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An operational methodology for applying dynamic Life Cycle Assessment to buildings

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ABSTRACT

While the Life Cycle Assessment (LCA) method is a powerful tool for environmental performance evaluation, the current LCA methodology faces some limitations in evaluating environmental performances of systems with a long time scales, such as buildings. Building systems have particularly long lifetimes as compared to other products or services. They are composed of elements that evolve over time and are characterized by time-dependent parameters. A literature review was performed in the aim of identifying the time-dependent characteristics of a building system at different levels: building technology level (e.g. technical performance degradations and technological innovations), end-user level (e.g. occupant behaviour) and external system level (e.g. infrastructures, energy mix, regulations). A new LCA framework including the time dimension, applied to a building system, is proposed. It involves operational and reproducible tools (computational software and databases) to perform effective temporal evaluations and incorporates dynamic Life Cycle Inventory (LCI, including the temporal evolution of a building system and of the related environment interventions, i.e. emissions and resource consumption) and dynamic Life Cycle Impact Assessment (LCIA, climate change and toxicity). To integrate the specificities of buildings in dynamic LCI modelling, different existing assets (at national and international level) in the field of LCA are analysed. This work proposes an original methodology for performing a dynamic LCA of buildings using new tools still under development.

1. Introduction

Life Cycle Assessment (LCA) has become an indispensable method for quantifying the environmental performance of products or services and is widely used in many sectors of activity. Environmental issues of buildings concerning both energy and embodied materials have increasingly been acknowledged by several scholars, who have illustrated their methodological developments for environmental assessment of buildings through case studies [1–3]. Different types of building structures, scenarios of replacement and refurbishment phases, construction products, and end-user energy consumption have been compared in terms of their environmental performance. Moreover, some studies have focused on energy use throughout the building lifetime, investigating how to estimate orders of magnitude of energy uses from the construction to demolition of the building [4,5]. The considerable amount of waste resulting from the construction activity and the dismantling of buildings has led us to consider demolition waste recycling. While building-LCA studies have seen methodological improvements integrating more and more complex elements of the building system, the evolution of that system over its life cycle has remained beyond the scope of studies, as buildings have particularly long lifetimes compared to other products or services. Building systems are composed of elements that evolve in time and are characterized by time-dependent parameters. At the technological level related to the building sector, the degradation of technical performances of buildings may be one of the key dynamic parameters. On the other hand, energy consumption varies with time and its variation is determined by technological parameters, occupant behaviour, energy equipment characteristics and climate conditions. Another aspect influencing energy consumption by a building system is the economic and environmental context. The evolution of policy rules, e.g. national energy strategies and environmental regulations, may encourage the construction sector to reduce material and energy use and can stimulate a reduction of related environmental impacts e.g. near zero energy and low carbon footprint buildings: the "E + C- approach", a large-scale experiment aiming to prepare a new environmental building regulation in France [6]. The European project "Levels" is also based on the concept of applying a life-cycle approach to building design [7,8]. Therefore, decisions for

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construction materials, maintenance, replacements, and refurbishment, together with scenarios of the end of life, should be placed in the context of national and European regulations that change over time depending on the energy, environmental and economic background. The electricity production mix and, more generally, the energy resources used vary over time with regard to the availability of energy resources, the economic situation of a country, climate and agriculture for renewable energy development, etc. Some of these dynamic parameters considerably impact LCA results for buildings.

Many environmental standards currently exist in the field, at national levels as well as in Europe. For example, the European standard EN 15978 on the assessment of the environmental performance of buildings is applicable to new and existing buildings, and refurbishment projects [9]. These standards give the rules for quantitatively evaluating the environmental performance of buildings based on the life cycle approach. Different life cycle-based tools complying with these rules or environmental regulations have been developed to help design sustainable buildings with respect to country-specific contexts, e.g. ELODIE in France [10]. The specificities of some existing building-LCA tools will be mentioned in the following sections. Even though efforts are being made on the development of LCA tools along with efforts to regularly upload environmental data, none of these tools allow the temporal dimension to be considered, either at the level of material and energy balance, or at the level of environmental impact calculations. Actually, there are no tools (methods, norms, or databases) enabling temporal characteristics to be taken into account that are explicit and specific to buildings. Nevertheless, prospective evaluations can be performed by using specific energy and material balances averaged over given time periods.

In this context, the need for a more realistic evaluation of the environmental performances over long time frames leads us to consider a dynamic LCA approach adapted and completed for application to the building sector. Thus, the general goal of this work is to propose a methodology for considering time in LCA of buildings. In order to reach our goal, the present paper (i) aims to identify the main temporal aspects of a building system (section 2), (ii) analyses the literature related to the dynamic LCA assessment in the field of buildings, and (iii) proposes a framework for temporal LCA applied to buildings. Key dynamic parameters of the building system, the method of dynamic inventory data, calculation tools, expected results and also the main limitations of the proposed general framework are presented.

2. Time-dependent factors and parameters of a building system

Before analysing the temporal aspect in LCA applied to buildings, this section will present the temporal variation of building systems encountered from a variety of aspects.

Energy consumption varies from hour to hour, day to day, week to week, season to season, and year to year, depending on various factors. The typology of inhabitants and their behaviour are variable depending on the economy, culture, and climate, and play an important role in determining the energy consumption level and its temporal behaviour. From a literature review, de Meester et al. [11] selected the three parameters having most influence on the heating loads in a single-family house: 1) type of occupancy (e.g. family size, age), 2) management of thermal comfort (e.g. temperature set point, functioning time of energy systems) and 3) area heated. They created 7 levels of thermal performance for the house (from zero insulation to standard level insulation for a passive house). Each scenario uses different insulation materials in the wall, floors, and roof. If the insulation level is low, the heat load management (temperature specification and heating time) becomes important to reduce energy consumption. On the other hand, when the house is well insulated, the type of occupancy greatly impacts the energy consumption level. Four scenarios of occupancy over 100 years, combining the above three parameters, were evaluated in terms of heating loads, and the maximal difference between scenarios reached 26%. As evoked in their discussion, in a long time scale analysis, the house should be adapted to the evolution of the family, including possible improvements in thermal insulation.

Technical performances related to construction products and energy equipment degrade over the long lifetime of buildings. Insulation materials deteriorate over time due to climate conditions (e.g. humidity) and the occupant needs to replace such building materials in order to maintain the thermal comfort. Studies exist on how the degradation of building components (especially insulation materials) occurs over time, affecting the energy consumption [12–14]. One of these research works examined the durability of insulation materials in terms of their thermal-hygrometric and mechanical performances, showing a 12% increase in thermal conductivity over 25 years. The effects of such degradations on the energy performance of buildings was observed and simulated over time for different envelope structures e.g. exterior walls, floors, and roof. Marceau et al. [15] showed that bio-based insulation materials, such as wood wool are particularly sensitive to climate conditions, and their thermal performance can deteriorate due to the variation of water content in the products. Degradations of technical performance will lead to changes in energy consumption. Besides, the interaction with external factors like gases from atmosphere may lead to some carbon dioxide absorption in case of lime-containing materials (concrete, hempcrete, …) [16,17].

The real durability of construction products can be significantly different from the theoretical and declared one [18]. ISO 15686-8 defines a methodology and factors to determine the service lifespan of construction products and building equipment. According to the literature review, many building-LCA studies refer to 50–100 years as a lifetime of buildings. The service life of 30 years is typically used for principal components of a building (e.g. floors, façades, and roof) [8] and products should be replaced or refurbished at their end of life using new technologies that have emerged.

Although the technical performances of building components may diminish during the building's long lifetime, this very longevity of the building implies that it will be able to benefit from technological innovations occurring after its original construction. The relevance of taking this prospective aspect into account in LCA for long time scale studies has been discussed by Frischknecht et al. [19]. Prospective factors should be considered for different scales and depending on the scope of the study. Replacement, refurbishment and also the treatment of construction waste products occurring several decades after the first construction may use new technologies that are more efficient in terms of energy consumption or environmental emissions. Thus, industrial and technological improvements should lead to long time scale scenarios with high environmental quality of the buildings.

Reducing energy consumption during the building component production and during its service lifetime is a continuing goal. Lowering the environmental load of the energy used is another improvement criterion. Heat production can use thermal resources like fossil fuels, biomass, and thermo-solar systems. A large panel of electricity production technologies exist, based on fossil or renewable resources. French electricity production depends strongly on nuclear power and is characterized by a low carbon footprint, with an annual average of 105 gCO_2 eq/kWh, compared to the power production technologies of other European countries, which are mostly based on fossil fuels. For example, the average carbon intensity of electricity consumed in Europe was 447 g CO_2-eq/kWh in 2013 [20].

To meet the target concerning the reduction of GHG emissions, the European Commission has proposed a framework for energy pathways towards 2050. Following this strategy, 75% of the European electricity consumption would be covered by renewable sources, with a shift in the electricity production mix and improvements in energy system efficiency [21]. Decarbonisation is also encouraged for heating and cooling systems to ensure that the goal of limiting climate change is achieved [22]. According to this study, increasing the share of district heating with respect to the total energy demand, and also accounting for the