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Life cycle assessment and data envelopment analysis approach for the selection of building components according to their environmental impact efficiency: a case study for external walls

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A B S T R A C T

Environmental criteria have to be taken into account when it comes to selecting a specific building component among a set of candidates with the same function. This article presents a methodological approach – based on both Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) – for the selection of building components according to their environmental impact efficiency. A three-step LCA + DEA approach is proposed and tested through a case study for 175 external walls. The three steps of this approach involve data collection, life cycle impact assessment, and DEA of the sample of building components using environmental impacts as DEA inputs. Overall, from the availability of multiple data on the material and energy flows of each building component, the method provides decision makers with eco-efficiency scores and environmental benchmarks. A cautious definition of the set of candidates is critical, as relative efficiency scores are calculated. Data availability and functional homogeneity regarding the building components evaluated are the key requirements for the general use of the method. The three-step LCA + DEA approach proposed is proven to be a useful method to enhance decision making and environmental benchmarking in the building sector.

1. Introduction

The building sector accounts for ca. 50% of the total energy consumption in Europe and 40% of the greenhouse gas (GHG) emissions (Arena and de Rosa, 2003; European Commission, 2013), as well as for 24% of the raw materials extracted from the lithosphere at the world level (Zabalza Bribián et al., 2011). Hence, this sector arises as a major contributor to environmental impacts.

Energy reduction strategies in buildings hold a great potential for offsetting GHG emissions in the near- and long-term (Kharecha et al., 2010; Metz et al., 2007). This implies the need for efficient design and sustainability-oriented construction policies, including the choice of construction materials with suitable life-cycle environmental profiles and recycling potentials (Thormark, 2002).

Life Cycle Assessment (LCA) is a well-established methodology for the evaluation of the potential environmental impacts of products (ISO, 2006a,b). LCA has already been used for environmental evaluation in the building sector (Zabalza Bribián et al., 2009). Basbagill et al. (2013) highlighted the importance of building's early stage design when determining the environmental impacts of a building. They proposed a decision support method based on the integration of building information modelling (BIM), LCA and energy simulation to help designers predict the decisions that most critically determine a building's embodied impact.

Ortiz (2009) analysed 33 LCA case studies (spanning from 2000 to 2009) belonging to the construction sector. 58% of these case studies applied LCA to building materials and components, while 42% applied LCA to the whole process of constructions. Three distinguishing features of the analysed studies were identified (Ortiz, 2009): (i) the type of construction (with three common scenarios: dwellings, commercial buildings, and civil engineering constructions); (ii) the lack of consideration of cost aspects (except for those studies considering shadow prices); and (iii) the functional unit (FU) used as the reference amount of the function delivered by the

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system (usually 1 kg of final product for the LCAs of building materials, and 1 m^2 of usable floor area for the LCAs of dwellings).

In the life cycle of a building, operational energy services (e.g., heating, ventilation and air conditioning, HVAC) usually contribute to approximately 80% of the total energy consumption (Ihm et al., 2009; Juan et al., 2010; Ramesh et al., 2010; Sharma et al., 2011). Cuéllar-Franca and Azapagic (2012) performed an LCA study of the three most common types of house in the UK, showing that the large majority of the impact in terms of global warming potential (GWP) comes from the use stage.

Sartori and Hestnes (2007) performed a literature review on energy use in the life cycle of conventional and low-energy buildings (60 cases from 9 countries). The authors observed that the increased awareness of environmental problems has led to changes in the relative importance of operating and embodied energy. In particular, the energy demand in the use phase of the building has decreased, but at the expense of using energy-intensive materials (with high embodied energy and high insulation capacity) both in the building envelope and in technical installations. Thus, the benefit of reducing energy consumption in the use phase of the building is largely counterbalanced by similar increases in the embodied energy (Sartori and Hestnes, 2007; Winther and Hestnes, 1999). In this respect, some authors (Huberman and Pearlmutter, 2008; Zabalza Bribián et al., 2009) claim that ca. 20% of the cumulative energy demand of the building could be saved by replacing high embodied energy materials (e.g., reinforced concrete) with alternative materials (such as hollow concrete blocks, stabilised soil blocks or fly ashes).

Other studies focus on the environmental assessment of single building materials or groups of materials. For instance, Sun et al. (2003) identified 16 groups of materials used in building construction and their environmental impact drivers by using the clustering criteria of material type and environmental indicator. An aggregated LCA single score was used as environmental indicator for the clustering. Asif et al. (2007) evaluated eight different construction materials of relevance for a Scottish house (viz., timber, glass, concrete, aluminium, ceramic tiles, plaster board, slate and damp course). The study identified concrete, timber and ceramic tiles as the three major energy expensive materials.

Within this context, sensible decision-making processes are required when it comes to selecting a specific building component among a set of candidates fulfilling the same function. In particular, in addition to socioeconomic criteria, environmental aspects have to be taken into account. In this respect, eco-efficient components should be the preferred option. The term “building components” refers herein to the smallest elements of the building showing comparable relevant properties and thus allowing for the definition of comparable functions (Kellenberger and Althaus, 2009).

This article presents a methodological approach for the selection or short-listing of building components according to their relative eco-efficiency, measured as environmental impact efficiency (Lozano et al., 2010). The method is applicable at the level of components, thus avoiding the direct comparison of single materials (which is usually inappropriate as the properties of the materials can vary in a significant way and therefore an unambiguous definition of their common function might not be possible) (Kellenberger and Althaus, 2009). The building components used in this article to show the applicability of the method are samples of external walls of 1 m^2 of surface. In this respect, current literature seems to suffer from the lack of a methodology to select efficient building components with sound environmental profiles. Even though tools provided with a holistic perspective have been developed (Ding, 2008; Ortiz et al., 2009), they apply at the building level but not at the component level, e.g. the “sustainability index” presented in Langston and Ding (2002).

The LCA + DEA methodology, based on the combined use of LCA and Data Envelopment Analysis (DEA), has recently been proposed as a framework for the evaluation of operational and environmental aspects (Iribarren, 2010). DEA is a linear programming methodology to measure the relative efficiency of multiple similar entities (named decision making units, DMUs) that involve multiple inputs and outputs (Cooper et al., 2007). To date, several LCA + DEA approaches have been developed to deal with a number of analytical challenges such as the quantitative verification of the link between operational efficiency and environmental impacts (Lozano et al., 2009; Vázquez-Rowe and Iribarren, 2014; Vázquez-Rowe et al., 2010), the simultaneous benchmarking of operational and environmental items (Lozano et al., 2010), multidimensional sustainability assessment (Iribarren and Vázquez-Rowe, 2013), and eco-centric benchmarking (Iribarren et al., 2014). The ultimate goal of all these approaches is to facilitate decision-making processes through the analysis of a thorough inventory of data from multiple homogenous entities (i.e., multiple DMUs).

Regarding decision making in the building sector, the present paper develops and exemplifies a synergistic LCA + DEA approach oriented towards environmental sustainability when selecting the most suitable option among a set of comparable (and therefore mutually replaceable) building components. While the LCA + DEA methodology has been extensively used in the agri-food sector (Avadí et al., 2014; Iribarren et al., 2011; Lozano et al., 2009, 2010; Mohammadi et al., 2013, 2014; Vázquez-Rowe et al., 2010, 2011, 2012) and, to a lesser extent, in the energy sector (Iribarren et al., 2013, 2014), its use in the building sector has not yet been examined in detail.

2. Material and methods

2.1. Definition of the case study

The LCA + DEA methodology can be applied to any sector provided that input and output data are available for a set of multiple homogenous entities (DMUs) (Iribarren et al., 2010). In order to exemplify and discuss the LCA + DEA approach for building components presented later in Section 2.2, a case study for external walls is developed. The objective of the study is to determine (in terms of relative eco-efficiency) the most suitable external wall configuration(s) among a set of 175 external walls used in common construction practice. In DEA terminology, each external wall constitutes a DMU (Fig. 1). The FU of the study was defined as 1.00 m^2 of external (visible) surface of each DMU. As can be observed in Fig. 1, each wall configuration involves a specific combination of material layers and results in different environmental impacts.

Table 1 presents a description of the sample of 175 external walls to be assessed. The sample is based on expert knowledge

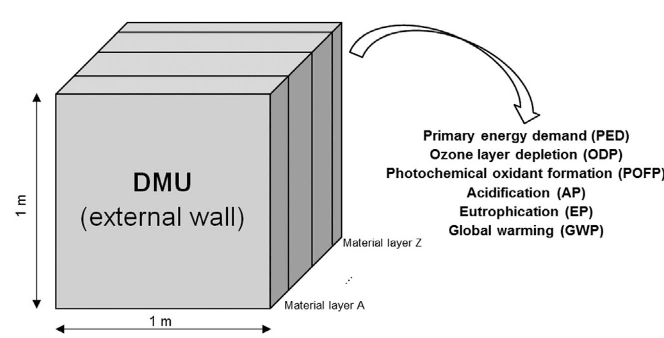

Fig. 1. Simplified representation of the DMU considered.