Journal of Cleaner Production xxx (2015) 1–10

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study

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ARTICLE INFO

Article history:
Received 19 January 2015
Received in revised form
7 August 2015
Accepted 25 August 2015
Available online xxx

Keywords:
Sustainable development
Energy efficiency
Life cycle assessment
SimaPro
MCDA
Life cycle costs

ABSTRACT

Improvements in the design of energy efficient houses lead to the increase of environmental impact in construction and demolition phases, creating a need to investigate the use of construction materials more carefully. The approach presented herein is based on a complex system of criteria that allows performing comprehensive evaluation of the alternative design solutions. This article presents a case study which illustrates the proposed approach. In this study we estimate the environmental impacts of three alternative types of envelopes (masonry, log and timber frame) of an energy efficient single-family house, simultaneously identifying the most rational alternative according to the considered criteria (reduction of expenses, non-renewable primary energy, Green House Gases and ozone layer depletion). Results of the life cycle assessment and life cycle cost analysis are evaluated by the multi-criteria decision analysis method and criteria weights of impact categories are determined by the analytic hierarchy process method. The results obtained with the life cycle assessment and life cycle cost show that in the case of buildings, which are designed according to the passive house requirements, the share of the embodied input and output flows in the whole life cycle generally constitutes more than 1/3.

1. Introduction

The construction sector plays an important role in the European economy. It generates almost 10% of GDP and provides 20 million jobs (European Commission, 2012). Construction is also a major consumer of natural resources. The energy performance of buildings and resource efficiency in manufacturing, transport and the use of products for the construction of buildings have an important impact on energy, climate change and the environment. Residential building sector is one of the biggest consumers of energy with one of the largest cost-effective energy saving potentials (Commission of the European Communities, 2006). Single-family houses are also identified as significantly important, since they are responsible for 60% of the EU CO_2 emission from residential sector (Petersdorff et al., 2006).

The increase of energy efficiency in the buildings' sector is also one of the key objectives of the European Union energy policy. With the adoption of recast Directive 2010/31/EU (European Parliament and the Council, 2010) – the main legislative measure in buildings' energy efficiency sector, Member States are obliged to move towards new and retrofitted nearly-zero energy buildings by 2020. Directive encourages architects and planners to properly consider the optimal combination of improvements in energy efficiency and the use of energy from renewable sources when planning, designing, building and renovating industrial or residential areas. Directive on energy efficiency 2012/27/EU (European Parliament and the Council of the European Union, 2012) also aims at increasing energy efficiency in buildings. However, within the framework of both directives, the energy efficiency is understood as a decrease of operational energy consumption of the building. Meanwhile, Directive 2009/125/EC on eco-design (European Parliament and the Council of the European Union, 2009) has

Abbreviations: AEC, architects, engineers and constructors; AHP, Analytic Hierarchy Process; BIM, Building information modelling; COPRAS, COmplex PRoportional ASsesment; CR, consistency ratio; DHW, domestic hot water; GDP, gross domestic product; GHG, Green House Gases; GW, global warming; LCA, life cycle assessment; LCC, life cycle cost; MCDA, Multi Criteria Decision Analysis; MCDM, Multi Criteria Decision Making; OLD, ozone layer depletion; PE, primary energy.

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http://dx.doi.org/10.1016/j.jclepro.2015.08.103
0959-6526/

established a framework for the setting of eco-design requirements for the energy-using products which are installed and used in a building. However, the building itself with its envelope is not considered as one complex product having significant potential for being improved in order to reduce environmental impacts and to achieve energy savings through better design. Multiple researchers have come to the conclusion that the demand for operating energy reduction appears to be the most important aspect for the design of energy efficient buildings (Kofoworola and Gheewala, 2009; Scheuer et al., 2003; Zhang et al., 2006; Ramesh et al., 2010; Rosselló-Batle et al., 2010; Sharma et al., 2011). However, this may be applied just for standard buildings. Following the recent requirements of the above-mentioned Directives, buildings' energy consumption during the operational phase will continue decreasing. The improvements to design a more energy efficient building, as a rule, require more materials and, consequently, the environmental impact of the building in its construction and demolition phases is likely to increase significantly. The increasing energy demand for an energy efficient building has already been illustrated by some authors (Blengini and Di Carlo, 2010; Blom et al., 2010; Motuziene et al., 2013). Therefore, Peuportier et al. (2013) proposes to link thermal simulation and LCA as a relevant mean in order to assess and possibly improve the performance of a building on a global basis.

In the processes of sustainable building design, the technological, institutional and cultural cooperation of architects, engineers and constructors (AEC) is very important. Unfortunately, due to the large number and diversity of participants the construction sector is characterised as a conservative and fragmented decision-making process and this results in innovation avoidance and missed opportunities (Altwies and Nemet, 2013). However, these problems are being attended to. The scientific community has recently emphasized the necessity of integration of new concepts, theories and approaches (Santibanez-Gonzalez and Huisingh, 2015). Hence, an overall judgment on building sustainability should encompass all the life phases (Blengini and Di Carlo, 2010; Blom et al., 2010). A holistic approach is also needed, as separate improvements might not be effective in a life cycle perspective. Such systematic approaches begin with the quantitative environmental assessment of the building designs and are followed by the iterative design and engineered improvement of the building materials and systems which reduce the impact and improve the overall sustainability (Russell-Smith et al., 2015).

The robust and flexible tools are a step towards comparability and transparency of any process, including LCA. LCA has now various evaluation indicators – from the primary energy to the individual components of pollution. Neither of them can be completely avoided. However, for the decision-making it is not enough to use only the aforementioned indicators. Many studies on environmental impacts during the operation phase of a building have been performed as well as the analysis of life cycle costs, but there are still many questions and uncertainties regarding the long-term and combined effects (Johansson, 2009).

Although LCA is a powerful tool to assess the environmental impacts, it does not actually solve all dilemmas or facilitate the selection process – it is not a decision-making method. For this reason, Multi Criteria Decision Analysis often appears here like a complementary tool to LCA or LCC (Bachmann, 2012; Mora et al., 2011). There are many attempts to apply different multi-criteria analysis methods, combine them or improve some gaps by developing new methods. One of the best known and widely used analytical techniques for the complex decision making problems is the analytic hierarchy process (AHP). It has originally been proposed by Saaty (2008) as a multi-criteria decision-making tool, which attempts to determine weighting factors for the criteria under consideration through pairwise comparisons (Lipuščcek et al., 2010). Zavadskas et al. (2014) presents a synopsis of numerous publications, which describe the use of traditional MCDM methods and some of the relatively recently developed methods. While some researchers focus on developing new methods, combining multi-criteria analysis and LCA, others (Flager et al., 2012; Hermann et al., 2007) have developed tools that could be adapted to suit the needs of organisation activities. Obviously, the MCDM is a great tool for the result generation in multidimensional assessment, however, its application that analyses objects in terms of the LCA is not common.

The total energy and ecological efficiency of modern buildings increasingly depends not only on their operational phase, but also on the selection of the building materials. This additional component can be evaluated using the LCA and supplemented by the economic evaluation which is performed using the LCC. Searching for the fully effective solutions, additional application of MCDA is appropriate. The proper combination of three methods, mentioned above, together with the buildings' energy simulation, enable to fill a major gap of knowledge.

The aim of this study is to propose the general algorithm for the selection of the most rational design solution, that combines LCA, LCC and MCDA methods, and to illustrate its performance in a case study of the building envelope selection for the energy efficient single-family house. The presented approach is based on a complex system of criteria that enables comprehensive evaluation of the alternative design solutions. The proposed algorithm can be applied on a large scale by using Building information modelling (BIM) tools and is applicable for different types of buildings at different locations.

2. Methods

This chapter covers the proposed algorithm and description of methods used for the building analysis. The proposed algorithm, combining the building energy simulation, LCA, LCC and MCDM, is presented in Fig. 1. The calculation procedure can be expressed in the following steps:

Step 1. Modelling a house in DesignBuilder. Here the different building envelope alternatives are created. The building services (lighting, heating, domestic water and ventilation systems) are modelled, and their operating mode is set. As a result, the dynamic energy simulation for the alternative building models in DesignBuilder is performed. The results show the energy demand for the operational stage of the building. The construction materials and their quantities for the building structures and service systems are used in further two steps.

Step 2. Life cycle assessment (Chapter 2.1.) is used to estimate the environmental impacts of the alternative envelopes. As a result, the indicator values for three impact categories – primary energy demand (PE), global warming (GW) potential, and ozone layer depletion (OLD) – are set for each alternative.

Step 3. LCC analysis includes the initial investment and the replacement costs, and the annually recurring operating, maintenance, repair and energy costs. Here the investment costs are determined according to the quantities of the materials for the construction and engineering systems, while the operating and energy costs are determined according to the energy simulation results in DesignBuilder.

Step 4. Decision making process (Chapter 2.2.) is used in order to choose the best building construction alternative according to the following criteria: PE, GW, OLD, and LCC results. Here the experts take part in the survey, where AHP and Saaty's evaluation scale are used to determine the criteria weights. The selection problem of the best alternative is analysed using