Abstract: - Reducing the ecological impact of buildings is receiving increasing attention by researchers, policymakers and industry. This paper gives an overview of the current situation of Life Cycle Assessment (LCA) in the construction industry, clarified by a discussion on case studies. After a short history of LCA, the focus is on LCA methodology and recent developments.

Despite some inherent limitations of LCA as analytic tool, some comprehensive conclusions can be drawn. In standard buildings, the use phase contributes up to 90 % of the total environmental burdens, mainly due to heating and/or cooling. When the energy efficiency of buildings increases, other aspects of the life cycle are gaining importance, like materials, construction, end-of-life measures and water use.

Key-Words: - Life Cycle Assessment, Construction industry, review, Sustainable development

1 Introduction

In our society buildings are omnipresent, but they inevitably entail negative consequences from an environmental point of view. During their lifespan, they consume plenty of resources and energy, occupy land and at the end they are demolished. As the interest in environmental issues is rapidly growing, also within the construction industry, more attention is being paid to sustainable housing technologies and construction methods. This general increasing awareness led to the Kyoto-protocol, an international agreement on reducing the emission of greenhouse gasses and global warming [1]. In the construction sector, this resulted for instance in regulations to decrease energy consumption of dwellings and consequently their ecological burdens, i.e. the Energy Performance of Buildings Directive 2002/91/EC (EPBD, 2003) and the revised EPBD 2010/31/EU issued by the European Union. These regulations make sense as for example in Flanders households have a share 36 – 40 % of the total energy consumption, and the residential sector in Belgium produces about 40 % of the emitted CO2 [2], [3].

These European regulations stimulated the emergence of new building concepts such as low-energy and even self-sufficient houses [4]. When only focusing on energy consumption, these low-energy houses excel compared to standard houses. But before any conclusions can be drawn about sustainability, the ecological impact of the whole life cycle has to be investigated, based on the methodology of a Life Cycle Assessment (LCA). LCA is a tool to investigate environmental burdens of a product or a process, considering the whole life...
cycle, from cradle to grave [5]. All aspects considering natural environment, human health and resources are taken into account and together with the life cycle perspective, LCA avoids problem-shifting between different life cycle stages, regions and environmental problems.

2 LCA Methodology

In current practice LCAs are executed within the framework of the ISO 14040 series [5]. To analyze the environmental burdens of processes and products during their entire life cycle, four steps have to be run through, facilitating the comparison of different studies: goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and an interpretation [6], [7].

Goal and scope define purpose, objectives, functional unit and system boundaries. One of the strengths of LCA is defining the investigated subjects based on their function instead on their physical characteristics. This way, products can be compared which are inherent different, but fulfill a similar function. The second step (LCI) consists of collecting all data of the whole life cycle regarding inputs, processes, emissions, etc. Third (LCIA), environmental impacts and used resources are quantified, based on the inventory analysis. This step contains three mandatory parts: selection of impact categories depending on the parameters of goal and scope, assignment of LCI results to the selected impact categories (classification) and calculation of category indicators (characterization).

In the current practice there is a large set of impact categories commonly used, for example global warming potential (GWP), but ISO 14044 states that when the existing categories are not sufficient, new ones can be defined. The LCIA step also contains two optional steps: normalization and weighting. Normalization is the calculation of the magnitude of category indicator results relative to some reference information, i.e. the average environmental impact of a European citizen in one year. Weighting is the process of converting indicator results of different impact categories into more general issues of concern or a single score, by using numerical factors based on value-choices, i.e. based on policy targets, monetarisation or panel weighting. The fourth and final step is the interpretation of the results. [5], [7]

Although ISO-standards describe the global framework of a LCA, the exact method to be used is not defined. Different methods applied to an identical case can generate different results, i.e. a narrow scope carbon footprint study versus studies with a set of more differentiated impact indicators [8], [9]. They may assign a different importance to properties or impacts, which can result in other suggestions of action to reduce the ecological burdens [10].

To quantify environmental impacts two approaches can be identified, namely the problem-oriented (midpoints) and damage-oriented (endpoints) ones [11]. In the first group impacts are classified on environmental themes such as global warming potential, acidification potential, ozone depletion potential, etc. This type of method generates a more complete picture of the ecological impacts, but requires good knowledge of LCA to interpret the results. In the second group midpoints are combined into more general issues of concern such as human health, natural environment and resources, which eventually can be calculated into a single score. The results of the latter are easier to understand, but tend to be less transparent [12], [13]. Another drawback of the endpoint approach is the use of more subjective factors in the conversion to general categories. This will entail greater uncertainties and affect the reliability of the results. The discussion on different existing methods is beyond the scope of this review.

3 Recent developments in the construction sector

In industrial processes, LCA is widely spread and it is used frequently to evaluate the environmental impact of products and processes. In the construction industry however, such a study is much more complex because of the long lifespan of buildings (50–100 years [14], [15]), a shorter lifespan of some parts, the use of many different materials and processes, the unique character of each building, the distance to factories, etc. [15]. Since the building process is less standardized than industrial processes, such a LCA is a challenging task.

One way to categorize the existing studies could be to classify them according to the scale of the subject, going from materials to building components and finally the analysis of whole buildings [11]. Studies on building components are easier to interpret compared to the ones on
materials, as structural and thermal requirements have been taken into account. They are often useful during the design process, because at this stage many decisions are made about structural concepts and used materials. Research on materials and components is strongly linked to the European policy, i.e. the Integrated Product Policy, with tools as EPDs and Ecodesign [11]. In this paper, the main focus lies on LCAs of whole buildings. Thus the contribution of the different stages within the life cycle becomes more clear and hotspots can be identified. The results reveal more about building concepts in general and less about the chosen materials. In this case, the entire building is the functional unit, with different properties in all the studies. Therefore results are not directly comparable, but common trends can be identified.

Table 1 contains an overview of published academic studies of LCAs of whole buildings and their main characteristics. A lot of these studies are simplified LCAs only discussing energy, especially the early studies. They are also known as a Life Cycle Energy Assessment (LCEA). As stated by Huberman and Pearlmutter, this method is a single score indicator. Therefore the same remarks can be made as for the endpoint methods: it is easier to draw conclusions, but the results are much more uncertain [16]. A variation on this method is Life Cycle Exergy Assessment, developed by De Meester and Dewulf, which also takes the quality of the energy into account [17], [18]. Exergy is the work potential of an amount of energy with respect to its environmental conditions [19]. High grade energy (electricity) is more valuable and conversions of this high grade into low grade energy (heat) is highly discouraged in this method.

Before looking at the results of the studies, some remarks must be made, since the characteristics of the cases differ sometimes substantially. First, not all studies have the same accuracy. The following aspects are sometimes excluded: transportation, waste factors, maintenance, water use, etc. Therefore a distinction is made between full LCA and screening LCA, not based on methods, but on the depth of the analysis. Next, various topics were the subject of research. Most of the studies consider

<table>
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<th>Author</th>
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Table 1: Recent Case Studies

R = residential, O = office, S = school, x= included, - = excluded
residential buildings, but schools and office buildings have been investigated too. The cases differ in construction period, level of technology or building concept. Finally, not always all phases of the life cycle have been included (partial LCA). This variety makes it hard to draw general conclusions.

In addition, some extra steps can be included beside the mandatory steps of a LCA, namely a sensitivity check and an uncertainty analysis. The first one is to verify the robustness of the results by varying parameters, choice of data, assumptions or impact assessment methods to check if the results are still valid. If not, this has to be documented. The uncertainty analysis investigates the reliability and completeness of the model. Since a LCA is always a simplification of reality, the calculated uncertainty range and distribution gives insight in the reliability of results. However data quality indicators are sufficiently available, for example in the Ecoinvent database, only the study of Blengini and Di Carlo included this step [12].

As mentioned before, most parameters of the existing research vary substantially, but nevertheless some common trends can be indicated. One of the conclusions of almost every research is the dominance of the use phase, especially due to energy consumption of heating and cooling. The share of the use phase of standard houses is in the range of 60 - 90% of the total environmental burdens, mainly with a contribution to global warming potential [20], [21]. A common conclusion of these studies is therefore the necessity of reducing the need for heating and/or cooling by improving insulation, air-tightness and controlled ventilation. Some of these aspects can be found in the European Policy (EPBD 2010), which is strongly focused on reducing energy consumption.

All this aspects are put into practice in low-energy houses. Several studies analyze the impact of measures in this kind of buildings, however only on dwellings so far. Blengini and Di Carlo investigated a low energy dwelling in Italy. Although the energy consumption was 10 times lower than the reference standard house, the total environmental impact was only reduced by a factor 2.1 [12]. So when the energy use is pushed back, the other phases of the life cycle are growing in importance, like for example construction, the choice of materials and end-of-life scenarios. Huberman reaches similar conclusions: if operational energy (use) decreases, embodied energy (materials) increases relatively and often also in absolute values, a trend which occurs more often since industrialization [16]. Citherlet and Defaux mention that it is only relevant to pay much attention to the indirect impacts like construction and demolition when the yearly energy consumption is below 150 MJ/m² [22].

As new buildings are designed more energy-efficient, a next step in research is to pay more attention to the growing relevance of the other phases. Thormark focuses on the recycling potential and the concept ‘Design for disassembly’, while Blengini examined the demolition of a flat to verify and/or complete literature data [9], [23–25]. Both studies show the benefits of reuse in the first place, which is slightly superior to recycling, yet they do have reservations about the feasibility of reuse on a large scale. Govers et al. describe problems of a such switch-over of existing economic structures, especially in this case, where large changes in technical and network dimensions are necessary [26]. In line is the research of Erlandsson and Levin focusing on the benefits of renovation, a construction method that is gaining importance as can be seen in Belgian statistics: the share of renovations increased with more than 30% over the last 15 years [27]. Renovation is generally more eco-friendly, but urban regulations are a limitation that often do not allow all optimal measures, especially if they occur on the outside of the building, i.e. additional insulation [28].

Not only energetic but also structural concepts have been compared, mainly renewable (wood) versus non-renewable materials (masonry, concrete, steel) in the context of low-energy dwellings. Most research assigns better results to wooden structures [29-31]. Wood is easier to manipulate and CO₂ neutral (or even negative depending on the point of view), while production of steel and concrete induces more burdens due to production and processing and has a higher embodied energy. However, the use of timber frames is limited to buildings up to three storeys [31]. Only the research of Marceau and VanGeem comes to opposite conclusions, with a preference for concrete structures, mainly because of the higher land use of wood [32].

Another frequent conclusion is the minor importance of the transportation of materials during
the construction phase. Almost all the research included this aspect, but as building materials are often locally produced, the travel distances and associated impacts are limited, for example 1 % or less according to Adalberth and Ortiz et al. [20], [33]. Even when some parts are transported over a long distance, the associated impact does not play a major role. Designers and public administrators participating in the Italian study by Blengini and Di Carlo on a low energy house were surprised by the minor contribution of transportation, as it was feared that i.e. triple glazed windows imported from Germany and cork slab transported over long distances by truck and ship would compromise the environmental performances [12]. Only when almost all materials are transported over a great distance, transportation becomes an issue of concern, which can be seen in the research of Chen et al.: materials of two analyzed office buildings in Hong Kong are mostly imported, often overseas, which can be seen in the contribution of transportation of 7 % to the total environmental burdens [34].

4 Discussion and limitations

This review focuses on case studies of whole buildings, which is a great tool to investigate building concepts and to support decision-making to reduce environmental burdens. Nevertheless the LCA methodology has some inherent limitations, so results should be interpreted and used with care. The cases are difficult to compare because of their specific properties like lay-out, climate, comfort requirements, local regulations, etc. The difference in estimated lifespan is a second limitation. These two limitations can be partly overcome by calculating the annual burdens per square meter useful floor surface.

As mentioned before, the use phase is dominant, especially through energy consumption. The burdens of this phase are based on estimations, taking average values of the whole society into account. Since individual inhabitant behavior is difficult to predict, it is also an issue of concern when considering the reliability of any conclusion on energy consumption. This limits the practical importance of LCA, no matter how accurate calculations may have been carried out. Thereafter, research concluded that many efficiency improvements do not reduce energy consumption as much as predicted. As they make energy services cheaper, the demand for these services will increase. For example, if a dwelling is well insulated, residents are more likely to heat up the spaces above the calculated temperature, since this entails only a limited additional cost. This psychological phenomena is called the rebound effect and until now this has not been taken into account [35].

Another drawback of current LCA practice within the construction sector is the isolated approach of environmental issues. Often the focus is limited to the search for environmental optima, but without linking it to other aspects. For example, LCA does not take into account any quality, energetic, structural nor esthetic requirements. According to Allacker, the design plays a major role in the environmental profile, but this has been barely investigated yet [50]. Also financial feasibility is hardly ever taken into account, although ready-to-use tools are available, for example Life Cycle Costing (LCC). Only a few researchers include both financial and environmental aspects to give a more complete picture, like Allacker, Blanchard and Reppe, and Verbeeck [36-38].

5 Research opportunities

The growing importance of LCA as a scientific tool to evaluate environmental burdens is a positive trend, however there are still many research opportunities and areas to improve current practice. The construction sector causes unwanted environmental effects, but economic costs to repair or avoid them rarely appear in the resulting prices of goods and services. Internalization is nevertheless crucial if our society wishes to enhance its sustainability on the long term, without burdening future generations. As this is currently not occurring systematically, it is a challenge to reflect environmental costs of building materials and processes in their sales prices. This way manufacturers or service providers should be held responsible to repair or counter the environmental effects of their production processes. The link between environmental impact and cost implications needs to be established and clearly communicated.

Currently the main focus is at energy reduction, both in policy and research. However, the research of Allacker states that other aspects may play an important role too, like water consumption. The impact of water consumption equals 18 % for a non-
insulated dwelling and up to 88% for a low-energy dwelling of the burdens of heating. As reducing energy consumption is starting to get established, it is possible to pay increased attention to other issues. So now, besides the impact of materials and end-of-life treatment, reducing the water consumption of households is gaining importance too [36]. The reduction of water consumption will have to be examined more thoroughly in future research.

Another conclusion of the same research is the importance of architectural design, which has often more effect than pure technological improvements. Solar gains, orientation and compactness are quickly overlooked, since they are very site dependent and subject to urban regulations. A set of instructions, guidelines and the incorporation within the urban policy could trigger a positive evolution towards a more sustainable building stock.

6 Conclusion
This analysis of case studies indicates a growing attention for sustainability in the construction sector. Despite some limitations of the LCA technique, it is still a powerful and science-based tool to evaluate the environmental burdens. The listed cases focus on analysis of whole buildings, so environmental hotspots can be indicated and priorities for action can be defined. A recurrent conclusion is the dominance of the use phase, especially in conventional buildings, mainly caused by the need for heating and cooling. As a consequence new building concepts, focusing on energy efficiency, have arisen. Within the life cycle of the latter, there occurs a shift of environmental burdens from use phase to construction, materials and end-of-life treatment. As well-insulated buildings will become the new standard, these other issues deserve more attention. Until now, European policy focused mainly on controlling energy consumption, but as illustrated by this review, new fields of action emerge, like for example controlling and reducing water consumption. Finally, to enhance a sustainable society, people should be aware of the ecological impact of products and services. This could be achieved by internalization, so the environmental effects would be reflected in market prices.

References:


