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Decision-making tool for the assessment and selection of construction processes based on environmental criteria: Application to precast and cast-in-situ alternatives

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ABSTRACT

This paper presents a quantitative environmental impact assessment tool for the decision making of construction processes including structures, infrastructures and buildings by means of an Environmental Impact Index (EII) to be applied at design and/or construction stages. The research is based on multi-attribute utility theory, interviews with experts representatives of the different stakeholders in construction, and an analysis of fifty-nine European and Spanish environmental legislative acts. The resulting tool was applied to two construction alternatives for road drains (one precast and one cast-in-place). The findings show that the tool enables the prioritisation of construction processes and the selection of the best alternative in terms of environmental impact and that the results are stable to reasonable weight variations. The tool contributes to decision making in the context of project management in construction: it can help professionals in public administration, and design and construction companies. It helps to quantify the cradle-to-gate impact of construction work, which has usually been less studied than the operational impact in the life-cycle assessment of buildings. The tool is being piloted in construction projects of the Barcelona City Council.

1. Introduction

The construction industry is one of the largest consumers of energy, material resources and water, and it is responsible for a significant portion of pollution through its harmful emissions and waste (Bakhoum and Brown, 2012; Huang et al., 2013; Li et al., 2016). According to Eurostat (2017b), the domestic material consumption in the EU accounted for 6.6 million tonnes in 2016 from which 46% were non-metallic minerals including sand and gravel, which are mainly used by the construction industry. Natural aggregates are regarded as an enormous natural resource at the global level, but their supply might be regionally constrained due to their overexploitation in construction (Ioannidou et al., 2017). In 2014, the total waste and total hazardous waste generated in the EU amounted to 2503 and 95 million tonnes respectively, with a construction contribution of 868 (35%) and 16 (17%) million tonnes respectively (Eurostat, 2017a). Therefore, it is important to be conscious of the production of waste in construction and to prevent its generation in the early stages of construction projects (Udawatta et al., 2015). The ineffective waste management in construction is due to a lack of preventive solutions (Ajayi et al., 2015).

Making construction more environmentally friendly improves efficiency and profits. These improvements result from the efficient use of resources, energy savings, increased recycling, reduced waste disposal costs and lower transport costs because of local suppliers (ICE et al., 2002). The selection of the construction process has key implications on the environmental performance (Toller et al., 2013). The environmental impact of construction work should thus be considered in the design of the construction process and during the construction work itself.

There is a lack of information regarding sustainability related to construction (Bakhoum and Brown, 2012). Modest literature focus towards energy reduction within the construction process (Davies et al., 2013). It is difficult to arrive at greenhouse gas (GHG) emission estimates that can be reliably used to discriminate between alternatives due to the uncertain and non-prototypical nature of construction processes (Cass and Mukherjee, 2011). Quantifying civil engineering projects in terms of sustainability is a new challenge for the civil engineering industry (Spencer et al., 2012).

The environmental assessment of buildings seems to be more developed than that of the infrastructures. Nevertheless, Ng et al. (2013) found that around a half of the indicators of six widely recognised building environmental assessment tools (BREEAM, BEAM Plus, LEED,

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CASBEE, Green Mark, and Green Star) are qualitative, not quantitative, and that they lack a quantitative method to analyse life-cycle CO_2 emissions.

Cradle-to-gate impacts in buildings (those from material extraction, manufacturing, transport to site, and onsite construction) are often ignored because they have historically been outweighed by operational impacts (Davies et al., 2013; Dimoudi and Tompa, 2008; Hong et al., 2014; Ng et al., 2013; Ortiz et al., 2010; Russell-Smith and Lepech, 2015). According to a review performed by Faludi and Lepech (2012), occupational impacts account for 90–95% of life-cycle energy consumption, 80% of life-cycle CO_2 emissions and 65% of life-cycle SO_2 and NO_x emissions. However, cradle-to-gate impacts become a larger percentage of a building's total life cycle impacts as the use phase impacts decrease due to more efficient systems (Motuzienė et al., 2016). In a study performed by Faludi and Lepech (2012), the cradle-to-gate impact of a prefabricated commercial building with 30% of power supplied by photovoltaics is a third of the total life-cycle environmental impact.

The main objective of this research is to provide a tool that helps to choose the best construction process in terms of environmental impact for a given project once the main characteristics of the project have been defined. A second objective is to provide a tool to compare the real environmental impact produced by a construction work with the impact predicted from the project.

The research presented in this paper addresses these challenges and defines a new systematic quantitative tool with the following key strengths: (1) it is a useful tool for comparing construction alternatives, (2) it quantifies the cradle-to-gate impact of construction work, which has usually been less studied than operational impact in the life-cycle assessment of buildings, (3) it can be applied to different types of construction work including structures, infrastructures and buildings, and (4) it can be applied at both pre-construction stage planning and at construction stage for monitoring.

2. Methods

Multi-criteria decision analysis is a valuable tool to assist the decision maker with the decision-making process and can be used to evaluate the environmental impact of construction work. The five main multi-criteria decision theories (ordinal multi-criteria methods, multi-objective mathematical programming, multi-attribute utility theory, outranking relation theory and preference disaggregation analysis) and their methods have been analysed for the research. The widely known multi-attribute utility theory (Keeney and Raiffa, 1976) has been selected for decision-making of construction processes as it helps solve discrete problems, it can be understood intuitively and it is based on a solid foundation (Casanovas-Rubio, 2014). It has been successfully applied to decision making in construction (Arif et al., 2015; Perera et al., 2016) and to evaluate sustainability in construction, including the environmental impact (de la Fuente et al., 2016; Wei et al., 2016). Based on the multi-attribute utility theory, new criteria, subcriteria, weights and indicators have been defined for developing the tool presented in this paper. Fig. 1 shows the steps followed to develop the tool. These steps are those of the multi-attribute utility theory adapted to the environmental impact of construction work.

2.1. Establishing the limits

The tool is defined to compare different construction processes (alternatives) for the same or very similar finished construction and same performance, thus, with the same environmental impact during the use phase. Consequently, the use phase does not help to discriminate between alternatives and, therefore, is not included in the study. The comparison focuses on the cradle-to-gate stages (the construction work itself and the previous stages) because they help to discriminate between construction processes (Fig. 2). Hence, the tool considers the embodied environmental impacts of construction materials.

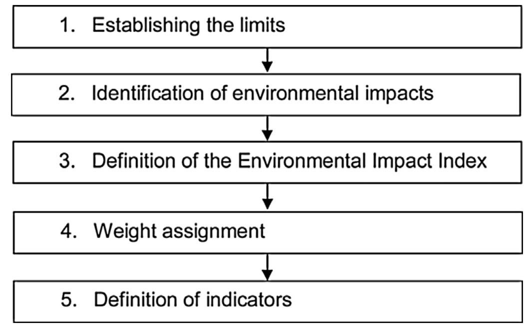

Fig. 1. The main steps followed to develop the environmental impact model.

2.2. Identification of environmental impacts

The identification of the environmental impacts caused by construction work was based on a first round of interviews with experts in decision making in construction, an analysis of fifty-nine European and Spanish legislative acts on environmental matters and the publications cited further on. The number of panel members for the first round of interviews was eleven representing the different stakeholders in construction: local, regional and state public administration, construction companies, environmental and engineering consultancy, concessionaires, academia and civil engineer associations. A larger number of European and Spanish environmental legislative acts were initially consulted. Those found to be more relevant to the research were analysed and are listed in Table 1.

The environmental impacts identified in this step are presented in Fig. 3. They are classified into three criteria and twelve subcriteria. The three criteria correspond to the main three aspects of construction work that cause an impact: input, output and interaction with the environment.

2.3. Environmental impact index (EII)

The Environmental Impact Index (EII_i) of the i construction process (alternative) is a measure of the environmental impact generated by the construction work and can be calculated according to Eq. (1). The best alternative is the one with the lowest EII.

$$EII_i = \sum_j w_j \cdot Env.\ Impact_{ij} \tag{1}$$

Where w_j is the global importance or weight assigned to the j subcriterion from Fig. 3. A set of reference weights for each type of environment is provided in Section 2.4. The $Env.\ Impact_{ij}$ is the relative environmental impact produced by the i construction process for the j subcriterion. The $Env.\ Impact_{ij}$ can be defined using an alternative as reference as presented in Eq. (2).

$$Env.\ Impact_{ij} = \frac{I_{ij}}{I_{refj}} \tag{2}$$

Where I_{ij} is the measurement of the j indicator of the i alternative and I_{refj} is the measurement of the j indicator for the alternative taken as reference. The impact of the alternatives is compared with the impact of a real alternative. The alternative taken as reference generates a relative impact equal to 1 and the remaining alternatives, a proportionate impact, higher or lower than 1. Eq. (2) can be applied when there is at least an alternative that produces all the impact types generated by the other alternatives and that alternative would be the one taken as reference. Otherwise, if a measurement of the reference alternative were 0, according to Eq. (2), the relative impact of the rest of the alternatives