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Life cycle assessment as a decision-making tool for selecting building systems in heritage intervention: Case study of Roman Theatre in Itálica, Spain

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This paper develops a method based on life cycle assessment (LCA) as a useful decision-making tool for analysing the most suitable building system for intervention in heritage sites. It focuses on a case study based on the Roman Theatre heritage site in Itálica (Spain), where several activities have taken place every two years since 2011 that require the addition of a reversible construction to support the lighting and electroacoustic elements, and improve the stage use. Based on the constraints on interventions in protected heritage settings, three suitable building options have been proposed: a standard system (option 1) and two innovative building systems (options 2 and 3). All three options are reversible, lightweight and quick assembly/disassembly systems. Option 1 is a standard aluminium system currently available on the market, while options 2 and 3 were originally created for this specific setting, using laminated wood beams and steel spatial lattices, respectively. All three lightweight construction systems that use the most common materials (aluminium, wood and steel) are compared. The LCA-based methodology aids in establishing the most suitable option for use in the construction of the case study. The LCA analysis includes the production, construction, deconstruction and end-of-life stages and two environmental indicators: global warming potential and cumulative energy demand. The results of the environmental impact of each option are compared, using the values obtained for option 1 (standard solution of frequent use) as references. In the case of option 3, the results demonstrate that the design decisions, supported by LCA, are determining factors in the choices made. The selected geometry, materials and construction system (production), assembly/disassembly process (construction/demolition) and recycling (end-of-life) reduce the environmental impact. Therefore, finally, option 3 was constructed. The results indicate that LCA can be of assistance in selecting the most suitable option for intervention at a heritage site.

1. Introduction

The increase in the world population and depletion of natural resources are currently high priority issues (Yeheyis et al., 2012; Wackernagel and Rees, 2014; Karami et al., 2015), with the construction industry considered as the worst offender in resource consumption and waste production (Gervásio et al., 2014). This industry is responsible for 40.0% of global energy consumption, 12.0% of global drinking water use and 40.0% of solid waste generation in developed countries (Agustí-Juan and Habert, 2017; Soust-Verdaguer et al., 2017), as well as 33.0% of CO_2 emissions (Gundes, 2016; Zhuguo, 2006). Owing to the pressing need for adopting measures to improve built environment sustainability, sustainable development is recognised as one of the best potential strategies for environmental impact reduction (Brockhaus et al., 2017; UNE-EN 15978, 2012). Various tools can be used in the implementation of sustainable development within the building industry (Soust-Verdaguer et al., 2017). Life cycle assessment (LCA) has been established as a decision-making support tool for

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evaluating environmental loads based on the building life cycle (Gundes, 2016; Anand and Amor, 2017) and its methodology is defined in ISO 14040:2006 (UNE-EN ISO 14040 2006), ISO 14044:2006 (UNE-EN ISO 14044 2006), and UNE EN 15978 (UNE-EN 15978 2012).

Over the past 20 years, LCA, which is of increasing importance in the scientific community and building industry, has been used to quantify and reduce the potential environmental impact of products and elements (Eleftheriadis et al., 2017; Vilches et al., 2016). Cabeza et al. (2014) reviewed the use of LCA in the building sector in the literature. Many studies on building materials or elements focusing on LCA (Sierra-Pérez et al., 2016; Liu et al., 2016; Ingrao et al., 2016; Fernádez-García et al., 2016; Guardigli et al., 2011) have carried out comparisons of the environmental impact produced. Moreover, despite the complexity of the analysis, numerous studies have been based on the evaluation of the environmental impact of complete buildings (Motuziene et al., 2016; Kylili et al., 2017; Karami et al., 2015; Atmaca and Atmaca, 2015; Asdrubali et al., 2013). However, few studies have focused on LCA and building systems in heritage sites.

Selecting the most suitable building system should be the primary concern (Pineda et al., 2017) when heritage intervention is required. Although the preservation of cultural heritage sites is a priority, reduction of the environmental impact of the building system must also be considered during the early design stages. Certain studies have demonstrated that approximately 20.0% of the global environmental impact is related to the manufacture, construction, demolition and end use of building materials in conventional buildings, where the operational stage has higher impacts. In heritage buildings, these phases could represent an even higher percentage compared to the overall impact. Given the direct influence of architects in selecting the materials, construction systems and construction processes used (Galán-Marín et al., 2015), their decision-making may be crucial in reducing the environmental impact.

According to different studies (Gómez de Cózar, 2001; Gómez-de Cózar, 2006; Gómez de Cózar et al., 2006; Gómez de Cózar et al., 2008; Gómez de Cózar & Ariza López, 2014) various strategies and factors should be taken into account during the design stage: (i) parameterisation-simulation-optimisation, (ii) light weight, (iii) industrialised processes, (iv) quick assembly, (v) quick disassembly, (vi) reversibility and (vii) reuse/recycling. These design strategies, particularly reversibility (International Council on Monuments and Sites, 2003), are essential to proper heritage intervention.

Building systems designed according to the above strategies are the most suitable for heritage site interventions. Recent interventions in heritage have, at times, added lightweight covering to archaeological sites. The most appropriate designed solutions have taken into account several design strategies mentioned above, such as light weight, industrialised processes and reversibility (Martínez Díaz, 2005). A study by Ordóñez (Ordóñez Martín, 2011) focused on an extensive review of the organisation of building models relating to heritage intervention in Spain.

Taking these design strategies into account, the building systems proposed in this paper follow the same principles as ecodesign (Lindahl, 2003). Furthermore, an optimised, lightweight, industrialised, reversible and reusable building system that can be assembled and disassembled quickly reduces costs and energy consumption (Wadel and Cuchí, 2010).

The selected case study is that of the protected heritage setting of the Roman Theatre in Itálica (Santiponce, Seville, Spain). The theatre events hosted biannually require the addition of a reversible construction that can provide adequate support for the lighting and electroacoustic stage equipment.

This study aims to develop a LCA method to assess the environmental impact, aiding decision-making during the project stage in protected heritage environments. To this end, three options for optimised, lightweight, quick assembly/disassembly, reversible and reusable systems are proposed. Considering that no minimum impact reference values exist (Rasmussen et al., 2013), option 1 (a widely used standard system) is taken as reference to establish the minimum impact to be produced by the different tested options.

This paper therefore aims to use LCA to identify the most suitable construction system for the proposed case study.

2. Methodology

The proposed method applies LCA in order to assess building solutions for intervention in a heritage site case study, merging environmental and design strategy issues. The different phases are as follows:

- Case study and building system proposal options. This phase consists of the proposal of a case study based on a heritage site. Three building system options are presented for the necessary intervention in the case study. This phase includes the definition of requirements and demands relating to the case study in order to identify the design strategies to be considered in proposing the most suitable building systems.

Furthermore, this phase includes the success degree of each building system in relation to the design strategies considered, as well as a complete definition of these building systems.

The proposed method follows ISO 14040 (UNE-EN ISO 14040 2006) and ISO 14044 (UNE-EN ISO 14044 2006), international references on LCA and EN 15978 (UNE-EN 15978 2012), the European reference on LCA for buildings. Moreover, the proposed method is based on previous studies on LCA application: Baumann and Tillman (2004) described the method, while García-Martínez (2010) developed it for LCA application to buildings. The application of this method has also been studied in several masters' dissertations (Mesa González, 2014; Gómez Pérez, 2014; Navarro Osta, 2014; Ruiz Alfonsea, 2016; Lobato Fernández, 2016; Miranda Martín, 2016; Molinero Morente, 2017).

2.1. Case study description and building system proposals

The case study examines the ancient Roman Theatre located within the ruins of the Roman city of Itálica (Santiponce, Seville, Spain) (Fig. 1). The Provincial Council of Seville commissioned architects Juan Carlos Gómez de Cózar and Santiago Bermejo Oroz to design a building system for the installations at the International Dance Festival, held at the heritage site of the Roman Theatre in Itálica.

The main requirement was for the building system design for the heritage site intervention to be dismantled easily and quickly, without altering the normal appearance of the heritage site once the event ends. Therefore, in order to enable easy disassembly and minimise damage to the heritage site, the building system must be lightweight and industrialised: an off-site construction. Furthermore, as this event is hosted biannually, the building system needs to be reversible and reusable. The building proposed system was assembled in 2011, 2013, 2015 and 2017. The requirements of this heritage site, the decision-making based on LCA tools considered in this paper and the subsequent assembly of the most suitable option therefore justify the selection of this case study.

In order to solve the problem, and bearing in mind the detailed