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Life cycle inventory of buildings: A calculation method

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ABSTRACT

Traditionally, life cycle assessment (LCA) is mostly concerned with product design and hardly considers large systems, such as buildings, as a whole. Though, by limiting LCA to building materials or building components, boundary conditions, such as thermal comfort and indoor air quality, cannot be taken into account. The life cycle inventory (LCI) model presented in this paper forms part of a global methodology that combines advanced optimisation techniques, LCI and cost-benefit assessment to optimise low energy buildings simultaneously for energy, environmental impact and costs without neglecting the boundary conditions for thermal comfort, indoor air quality and legal requirements for energy performance. This paper first outlines the goal and scope of the LCI. Then, the partial inventory models as well as the overall building inventory model are presented. Finally, the LCI results are shown and discussed for one reference dwelling for the context of Belgium.

1. Introduction

In LCA, products are modelled as a system in order to assess its material and energy balance [1]. However, since the traditional LCA methodology has historically grown from the industry, most available LCA tools are suitable for the assessment of industrial products, but much less for buildings. Firstly, buildings and constructions are neither bulk material nor serial products. This way, the one-of-a-kind character of buildings makes comparisons of LCA results difficult [2].

Furthermore, some basic hypotheses of the LCA methodology, such as time stability, do not cope with the characteristics of buildings. Time stability, meaning that the product system is considered as a time stable system, implies that when a product reaches the end of its service life, the LCA assumes that the resulting waste will be treated as it used to be at the beginning of its service life [1]. Due to the very long lifetime of building products and buildings, this hypothesis will result in highly uncertain results. At the same time, apart from replacement of glazing or system components, most LCA's of buildings never take into account the renovations or thorough modifications that most buildings undergo before reaching its end of life.

Probably because of the complexity of the course of life of a building, researchers in the past often opted for building materials, building products or building components as subject for LCA research, also in comparative studies [1,3–7]. However, by limiting the functional unit of an LCA to a building material or component, a number of functions, that should be provided by buildings, such as thermal comfort in winter and summer, indoor air quality, etc., cannot be taken into account. This way, decisions based on isolated LCA for materials or components might lead to unexpected secondary effects when the materials or components are applied in buildings without taking into account their impact on the performance of the building as a whole.

Recently, research has been executed on the application and adaptation of the LCA framework to buildings as a whole. In analogy with the proposal of Erlandsson and Borg [8] to treat the different life cycle phases separately, the EU REGENER project has established a basic framework composed of partial models for the different phases and processes [2]. Also in the literature, several reports can be found on LCA studies of particular buildings in Sweden, Germany, USA, France and New Zealand [8–14].

This paper presents the life cycle inventory model developed within the EL^2EP research project that developed a global methodology for life cycle optimisation of extremely low energy dwellings for energy, emissions and cost [15,16]. Firstly, the LCI model is outlined, with a presentation of the goal and scope of the LCI. The partial inventory models as well as the overall building inventory model are presented. Subsequently the reference dwellings are presented. Finally, the LCI results for one of the reference dwellings are presented and discussed.

2. Methodology

2.1. Goal and scope of the LCI

The primary goal of the LCI model was to create global LCI data for buildings that could be incorporated in the global optimisation methodology. Therefore an inventory of energy flows and emissions

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for all considered phases in the life cycle of the buildings was executed. Although the original LCI study considered energy flows, global warming potential (GWP) and emissions of CO_2, NO_x, SO_x, non-methane volatile organic compounds (NMVOC) and particulates, this paper only presents the energy flows and GWP in order to limit its extent.

As the optimisation methodology aimed at developing dwellings, globally optimised for energy, emissions and cost and at the same time satisfying the boundary conditions for thermal comfort and indoor air quality, the functional unit for the LCI was not limited to materials, building components or the energy saving measures only, but contained the whole building. The reference dwellings that are described further below can be considered each as a different functional unit that has to yield a comfortable living environment in winter and summer for a family of one to four persons.

2.2. System boundaries and LCI data

Since the life span of a dwelling exceeds the usage period by one generation, resulting in large uncertainties on modifications and destination of the building afterwards, the mean adopted time scale here is the usage phase by one generation, during a period of 30 years, plus the phases upstream (extraction, production and transport of building materials and components). No assumptions are made in this research on the destination of the building after passing to the next generation. However, to analyze the sensitivity of the results for the assumptions on the usage period, also a usage period of 60 and 90 years is calculated.

In order to have qualitative and representative input data for the LCI of Belgian buildings, the ecoinvent database [17] has been selected, since it is the most extensive and most complete database at the moment, with representative data for Western Europe, including Belgium, and frequently updated. More details on the methodology of the ecoinvent database (version v2.0) can be found in [18].

Not all 2500 available process datasets from the ecoinvent database were of interest for this research. Only 47 building related process datasets have been extracted to calculate the LCI of 54 building related commodities.

The energy consumption during the usage phase, needed to fulfill the boundary conditions for thermal comfort and indoor air quality, is calculated through a coupling of the dynamic building simulation program TRNSYS15 and the multizone air flow program COMIS. The weather data are hourly average data for the Test Reference Year of Brussels, Belgium.

2.3. Reference dwellings and energy saving measures

In order to obtain representative results for Belgium, five reference dwellings are designed following the statistical average of the Belgian residential sector: one terraced dwelling, one semi-detached house, two individual dwellings (one with a simple square plan and one with a fragmented plan) and an apartment flat. The non-insulated version of the dwellings is defined as the reference situation. Thermal capacity is included by incorporating for each reference dwelling both lightweight (wood frame) and massive variants (cavity wall and massive wall with outer insulation).

Energy saving measures are applied to both building envelope and heating system. Different types and levels of insulation, glazing, solar shading and air tightness are considered as well as different systems for production, storage, distribution, emission and control of heat, various ventilation systems and renewable energy systems.

In order to only achieve building variants with acceptable indoor climate, good indoor air quality is guaranteed by calculating the needed air flow rates with COMIS. Depending on the glazing area, construction type and occupant behaviour, different comfort measures, such as night ventilation and/or solar shading might be added to the building variant in order to achieve acceptable thermal comfort. For each building variant thermal comfort is controlled with TRNSYS calculations of the weighted temperature exceeding in every zone based on the comfort theory of Fanger [21,22]. Only variants with acceptable thermal comfort in winter and summer are restrained for further analysis.

Also the impact of thermal bridges, depending on the insulation thickness and construction type is taken into account in the energy consumption during usage.

2.4. LCI model

The overall LCI building model developed within this research consists of partial LCI models that calculate the energy flow and GWP for the production of materials and components, a model for the transport phase and a model for the usage phase. In this paragraph the different models are presented.

Since existing LCA techniques apply as well to the production of building materials as to any kind of other material, the LCI results for several materials in the research database, such as brick, concrete, plywood, rock wool, etc., could directly be imported from the datasets in the ecoinvent database. For other commodities, such as window frames, sun shading or installation components, a product model was developed taking into account the amount of material used and the processes applied in the production process, based on [6,19], completed with own analysis of product composition. All composing materials and processes are extracted from the ecoinvent database to calculate the embodied energy of a product, being the non renewable primary energy needed for extraction of raw materials and for production of all composing materials. Some of the 33 product models are presented in Table 1 and Table 2. For building materials (Table 1) the functional unit is kg, m^3, m^2 or m, depending on the material; for system components (Table 2) the functional unit per component is kW.

As starting point for the transport model, all materials or products are assumed to be stored at the production plant. For constructional materials, two transport steps are assumed: (1) from the production plant to a distribution or assemblage centre and (2) from there to the construction site. For system components, step 1 always assumes transport of the composing materials to the assemblage site, whereas step 2 reflects transport of the finished

Table 1
Extraction from the product models for building materials based on materials and production processes from ecoinvent database.

Material	Unit	Composing materials	Product model
Inner plasterwork	1 kg	Stucco	0.67 kg
		Plaster mixing	1 unit
Hard timber wood	1 m^3	Sawn timber, hardwood, planed, kiln dried, at plant	1 m^3
		Preservative treatment, sawn timber, pressure vessel	1 unit
		Wood preservative, organic salt, Cr-free, at plant	4 kg
Aluminium window frame	1 m	Aluminium, production mix, cast alloy at plant	3.1 kg
		Section bar, extrusion, aluminium	3.1 units
		Electricity, medium voltage, at grid	2.53 kWh
		Heat, heavy fuel oil at industrial furnace, 1 MW	13.46 MJ
Inner sun shading (textile + fixation)	1 m^2	Glass fibre, at plant	0.22 kg
		PVC, at regional storage	0.30 kg
		Aluminium, production mix, cast alloy at plant	0.3 kg
		Sheet rolling aluminium	0.3 units