential saving with solar supported domestic hot water production is 13 % compared to the non-renewable cumulative energy demand for the whole life cycle and including both building and user-related components. Due to technological constraints the use of renewable energy in the production and maintenance phases is very limited.

7.

In case of major renovation, the optimal solution from an environmental point of view is the function of many factors.

I showed that, when evaluating the environmental impacts of building retrofit, it is insufficient to compare the embodied energy investment and the reduction of operational energy only. These items have to be complemented with the possible life prolongation effect of the renovation, the conservation of the original built-in energy, the reduction in the maintenance needs, and the postponement of the demolition and the new construction.

8.

The European Directive on the Energy Performance of Buildings and the national regulations, based on the Directive, assess the total operational energy demand of the building, but does not consider the other phases of the life cycle.

I worked out a method for complementing the regulation with the predominantly material-related life cycle phases of production, maintenance and disposal.

5 UTILISATION OF THE RESULTS AND FURTHER RESEARCH QUESTIONS

The database and the guidelines on how to calculate the life cycle phases developed in this study can be used in the evaluation and optimisation of specific buildings, together with the recommendations on the use of environmental indicators.

The method for generating a large building sample can be used to develop benchmark values and reference buildings in the environmental labelling of buildings or it can be the basis of future regulations.

In the future, the technique developed in this study can be applied to study the effect of different heating fuels, e.g. wood and of increased energy efficiency. This study analysed average buildings fulfilling the current energy standards, but it is also interesting to evaluate different measures, e.g. building-integrated solar systems or balanced ventilation with heat recovery applied in low-energy and passive houses. It is also possible to evaluate future scenarios and the effect of certain measures on a national scale.

The considerations for retrofit developed in this study can be the core of a decision-support tool.

In the study, I applied a static approach for taking into account future interventions. I assumed that the impacts of the material production, energy generation etc. remain the same in the long term and I weighted present and future interventions equally. A more sophisticated method, the calculation of net present value or discounting, commonly used in economics, could be used to bring present and future flows to a common denominator. Discounting is normally applied to money flows, but the approach could be applied to energy use and emissions as well. The question is whether to weight interventions today or tomorrow more heavily. Both approaches can be justified. Some environmental scientists say that a delay in emissions alone might contribute to the mitigation of environmental problems, such as climate change. Also, the marginal cost of extracting energy increases over time and future technologies are expected to correspond to lower emission levels. Hence today's interventions should be given a larger weight. On the other hand, the scarcity of fossil fuels and the prospect of their complete depletion in the near future suggest that future energy is more valuable. Using discounting techniques would provide further aspects in the evaluation of building measures.

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7 REFERENCES IN THE SUMMARY

DE MEESTER, BRAM; DEWULF, J.; VAN LANGENHOVE, H. (2006): eXoinvent. The exergy of ecoinvent reference flows, version 1.0, software tool. University of Gent.

ECOINVENT (2005): ecoinvent data v1.3 and reports. Swiss Centre for Life Cycle Inventories, Dübendorf.

EPBD (2002): Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Official Journal of the European Communities.

TNM 7/2006. (V.24.): Hungarian Government Decree on the energy performance of buildings.

8 LIST OF PUBLICATIONS IN THE TOPIC OF THE DISSERTATION

1. Zöld, A.; Szalay, Zs.: *What is missing from the concept of the new European Building Directive?* Building and Environment (IF 2005 = 0,676), 42 (2007), pp. 1761-1769.

2. Szalay, Zs.: *Timber Structures as Potential Carbon Storage.* Bulletin, BUTE, Faculty of Architecture, 2004, ISSN 1785-9565, pp. 177-184.

3. Szalay, Zs.: *Embodied Energy of Timber Buildings*. Proceedings, 4th International Seminar on Environmentally Compatible Structures and Structural Materials (ECS), IASS, Prága, June 2003, ISSN 80-01-02955-7, pp. 46-50.

4. Szalay, Zs.; Zöld, A.: *Kohlenstoffspeicherung von Holzbauten*. Wissenschaftliche Mitteilungen der 16. Frühlingsakademie, München- Wildbad Kreuth, 19-23. May 2004, ISBN 963 86697 0 5, pp. 104-107.

5. Szalay, Zs.: *The Role of Timber Buildings in Carbon Storage*. Proceedings, CD-ROM, XXXII IAHS World Congress, Trento, 21-25. September 2004.

6. Szalay, Zs.: *Ecological building retrofit*. Proceedings, CIB W70 Trondheim International Symposium, 12-14 June 2006, ISBN 82-7551-031-7, pp. 168-177.

7. Szalay, Zs.; Nebel, B.: *Life Cycle Assessment in Architectural Design*. Proceedings, CD-ROM, XXXIV IAHS World Congress, Naples, 20-23 September 2006, ISBN 88-6026-030-2.

8. Zöld, A.; Szalay, Zs.; Csoknyai,T.: *Energy performance and major renovation*. Proceedings, EPIC 2006, The 4th European Conference on Energy Performance & Indoor Climate in Buildings, Lyon, Franciaország, 20-22. November 2006, pp. 267-272.

9. Nebel, B.; Szalay, Zs.: *The Exemplar House – a generic LCA model for houses in New Zealand*. Proceedings, SETAC 13th Case Study Symposium, poster, 7-8. December 2006, pp. 165-166.

10. Szalay, Zs.: *Life Cycle Assessment of Timber Buildings* (in Hungarian). Proceedings, Tavaszi Szél National PhD-conference, Sopron, May 2003, ISBN 963-210-376-9, pp. 177-180.

11. Szalay, Zs. *Ökobilanz für das "micro-compact home"- Vorstudie*. Holzforschung München, September 2005.

12. Szalay, Zs.; Nebel, B.: *Analysis of Currently Available Environmental Profiles of Building Products*. Report TE200, prepared for Beacon Pathway Limited, New Zealand, April 2006.

13. Szalay, Zs.; Nebel, B.: *Life Cycle Assessment of a New Zealand house*. Scion report, New Zealand, June 2006.

14. Tiderenczl, G.; Medgyasszay, P.; Szalay, Zs.; Zorkóczy, Z.: *Building ecological and building biological evaluation system for building constructions based on national data* (in Hungarian). OTKA Research Project T/F 046265, Budapest, 2006.

15. Szalay, Zs.; Medgyasszay, P.; Zorkóczy, Z.: *Life Cycle Assessment of Brick – Production phase* (in Hungarian). Research report, Hungarian Brick Association, Budapest, 2007.