Towards ecological life-cycle design: measuring the environmental impact of housing transformations

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Summary
Life Cycle Assessment or LCA is a suitable method to support environmentally-sound decision-making in renewal processes in the housing stock. Nevertheless, renovation is not a standard part of LCA of buildings. There are some methodological issues to be solved. The aim of this paper is to present a framework for comparison of housing transformation options, such as new construction and renovation, and renovation options. The framework consists of solutions for the issues of life cycle, building stage and environmental data. Further research will test the framework in a couple of case studies on housing transformation and renovation of neighbourhoods.

Keywords: comparison, environmental assessment, environmental impact, environmental performance, housing stock, housing transformation, LCA, lifecycle, lifetime, renovation

1. Introduction
Renewal of the housing stock is a major building task for the coming years. With the aid of Life Cycle Assessment or LCA ecological considerations can be taken into account. Several tools have been developed for LCA of new buildings. There is a lack of LCA-based methods and tools, which support environmentally sound decision-making in the renewal process of housing quarters, such as considerations upon demolition or renovation of buildings. A major difficulty involves the basis of comparison of several transformation options. LCA implies that transformation options, among others renovation, joining houses together and new construction, will be compared on the basis of the same lifetime. Subsequently, once the choice has been made for a transformation option, for example renovation, again the issue rises how to compare different alternatives. The aim of this paper is to present a framework for this. The question is how to compare housing transformation options and renovation options regarding environmental impacts? The study is part of a PhD research on optimising the environmental performance of housing.

The second section contains some background information on the importance of the housing stock and on the lifecycle of buildings, including LCA. The third section deals with an overview of current approaches to environmental assessment of existing buildings. A framework for comparison is presented in the fourth section. Finally, conclusions are drawn in the fifth section.

2. Background
The majority of the housing stock in the European Union was built after the second world war. Quantitative shortages resulted in enormous mass housing production. Nowadays the volume of the housing stock is sufficient. Conversely qualitative shortages are growing. Especially the mass housing built after the war does not fulfil current needs and faces the threat of large-scale demolition. Thomsen and Van der Flier [1] argue that updating the housing stock asks for renovation-based approaches, because of the declining annual housing production (see Fig. 1). The annual housing production barely exceeds 1% of the total housing stock. Even if this housing
production is totally meant to replace demolished houses it takes more than a century to completely replace the housing stock. Finally they state that environmental sustainability and reduction of energy consumption according to the Kyoto treaty plea for renovation-based strategies instead of demolition. This does not have to be that obvious, because the environmental performance of housing also concerns buildings in operation. If there is a gap between the quality levels of renovated houses and newly constructed houses at least part of the environmental benefits as a result of preservation of the housing stock will be undone.

**Fig. 1 Annual housing production in the European Union as percentage of the total housing stock**

To assess environmental impacts Life Cycle Assessment or LCA is a widely accepted method. LCA is a method for the analysis of the environmental burden of products (goods and services) from cradle to grave, including extraction of raw materials, production of materials, product parts and products and discard, either by recycling, reuse or final disposal [2]. It is defined as the “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” [3]. The product system is the total system of processes needed for the product, which in this case is a house. Inputs and outputs are materials and energy, which enter and leave respectively the product system.

According to Vogtländer [4] renovation is part of the lifecycle of buildings. Complex products like buildings consist of many flows of material, which follow different paths in the life cycle after the construction phase. Ten paths up to and including the end-of-life of a building are distinguished (see Fig. 2): 1. extending of the product life; 2. object renovation; 3. re-use of components; 4. re-use of materials; 5. useful application of waste materials; 6. immobilisation with useful appliances; 7. immobilisation without useful appliances; 8. incineration with energy recovery; 9. incineration without energy recovery; 10. land fill. However, current whole building environmental assessment tools do not take into account changes in building characteristics over time. For environmental assessment of housing in many countries whole-building environmental assessment tools have been developed or are being developed, including Eco-Quantum in the Netherlands, Envest in the United Kingdom, EcoPro in Germany and ESCALE in France. These tools have been designed for use in the determination, analysis and improvement of the environmental performance of buildings [5]. They are dealing with the environmental impact of a building during its service life as it was originally constructed, but they do not address the environmental impact of building transformations like renovations [6]. Scenarios for all other nine end-of-life treatment of the flows of material exist, except for renovations, while renovations may completely disturb the foreseen lifecycle.
3. Overview of current approaches

The attention paid to methodological issues regarding environmental assessment of renovations is growing. Hansen and Petersen [7] have studied how to use LCA as a decision-support tool for refurbishment and retrofitting. They put forward that for the use of LCA tools in renovation projects system boundaries need to be clarified and supplementary facilities are needed that represent renovation measures in LCA tools. According to them the environmental impact related to the lifecycle of buildings are caused temporarily by interventions (e.g. construction, renovation and demolition) and continuously by operation and maintenance before and after these interventions. Therefore the environmental impact of existing buildings is composed of operation and management before and after renovation, production and waste management related to renovation works and service lives for the whole building as well as the building components. They argue that for comparative assessments existing building components which will not be affected by any of the alternatives and existing building components which will be removed do not have to be considered in LCA. However including existing building components to be removed may be useful if the expected service life has not yet been realised. Allocation of part of the environmental impact to the building component to be removed may be justified in that case. Then the building component has to be represented in LCA tools as the Danish BEAT. Besides they establish that comparative assessments of alternatives with different service lives should be based on the same period of time. Finally, LCA tools have to be provided with environmental data on the most common renovation measures.

Peuportier [8] and Milonas [9] simply compare several renovation alternatives to the existing situation. Peuportier compared several insulation options to the environmental performance of the building before renovation. Milonas assessed a low embodied energy scenario and a scenario contributing to low operational energy in comparison with the existing situation.

Zimmerman et al. [10] propose a framework for environmental assessment of existing buildings from another point of view. To their opinion four main issues should be addressed:
- a newly constructed building, as-built, may differ significantly from the design;
- the use, equipment and management of even a new building may differ significantly from that assumed by the designers;
- in operation an assessment system may be used to benchmark an existing building against other similar buildings in order to improve operations;
- in operation an assessment system may be used to gauge the potential for improvements when renovations or major repairs are undertaken.
Therefore they make a distinction between the potential and the actual environmental performance of a building. The potential environmental performance is the best performance that can be theoretically obtained. This potential performance is likely to vary owing to the built quality achieved and the changes in design, construction, equipment and use that will have occurred. As a result the actual environmental impacts often are higher than the potential. Subsequently they distinguish building performance and building management to determine the actual environmental performance. The building performance is a result of the technical and design characteristics of the building, which depends on the building standards and the efficiency of its fabric and installations. The building management refers to the use of the building and the effectiveness of the management practices in operating and controlling it. Already in the design stage the environmental performance based on inherent properties of the building and the environmental performance resulting from operation of the building should be assessed separately.

Regarding housing transformations Van den Dobbelsteen [11] argues that when buildings will be demolished before a certain reference age has been reached the environmental costs of the remaining expected service life have to be allocated to the new building. Although he speaks about environmental costs instead of environmental impacts he addressed a comparable approach as Hansen and Petersen towards allocation of the environmental impacts of a building to be demolished.

4. Comparison of housing transformations and renovations

The above overview shows that methodological issues to be solved to be able to compare different options for housing transformations or renovations concern the lifecycle, the building stage and the environmental data. Below a framework for comparison is proposed.

4.1 Lifecycle

Lifetime is the most important issue when comparing housing transformation options. This is due to the fact that interventions like renovations are often needed before the expected service life or reference service life has expired, while renovations are not included in current LCA. This is the case with renewal of the post-war housing stock in particular. Therefore starting the lifecycle at the time of transformation is disputable. Besides the service life of housing transformation options varies. This would be overcome by looking at the same period of time. However, the choice of the period of time is completely arbitrary. Instead the lifecycle of a house, including transformation, can be defined as the period from construction of the house to the end-of-life of the transformation of the house. Then the average environmental impacts per year are comparable. This is shown in Fig. 3. If an expected service life of a house of 75 years \(L_{\text{ref}}\) is assumed and after 60 years \(L_{\text{trans}}\) a housing transformation is planned, then the lifecycle of renovation \(L_{\text{total, renovation}}\) amounts 85 years and the lifecycle of new construction \(L_{\text{total, new construction}}\) amounts 135 years. These can be compared by accounting the average environmental impacts per year during the lifecycle.

Fig. 3 The lifecycle of housing transformation options
4.2 Building stage

The environmental impacts during the lifecycle of a transformation is caused by periodical interventions (i.e., construction and renovation) and continuous operation (e.g., energy consumption). Separation of construction-related environmental impacts and operation-related impacts may be useful, because housing transformations influence both. Fig. 4 shows that the environmental impact of the house before renovation ($I_{\text{total,ref}}$) consists of the environmental impact of construction and operation. The environmental impact of renovation ($I_{\text{total, renovation}}$) refers to a shorter operation period, after which the annual environmental impact in operation is lower than before. Although the environmental impact of construction of a new house is higher than renovation, the environmental impact in operation may be even lower, so the environmental impact of new construction ($I_{\text{total}}$) does not have to be higher than renovation through the whole lifecycle.

Fig. 4 The environmental impacts of housing transformation options

In contrast to comparison of housing transformation options comparison of renovation alternatives does not have to include all housing components. Then, components which will not be altered by any of the alternatives and components which have to be removed can be left out of consideration, with the exception of components to be removed before the expected service life has expired.

4.3 Environmental data

Current LCA tools generally do not hold data on renovation measures. Otherwise comparison of renovation alternatives with the situation before renovation is relatively easy, on condition that construction and operation can be separately investigated. For comparison of housing transformation options, as a matter of fact environmental data of all components in the house before renovation are needed. However this enormous effort seems quite useless or even impossible, all the more since accounting with current data is representative for housing transformations of the younger housing stock, which might be next. Therefore the house before renovation can vary well be a house built according to current environmental standards. Nevertheless for housing dimensions, energy consumption, et cetera actual values should be taken into account.

5. Conclusions and discussion

The framework for comparison of housing transformation options and renovation options presents solutions for three methodological issues:

− Lifecycle: housing transformation options with different lifetimes are compared by looking at the average annual environmental impacts. The lifetime of a housing transformation option is defined as the sum of the lifetime of the house to be transformed and the expected lifetime of the transformation option.

− Building stage: construction-related environmental impacts and operation-related environmental impacts are separated. For comparison of renovation options components which will not be altered by any of the alternatives and components which have to be removed after the expected service life has expired are left out of consideration.