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Life cycle assessment of buildings and city quarters comparing demolition and reconstruction with refurbishment

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ABSTRACT

In the building sector, the energy and the greenhouse gases embodied in the building materials are becoming increasingly important. Combined with the operational primary energy demand and the end-of-life, the whole life cycle of buildings can be assessed.

In this paper, a comprehensive method for calculating the life cycle of individual buildings is presented. First, their material composition has been determined and generic values for the embodied energy, embodied greenhouse gases, energy needed and greenhouse gases emitted during disposal of the different building materials have been calculated. Subsequently these values have been integrated into an urban energy simulation software to simulate energy and emission values for buildings.

A given building geometry with four different building standards was considered. The results can help to decide between building refurbishment or demolition and new construction. For example it could be shown that the share of the life cycle stage production compared to the total value rises with a better building insulation standard, as the share of the use stage decreases. The highest building refurbishment standard resulted in the best life cycle performance when compared with less ambitious refurbishment or construction of a new building of today's standards.

1. Introduction

The worldwide trend of urbanisation, which is assumed to exceed 70% of all people living in urban areas by 2050 [1], calls for more living space with increased comfort. Even now, cities account for about 67% of the global energy consumption, are responsible for more than 70% of all greenhouse gas emissions [2] and consume around 75% of all natural resources [3].

In this context, the building sector is accountable for about 40% of the annual global energy consumption and contributes approximately 30% to the global annual emissions of greenhouse gases [4].

Life cycle analysis (LCA) addresses the environmental aspects and potential environmental impacts throughout a product's life cycle including the production, use and end-of-life stages. In ISO 14040 and 14044, the requirements for conducting a LCA are defined [5,6]. The results can be displayed in various impact categories, e.g. primary energy demand or greenhouse gas emissions. For the analysis, different types of software can be used, for example GaBi or Umberto.

Since the operational energy, needed during the use stage of a building, accounts for the largest share of energy demand during the entire lifespan of a building [7], a lot of research was done to lower the operational energy demand.

In addition, levels and standards for efficient buildings are continuously tightening due to stronger regulations, for example in Germany and California (USA) [8,9]. With these new standards for efficient buildings, the energy demand and resulting emissions during the use stage are decreasing. At the same time, the energy needed during the production stage is increasing because of the higher material input, e.g. for insulation materials produced with a substantial amount of energy. Consequently, the energy ratio is gradually shifting from the use stage to the production stage. Several studies can be found which also point out these facts [10–12]. It is important to mention that the values for the energy consumption during the various life cycle stages differ between all these studies. Those differences are caused for example by the different climate zones in which the buildings are located, the considered lifespan of the buildings or the kind of building materials used for construction [13].

Consequently, buildings should be evaluated with regard to their whole life cycle, which includes the production and end-of-life stages, and not only based on the energy demand during the use stage.

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Quite a lot of research has been conducted in this thematic area, however most of the studies are linked to individual buildings and case studies [14–16]. As a result, these specific studies do not allow a direct transfer of the methodology to other buildings and cities.

The methodology in this paper is rather focused on generic data than on specific data for one building only. For example the transport distance of building materials is the same average value for all materials and not related to a specific region. Like this, the data can be used for different projects in different regions.

The goal is to develop and verify a method for calculating the different life cycle stages production, use and end-of-life of a building. To achieve this, the calculated values for energy and emissions for different building materials for the two life cycle stages production and end-of-life are integrated in a simulation platform for urban energy demand named SimStadt [17]. SimStadt was developed to simulate the energy needed during the use stage of a building or city quarter and was extended by this work to calculate the values for embodied energy and greenhouse gases as well as the energy needed and greenhouse gases emitted during the disposal of the materials used in a building. SimStadt is designed to analyse not only one building, but to evaluate whole city quarters, cities and even regions. Since the methodology of this research is based on generic data, it can be extended and applied in future studies. This allows an assessment and comparison of different city quarters.

2. Methodology

The aim of the methodology is to define the scope of the life cycle assessment of a building. Consequently, values for the embodied energy and embodied greenhouse gases as well as values for the energy needed and greenhouse gases emitted during the disposal of building materials can be calculated. By bringing these values in relation to the operational primary energy demand, an evaluation and comparison of the entire life cycle of different building cases can be made.

2.1. Approach and definitions

The chosen approach for the calculation of the mentioned values is cradle-to-grave, which means that all stages of the life cycle of the building materials are taken into account. Material and energetic flows are crossing the system boundary on the input side; emissions to air, water and soil are crossing the system boundary on the output side, as can be seen in Fig. 1.

The chosen allocation method is cut-off, which means that the initial or first production of a material is always allocated to the primary user of the material. At the end-of-life, the primary user of a material does not receive any credit if the material is recycled. Additionally it does not receive any credit for results out of any waste treatment, e.g. for heat generated through municipal incineration. This means that waste leaves the system without any associated burdens [18].

The terms 'embodied energy' and 'embodied greenhouse gases' and 'energy needed for disposal' and 'greenhouse gases emitted during disposal' are based on the definition of the 'cumulative energy demand (CED)', in German called 'kumulierter Energieaufwand (KEA)' (see Eq. (1)) published in the guideline 'VDI 4600' by 'Verein Deutscher Ingenieure'[19].

$$CED = CED_P + CED_U + CED_D \quad (1)$$

CED: cumulative energy demand [kWh/kg], CED_P: cumulative energy demand for production [kWh/kg], CED_U : cumulative energy demand for use [kWh/m^2], CED_D: cumulative energy demand for disposal [kWh/kg].

Since the definition of each cumulative energy demand is rather broad and leaves room for interpretation, more specific definitions are needed to specify the energy and emission values.

The embodied energy and embodied greenhouse gases of the production stage are based on the definition of the CED_P and are further defined by dividing the production stage into more specific stages. The energy needed and greenhouse gases emitted during the end-of-life stage are based on the definition of the CED_D and are also further defined by dividing the end-of-life stage into more specific stages. During the use stage, no energy is needed for the building materials and consequently the CED_U is, for reasons of completeness, taken into account with the value zero.

The three life cycle stages are divided into seven substages (see Fig. 2). The different material and energetic flows are assigned to the life cycle stages mentioned below.

Production stage: The production stage consists of the extraction of raw materials and manufacturing of building materials, the transportation of the materials to site and their assembly. In case of refurbishment, the additional energy and greenhouse gases for the refurbishment process are added to the assembly substage. The combination of the values from each substage amounts to the embodied energy related to 1 kg of building material and 1 m^2 of window area respectively with the unit kWh/kg and kWh/m^2. The windows need to be assessed by their area instead of their weight, since SimStadt uses this unit for the calculation. Subsequently the embodied greenhouse gases result from the addition of the respective emissions from these substages. The units are kg CO_2-eq./kg and kg CO_2-eq./m^2. The carbon dioxide equivalent (CO_2-eq.) is a unit which indicates the global warming potential of a product or a process. It is composed of different greenhouse gases (e.g. methane, ozone or nitrous gases) and the value is converted to the amount of CO_2 which would have the same global warming potential as CO_2 alone.

Use stage: Use is the only substage during the use stage. The unit is kWh/m^2 and refers to the heated floor area.

End-of-life stage: The end-of-life stage consists of the demolition of the building, the transportation of waste materials and their following treatment. The combination of the values from these substages results in the energy related to the disposal of 1 kg building material and 1 m^2 of window area respectively with the unit kWh/kg and kWh/m^2; the greenhouse gases emitted during disposal result from the addition of the respective emissions from these substages. The units are kg CO_2-eq./kg and kg CO_2-eq./m^2.

2.2. Software and assumptions

Different types of software are used to calculate the values needed for the assessment of the life cycle of buildings and city quarters.

The software SimStadt [17], developed at the University of Applied Sciences Stuttgart, uses a CityGML-file, which includes a 3D model of a building or city quarter. The software links this model to a building physics library, which includes the material composition of various building types.

This library is based on a study called 'Deutsche Wohngebäudetypologie' published by 'Institut Wohnen und Umwelt (IWU)' [20]. Contents of this study are among others several building types sorted by different periods of time, starting in 1859 up to newly constructed buildings as of 2016, including different energetic standards like the minimal requirements according to the German Energy Saving Ordinance [8] and higher standards. The KfW ('Kreditanstalt für Wiederaufbau') [21] grants different types of credit according to the energetic standard of the newly constructed building. Also included are two different refurbishment standards for existing buildings; 'medium refurbishment' corresponds roughly to a standard between KfW70 and KfW100 and