# LCA in the construction industry: a review

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***Abstract*—**The last decades, there is a growing interest for reducing the environmental impact of buildings. Mostly the focus is on reducing energy consumption and eco-friendly materials, but importance of life-cycle thinking is growing. This paper tries to give an overview of the current situation of Life cycle assessment (LCA) in the construction industry, both of regulatory developments and academic case studies. After a short history of LCA, the focus is on LCA methodology, new standards and frameworks and recent case studies.

Despite inherent limitations of LCA as an analytic tool and the differences between the individual cases, some common trends can be indicated. In standard buildings, the use phase contributes up to 90 % of the total environmental burdens, mainly due to heating and/or cooling. As new buildings become more energy efficient, other phases of the life cycle gain importance, like choice of materials, construction, end-of-life and water use. This are research topics which deserve more attention, together with economic issues and the improvement of data quality.

***Keywords*—**Life Cycle Assessment, Construction industry, review, Sustainable development

## I. 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 eventually 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 [2], [3]. Such 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 [4], [5].

These European regulations stimulated the emergence of new building concepts such as low-energy and even self-sufficient houses [6], [7]. When only focusing on energy consumption, low-energy houses excel compared to standard houses [8]. 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 [9]. All aspects considering natural environment, human health and resource depletion are taken into account and together with the life cycle perspective, LCA avoids problem-shifting between different life cycle stages, between regions and between environmental problems.

## II. A Brief History

The first studies on environmental impacts date from the 1960s and 1970s, focusing on the evaluation or comparison of consumer goods, with only a small contribution to the use phase [10]. According to Guinée et al. one of the first (unpublished) studies was executed by Midwest Research Institute (MRI) for The Coca Cola Company in 1969, including resources, emission loadings and waste flows for different beverage containers [10]. In the beginning of the 1980s, life cycle thinking appears in the construction sector with a study of Bekker, with focus on (renewable) resources [11]. These early researches applied diverging methods, approaches, terminologies and results. There was a clear lack of scientific discussion and consensus and the technique was often used for market claims with doubtful results, which prevented LCA from becoming a general accepted and applied analytical tool [12].

In the 1990s came a period of standardization, with the organization of workshops and the publication of several handbooks and scientific papers [12–17]. From this decade, the Society of Environmental Toxicology and Chemistry (SETAC) started playing a leading and coordinating role by bringing the LCA practitioners together and harmonizing the framework, methodology and terminology, which resulted in the SETAC 'Code of Practice' [18]. From 1994 the International Organization for Standardization (ISO) was involved too, whose main achievement has been the harmonization of methods and procedures, resulting in the ISO

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14040 standard series from 1997 [19]. The result of this standardization was the creation of a general methodological framework, which made it easier to compare different LCAs. It is important to keep in mind that even with the consensus on the framework, ISO never aimed at defining the exact methods by stating 'there is no single method for conducting LCA' [9].

From the start of the 21st century, interest in LCA has been increasing rapidly, as can be seen in the overview of case studies in table 1. Life cycle thinking is also growing in importance within European Policy as i.e., demonstrated by the Communication from the European Commission on Integrated Product Policy (IPP) [20]. To facilitate the use of LCA and to improve supporting tools and data quality, the United Nations Environment Programme (UNEP) and SETAC launched the Life Cycle Initiative [21], [22]. Another indication of the growing importance of life cycle thinking is the emergence of Environmental Product Declarations (EPDs) [23], [24]. An EPD is a set of quantified environmental data for a product with pre-set categories of parameters based on the LCA standards (ISO 14040 series), and additional environmental information is not excluded. This system makes it easier for designers to choose for eco-friendly products or materials.

In the last decade, there have been also some developments specifically targeting the construction sector, in addition to the ISO 14040 standards. In 2003, SETAC published a state-of-the-art report on Life-Cycle Assessment in Building and Construction, an outcome of the Life Cycle Initiative [25]. This study highlights the differences between the general approach of LCA and LCAs of buildings. Such standardization continued, with as two leading organizations the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN). The first, more specifically the ISO Technical committee (TC) 59 '*Building Construction*' and its subcommittee (SC) 17 '*Sustainability in Building construction*', published four standards describing a framework for investigating sustainability of buildings and the implementation of EPD's [26]. The CEN Technical Committee (TC) 350 '*Sustainability of construction works*' is developing standards for assessing all three aspects of sustainability (economical, ecological, social) both for new and existing construction works and for the environmental product declaration of construction products [27]. Since these standards are very recent, only very few studies have been executed according to them.

## III. LCA METHODOLOGY

As described in the previous section, in current practice LCAs are executed within the framework of the ISO 14040 series [9]. To analyze the environmental burdens of processes and products during their entire life cycle, four steps have to be run through, making it possible to compare different studies: goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and an interpretation [28], [29].

Goal and scope define purpose, objectives, functional unit and system boundaries. One of the strengths of LCA is defining investigated products and processes based on their function instead of on their specific physical characteristics. This way, products can be compared that are inherently different, but fulfill a similar function i.e., paper towels versus reusable cotton towels for drying hands. The second step (LCI) consists of collecting all data regarding inputs, processes, emissions, etc. of the whole life cycle. 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 (where the authors insist on a maximization approach), 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, for example 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 global issues of concern or a single score, by using numerical factors based on value-choices, for example based on policy targets, monetarisation or panel weighting – the authors emphasize the fact that this is the first and major step in a full LCA where non-objective measures come in. This is part of the environmental mechanism (see further). The fourth and final step is the interpretation of the results [9], [29].

The approaches to calculate environmental impacts can be subdivided into two types, attributional and consequential LCA. Attributional LCA is defined by its focus on describing the environmentally relevant flows within the chosen temporal window, while consequential LCA aims to describe how environmentally relevant flows will change in response to possible decisions [30], [31]. Generally, most authors state that consequential LCAs are more appropriate for decision-making, unless their uncertainties in the modeling outweigh the insights gained from it [32], [33]. When LCA is used to indicate hotspots of the environmental burdens as base for improvements, the consequences of these implementations should not be neglected. Such actions will influence the production of upstream products, other life cycles and more in general, other economic activities. Both positive and negative mechanisms can occur. If efficiency measures are profitable, economic activities may increase and diminish the environmental benefits. This negative mechanism is also called a rebound effect [34]. A positive mechanism is that investments in emerging technologies are likely to reduce manufacturing costs, which can trigger similar investments of other manufacturers [31]. If such a new technology has a lower impact, this can entail huge savings for the entire society and in that case a consequential approach is more appropriate.

Although ISO-standards describe the global framework of a LCA, the exact technique to be used is not defined. Depending on the nature of research, different methods can be chosen, defined by their environmental mechanisms. Such a mechanism is the process for any given impact category, linking the LCI results to category indicators, i.e. a sequence of effects that can cause certain level of damage to the environment. These category indicators can be combined to more comprehensible and general indicators. The valuation factors used in environmental mechanisms are the difference between LCA methods, as they may assign other importance to the same physical values.

To quantify environmental impacts two approaches can be identified, namely the problem-oriented (midpoints) and damage-oriented (endpoints) ones [35]. The first group of methods uses values at the beginning or middle of the environmental mechanism. 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. The second group is at the end of the mechanism, where the midpoints are grouped into 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 [36], [37]. 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.

A weakness in current practice of LCA is that different methods applied to an identical case can generate different results e.g., a narrow scope carbon footprint study versus

**TABLE 1**

**RECENT CASE STUDIES**

| Author | year | Country | Cases | Building | Type | Lifetime | Production | Use | EoL | Sensitivity | Transport |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Adalberth et al. [38] | 1997 | Sweden | 3 | R | LCEA | 50 | x | x | x | - | x |
| Arena and Rosa [39] | 2003 | Argentina | 2 | S | scr. LCA | 50 | x | x | - | - | x |
| Asif et al. [40] | 2007 | Schotland | 1 | R | LCEA | ? | x | - | - | - | - |
| Audenaert et al. [41] | 2012 | Belgium | 1 | R | Scr. LCA | ? | x | x | x | - | - |
| Blanchard and Reppe [42] | 1998 | USA | 2 | R | LCEA | 50 | x | x | x | x | x |
| Blengini and Di Carlo [43] | 2010 | Italy | 2 | R | LCA | 70 | x | x | x | - | x |
| Blengini [44] | 2009 | Italy | 1 | R | LCA | 40 | x | x | x | x | x |
| Chen et al. [45] | 2001 | China | 2 | R | LCEA | 40 | x | - | x | - | x |
| Citherlet and Defaux [46] | 2007 | Switzerland | 3 | R | LCA | ? | x | x | x | x | x |
| Cole and Kernan [47] | 1996 | Canada | 12 | O | LCEA | 50 | x | x | x | x | - |
| De Meester et al. [48] | 2009 | Belgium | 65 | R | LCEA | 75 | x | x | x | - | x |
| Dewulf et al. [49] | 2009 | Belgium | 1 | R | LCEA | 50 | - | - | x | x | x |
| Erlandsson and Levin [50] | 2005 | Sweden | 1 | R | LCA | 35 | x | x | - | - | - |
| Fay et al. [51] | 2000 | Australia | 2 | R | LCEA | 100 | x | x | - | x | x |
| Gerilla et al. [52] | 2007 | Japan | 2 | R | LCA | 35 | x | x | x | x | x |
| Huberman and Pearlmutter [53] | 2008 | Israel | 1 | R | LCEA | 50 | x | x | - | - | x |
| Junnila [54] | 2004 | Finland | 1 | O | LCA | 50 | x | x | x | - | x |
| Kofoworola and Gheewala [55] | 2008 | Thailand | 1 | O | LCA | 50 | x | x | x | - | x |
| Marceau and VanGeem [56] | 2006 | USA | 2 | R | LCA | 100 | x | x | - | x | x |
| Mithraratne and Vale [57] | 2004 | N.Zealand | 3 | R | LCEA | 100 | x | x | x | - | x |
| Ortiz et al. [58] | 2009 | Spain | 1 | R | LCA | 50 | x | x | - | x | x |
| Peuportier [59] | 2001 | France | 3 | R | LCA | 80 | x | x | x | x | x |
| Reddy and Jagadish [60] | 2003 | India | 3 | R | LCEA | ? | x | - | - | - | x |
| Scheuer et al. [61] | 2003 | USA | 1 | S | LCA | 75 | x | x | x | - | x |
| Suzuki and Oka [62] | 1998 | Japan | 10 | O | LCEA | 40 | x | x | - | - | - |
| Thormark [63] | 2000 | Sweden | 2 | R | LCA | ? | x | - | x | x | x |
| Thormark [64] | 2002 | Sweden | 1 | R | LCEA | 50 | x | x | x | x | x |
| Winther and Hestnes [65] | 1999 | Norway | 5 | R | LCEA | 50 | x | x | - | - | x |
| Xing et al. [66] | 2008 | China | 2 | O | LCA | 50 | x | x | - | - | - |
| Zimmermann et al. [67] | 2005 | Switzerland | - | All | LCA | ? | x | x | - | - | x |

R = residential, O = office, S = school, x= included, - = excluded studies with a set of more differentiated impact indicators [6], [63]. Various methods can assign a different importance to properties or impacts, which can result in other suggestions of action to reduce the ecological burdens [68]. Results of a Life Cycle Assessment are no absolute values and therefore can not serve as a certification on itself. They do not guarantee the sustainability of a product or service, but are valuable for the comparison of different products and processes. Comparing results of a LCA is only meaningful when the subjects fulfill exactly the same function in accordance with their goal and scope definitions.

## IV. Recent developments in the construction sector

### A. Academic research

In industrial processes, LCA is widely spread and it is used frequently to evaluate the environmental impact of products and processes [69]. In the construction industry however, such a study is much more complex because of the long lifespan of buildings (50 – 100 years [70–72]), a shorter lifespan of some elements, the use of many different materials and processes, the unique character of each building, the distance to factories, etc. [71]. Since the building process is less standardized than industrial processes, such a Life Cycle Assessment is a challenging task.

A 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 [35]. Discussing analysis of materials is beyond the scope of this review, but it is important to keep in mind that two possible alternatives have to fulfill the same function. Studies on building components are therefore easier to interpret, as structural and thermal requirements can be taken into account. They are often useful during the design process, as 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 [35].

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 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) and consider the energy consumption during the different phases of the life cycle: embodied (production and construction), operational, demolition and recycling energy. 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 and harder to interpret [53]. A variation on this method is Life Cycle Exergy Assessment, developed by De Meester and Dewulf, which takes the quality of the energy into account [48], [49]. Exergy is the work potential of an amount of energy with respect to its environmental conditions [73]. According to this method, the conversion of high grade energy (electricity) into low grade energy (heat) should be highly discouraged. Less frequent are the regular LCAs, full or partial, which are executed with a wide variety of methods. These methods differ from midpoint to endpoint and sometimes different methods are compared or linked to policy targets. The discussion on these methods is beyond the scope of this review.

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 completeness. The following aspects are sometimes excluded: transportation, waste factors, maintenance, water use, etc. Also the accuracy differs, therefore a distinction can be made between full LCA and screening LCA too, not based on methods, but on the depth of the analysis. Next, there is a wide variety in the methods used. Fourth, various topics were research subjects. Most of the studies consider 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.

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 sensitivity of significant data elements 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 and incorporates the basic uncertainties of the process parameters. 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 [36].

As mentioned before, the 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 [38], [55]. Even in very different climates this conclusion appears to be valid, as studies in

Nordic and Mediterranean countries come to similar results [38], [58]. An common conclusion of these studies is therefore the necessity of reducing the need for heating and/or cooling by improving insulation, air-tightness and controlling ventilation. Some of these aspects can be found in the European Policy, which is strongly focused on reducing energy consumption (EPBD 2010).

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 ten times lower than the reference standard house, the total environmental impact was only reduced by a factor 2.1 [36]. So when the energy use is pushed back, the other phases of the life cycle are growing in relative 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 [53]. Citherlet and Defaux mention that it is only relevant to pay much attention to the impact of the production and end-of-life phase (referred to as '*indirect impacts*') when the yearly energy consumption is below 150 MJ/m² [46].

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 focused on the recycling potential and the concept 'Design for disassembly', while Blengini examined the demolition of a flat to verify and/or complete the literature data [44], [63], [64], [74]. 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. Goverse et al. describe problems of a switch-over of existing economic structures, especially in this case, where large changes in technical and network dimensions are necessary [75]. 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 [76]. 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, for example additional insulation [50].

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 [47], [52], [57]. Wood is easier to manipulate and $CO_2$ neutral, 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 [47]. 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 [56].

Another frequent conclusion is the minor importance of the transportation of materials during construction. 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. [38], [58]. 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 triple glazed windows imported from Germany and cork slab transported over long distances by truck and ship would compromise the environmental performances [36]. 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 [45].

### *B. Regulatory developments*

The previous sections demonstrate that in current academic practice, only general trends can be derived from the examined studies. However buildings are not directly comparable. All these studies are executed according to the framework described in the ISO 14040 series, which is applicable to all types of studies. As life-cycle thinking becomes more integrated in policy and marketing, there will be a need for a more delineated framework, specifically for buildings. As mentioned in Section II, international organizations like ISO and CEN are working on the standardization of LCAs in the construction sector in order to improve the comparability of such studies. A main goal of the latter is documenting the environmental performance of a building for use in e.g, declaring environmental performance, labeling and marketing. As stated by CEN TC 350 in EN 15978:2011, 'the *purpose of this European Standard is to provide calculation rules for the assessment of the environmental performance of new and existing buildings*' [77]. These rules consist in the description of system boundaries, procedure to be used for the inventory analysis, a list of environmental indicators and procedures for the calculation of the impact categories, rules for reporting and communicating results, etc. This framework is very similar to the one of EPDs, which encourages and facilitates the incorporation of results of external studies.

The previous mentioned regulation is part of a larger set of standards, also focusing on other aspects of sustainability like social and economic performance, both at building and product level.

## V. Discussion and Limitations

This review focuses on case based LCA studies of entire buildings, being a great tool to investigate building concepts and to support decision-making to reduce environmental burdens. Nevertheless the LCA methodology has some inherent limitations, consequently results should be interpreted and used with care. First, 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, still other aspects of the studies can differ e.g., system boundaries, assumptions, level of detail, LCIA methods, etc. Next, LCA is merely a model and simplification of reality, so assumptions have to be made that can generate uncertainties on different levels: model, scenario and parameter uncertainties [78]. The first two aspects are difficult to process statistically and are often excluded, but with the latter this is possible as data quality indicators are available for all materials and processes in the Ecoinvent database. Parameter uncertainty is also often enhanced by data gaps, resulting in less accurate data to be used. These elements influence the reliability of results, but with the degree of uncertainty known, still useful conclusions can be drawn.

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. 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 [34].

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 [79]. Also financial feasibility is hardly ever taken into account, although ready-to-use tools are available, for example Life Cycle Costing. Only a few researchers include financial and environmental aspects and give a more complete picture, like Allacker, Blanchard and Reppe, and Verbeeck [42], [79], [80]. Although new regulations and frameworks have been worked out for assessing all aspects of sustainability, at the moment they are not frequently implemented.

## VI. 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 [79]. 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.

A last research opportunity is related to the commonly used data, which are mostly deterministic values. Although these values often come from averages, more research is needed to evaluate if they are representative for a specific case study. A study of Aktas and Bilec investigates the influence of the assumptions on the functional lifetime: they consider the lifetime as a distribution, compared to the deterministic derived from average values [81]. They state that the use of distributions instead of deterministic values for lifetime of products and buildings improves accuracy of the study and make results more objective. This approach has a huge potential for improving the reliability of LCA results, by expanding the use of distributions. Aspects as energy and water use, transport loads and distances, cutting waste, etc. should be evaluated by using distributions. Especially all aspects related to the dominant phases of the life cycle (energy) can have a great influence, although a major problem can be the lack of data.

## VII. CONCLUSION

This analysis of case studies indicates a growing attention for sustainability in the construction sector. Current regulatory frameworks are developed to facilitate the implementation of the assessment of environmental performances. 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 and paying more attention to a smart design. To increase the reliability of results, there should also be more attention for the use of distributions instead of deterministic values. 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.

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