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Esta es la versión aceptada del artículo publicado en:

This is a accepted manuscript of a paper published in:

Journal of Cleaner Production, vol. 206, pág. 27-39

DOI: https://doi.org/10.1016/j.jclepro.2018.09.169

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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

Juan Carlos Gómez de Cózar, Antonio García Martínez, Íñigo Ariza López, Marta Ruiz Alfonsea

Abstract

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.

Keywords
Life cycle assessment, Architecture, Environmental impact, Heritage

1. Introduction

The increase in the world population and depletion of natural resources are currently high priority issues (Yeheyis et al. 2012; Wackernagel & 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 & 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 evaluating environmental loads based on the building life cycle (Gundes 2016; Anand & 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

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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 & 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 (De Cózar 2001; De Cózar 2006; De Cózar et al. 2006; De Cózar et al. 2008; De Cózar & 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 (Díaz 2005). A study by 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 & 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:

Fig. 1. Heritage site: Roman Theatre stage in Itálica.

- 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.
- Definition of main goal and scope of the study. The impact categories and life cycle stages taken into account are also detailed in this phase.
- Data inventory, organising and quantifying the materials and processes relating to the three building solutions. This phase includes the quantification of materials, transport, and processes, and their links to the environmental impact factors, using the Ecoinvent database.
- Life cycle impact assessment by means of an environmental impact calculation. Spreadsheet software is used to calculate the environmental impact of each building system in the impact categories selected.
- Results analysis. The results are compared to establish the total environmental impact of building systems and identify the one producing the least impact.

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 & 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 (González 2014; Pérez 2014; Osta 2014; Alfonsea 2016; Fernández 2016; Martín 2016; 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 (Anon n.d.) 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 requirements, the architects designed a system behind the existing wall and overhanging to support the equipment required above the stage, such as truss lighting and acoustic installations. This equipment had to be supported by an existing stone load-bearing wall and overhang the stage by 13.0 m. The optimised building design should have no front pillars or columns in order to ensure the spectator view is not obstructed.

The stage area consisted of three main elements: a) a frame structure to support the stage flooring, b) a suspended structure to support the equipment and c) a building system to support the suspended structure. Elements a) and b) used the same system for all solutions.

Based on the project requirements for the case study, three possible solutions were proposed for building systems to support the suspended structure, as follows.

- Option 1: standard solution (Fig. 2), based on the Layher® system. This consisted of a building system constructed from aluminium elements with a pre-set geometry, intended to be assembled and disassembled several times. The main advantage of this solution was the wide variety of geometric shape solutions. However, one disadvantage was the need for front pillars in this building system.
- Option 2: innovative industrialised timber system (Fig. 3a). This solution consisted of a lightweight, reversible and reusable building system that could be assembled and disassembled quickly. Constructed from laminated timber sections and tubular steel profiles, this solution had no front pillars or columns and was therefore an optimised building system. Two different options were considered for this solution:

  Option 2a: innovative timber design, painted.

  Option 2b: innovative timber design, unpainted.
- Option 3: innovative industrialised steel system (Fig. 3b). This solution consisted of an optimised, lightweight, quick assembly/disassembly, reversible and reusable building system, with profiles in tubular steel. This solution had no front pillars or columns and was therefore an optimised building system.

Option 1 was rejected during the design phase, as front supports were required for this system. However, LCA analysis of the Layher® system was considered necessary to calculate the environmental impact produced by a standard system, and these results were used as reference values for the evaluation and comparison of the results of the remaining options.

Options 2 and 3 were based on an original design of two different cantilever trusses (projected 13.0 m), balanced out behind their supports by cantilever and steel straps countering a dead load to prevent the existing wall from collapsing. The materials and geometry of the cantilever truss were different for each studied option studied. Moreover, the design strategies of both building systems were based on the following factors.

- Light weight: the reduction in materials used could minimise the environmental impact of the building systems (Monticelli et al. 2013). Therefore, the designs had to be parameterised, simulated and optimised in order to propose two lightweight case studies based on the original systems for intervention in a heritage site.
- Quick assembly and disassembly: the assembly and disassembly time had to be kept to a minimum as the case studies are ephemeral building systems. Moreover, this reduction in assembly and disassembly time could minimise the environmental impact of the building systems (Kamali & Hewage 2016).
- Reversibility: the building system needed to be disassembled so that the normal appearance of the heritage site could be preserved after the International Dance Festival.

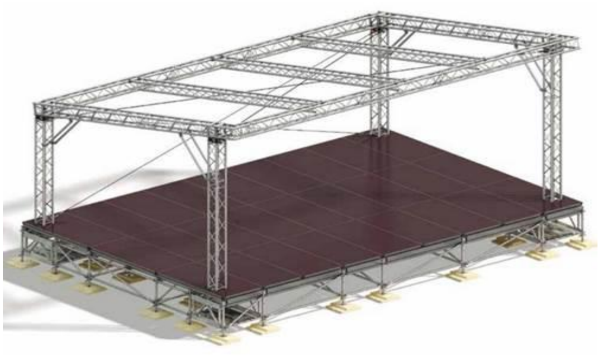

Fig. 2. Standard aluminium system (option 1).

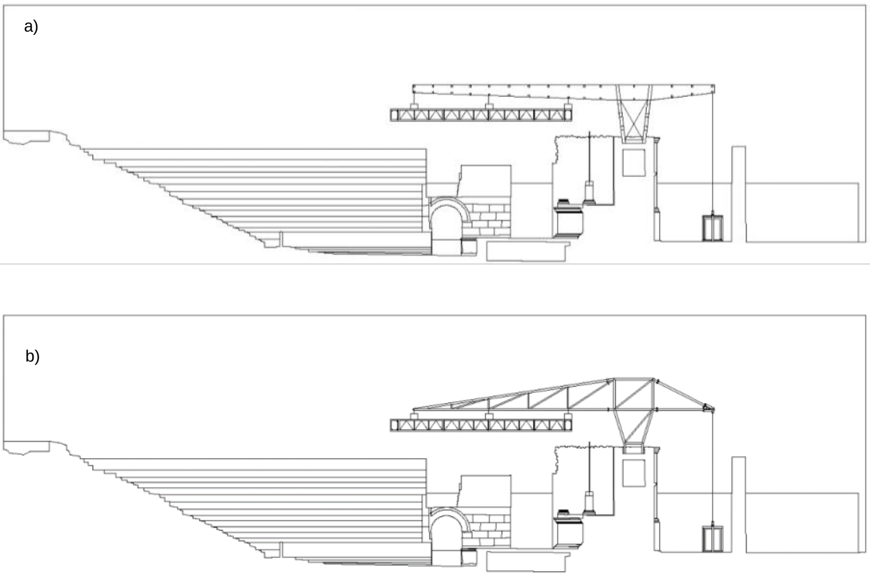

Fig. 3. Innovative systems: a) timber (option 2), b) steel (option 3).

The success degrees of these strategies in each construction system are displayed in Table 1 and explained below.

Table 1
Design strategies.

Building system	Light weight	Quick assembly	Reversibility
Option 1	14.90 kg/m^2	1 day	1 day
Option 2	139.42 kg/m^2	½ day	½ day
Option 3	98.23 kg/m^2	½ day	½ day

Light weight. This strategy relates to the mass of each construction system, and depends on the design and materials used (the stage is the same for all options and is not considered). Option 1 (with front pillars) is lighter than options 2 and 3 (without front pillars). The design strategy values displayed in Table 1 were obtained by the project architects during the option selection process.

Quick assembly and reversibility. The values for these features were obtained from previous experience acquired in the construction of similar systems. The size of the pieces for options 2 and 3 accelerates the assembly and disassembly processes.

2.2 LCA application to case studies

The LCA application follows ISO 14040 (UNE-EN ISO 14040 2006), ISO 14044 (UNE-EN ISO 14044 2006) and EN 15978 (UNE-EN 15978 2012). The method consists of four main phases: scope and goal definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation.

2.2.1 Scope and goal definition

The main goal of this study was to compare the environmental impact of three building systems designed for intervention at the Roman Theatre heritage site in Itálica (Santiponce, Seville), by merging environmental and design strategy issues.

The environmental impact categories and indicators included in the analysis were based on Galán-Marín et al. (2015) and Asdrubali et al. (2017). The authors identified the most relevant impact indicators to be taken into account in LCA building application, namely global warming potential (GWP) and cumulative energy demand (CED). Therefore, the impact indicators calculated in this study are GWP, based on the CML 2001 method, and CED.

System boundaries

According to the building system context, the most relevant LCA phases were selected based on EN 15978 (UNE-EN 15978 2012). Therefore, the stages considered in this study were production, construction and end-of-life.

The life cycle was organised into three main phases, including different modules complying with the standard classification, as follows.

- Production phase, including raw materials (A1), transport of materials to the factory (A2) and manufacture (A3) (Fig. 4).

- Construction/deconstruction phase, including transport to the construction site (A4), the construction process (A5) (Fig. 5), the deconstruction process (C1) and transport to the waste or recycling plant (C2).

- End-of-life phase, including waste processing for reuse, recovery or/and recycling (C3) and final disposal (C4).

The lifespan considered for the case studies was 50 years, with the building system to be assembled and disassembled every two years.

The use stages B1 to 7 were not included in the system boundaries as the case studies were ephemeral building systems. Several authors have focused their studies on embodied and operational energy over the entire life cycle (Langston & Langston 2008). However, as operational energy throughout the use stage is not relevant, it is not considered in this paper. The study focuses on the design strategies and materials of the case studies analysed.

Fig. 4. Production stage of option 3.

Fig. 5. Construction stage of option 3.

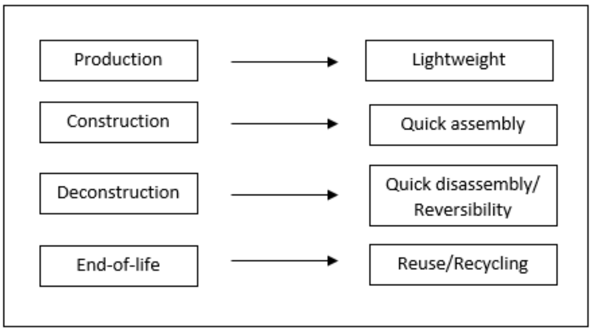

Fig. 6. LCA stages and design strategies.

A relationship was established between the life cycle stages considered and the design strategies defined, in order to identify the most appropriate construction system (Fig. 6).

Allocation

A recycling scenario was established for metal components such as steel and aluminium in structural elements. It was proposed to sell these metal elements as scrap, following information from the Ecoinvent database version 2.0 (Frischknecht et al. 2007).

Functional unit

The functional unit considered in the study was the building system.

Limitations and assumptions

Real scenarios for the assembly and disassembly cycles were assumed, and the temporary structure is constructed every two years and used over a two-month period. For energy quantification during the construction and deconstruction phase, the proportions of the volume of building materials used as well as the diesel and electricity consumed were taken into account following the recommendations of Kellenberger (2004). Processes relating to health and safety measures during the construction processes (individual protection gear, perimeter security system, temporary fences) were ignored. The use stage phase was not considered and the energy consumption during the operation of the building systems was excluded from the system boundaries. The disposal scenario for end-of-life assumes that the steel and aluminum are recycled, while concrete and wood are sent to landfill.

2.2.2 LCI

The LCI consists of the quantification of materials, processes and elements included in the system (UNE-EN ISO 14040 2006). This phase was organised and applied based on García-Martínez (2010); therefore, the LCI stage was classified into three phases: inventory of materials; inventory of transport, construction and deconstruction processes; and inventory of end-of-life processes.

Inventory of materials

The inventory of materials quantifies the materials constituting the three building systems.

This study examined five main materials in the building systems analysed in the case studies, as follows. (i) Aluminium in the structural tubes and ancillary elements of the Layher® standard system; in the platform supporting the plywood floor; and in one of the options of the suspended structure for supporting the equipment. (ii) Rolled coated steel in the structural tubes and other structural elements such as plates, rods, bars and beams. (iii) Glued laminated timber in the girders used in one building system solution and in the plywood floor. (iv) Concrete used as ballast in the cantilever steel truss and laminated timber solution. (v) Organic salt for wood preservation and acrylic paint dispersion, both for wood protection. The materials inventory is displayed in Table 2.

Table 2
Material quantification.

	Option 1		Option 2a		Option 2b		Option 3	
Material	Mass (kg)	Vol. (m^3)	Mass (kg)	Vol. (m^3)	Mass (kg)	Vol. (m^3)	Mass (kg)	Vol. (m^3)
Steel	726.87	0.09	2470.75	0.32	2470.75	0.32	5470.71	0.70
Aluminium	13480.40	4.99	11617.40	4.75	11617.40	4.75	11617.40	4.75
Timber	2520.00	3.36	9843.51	16.68	9843.51	16.68	2520.00	3.36
Concrete	0.00	0.00	12000.00	4.80	12000.00	4.80	12000.00	4.80
Paint for steel	0.00	0.00	23.88	0.02	23.88	0.02	110.86	0.09
Wood preservative	0.00	0.00	266.31	0.20	266.31	0.20	0.00	0.00
Wood paint	0.00	0.00	254.87	0.20	834.11	0.64	0.00	0.00
Total	16727.27	8.45	36476.73	26.96	37055.97	27.41	31718.97	13.70

Inventory of transport, assembly and disassembly processes

This inventory quantifies the processes relating to the assembly/disassembly stage.

The elements and materials were acquired and transported by truck (32 ton) from the factory to a storage building in Dos Hermanas (Spain). The aluminium components were manufactured in Eibensbach (Germany), while the steel, timber elements and protective paint were manufactured in Álava (Spain). Every two years, the building system is transported by a 16-ton truck 10.75 km from the storage building to the site and back to the storage building after use. Every two years, the building system is assembled and disassembled at the heritage site. At the end of its life cycle, all of the components are transported by truck (16 ton) to a final disposal site 20.90 km from the building site.

The transport, construction and deconstruction processes were measured using the values from the materials inventory (Table 2), together with the values in Table 3 relating to the electricity and diesel consumed during the assembly/disassembly stage, as defined by Kellenberger (2004). The energy consumption inventory was based on the method of Kellenberger (2004).

Table 3
Site energy consumption.

Primary energy consumption	(MJ/m^3 material)	(MJ/m^3 building)
Construction	481	72.15
Refurbishment	741	111.15
Demolition	370	55.50
Total	1222	183.30
Diesel consumption (70%) (diesel in building machine)	855	128.25
Electricity (30%) (Swiss consumption mix)	136	20.40

Inventory of final disposal processes

This inventory consists of the quantification of materials and elements from the disassembly stage.

The metal elements (steel and aluminium) were considered as recyclable. The remaining materials and elements were to be sent to landfill, which is the most frequent end-of-life scenario. Table 3 displays the quantification of inventory materials for final disposal.

LCIA

In this study, the LCIA was calculated based on the quantification of materials and processes, as well as the Ecoinvent database version 2.0 (Frischknecht et al. 2007). Ecoinvent is the most widely used database in LCA applications (Soust-Verdaguer et al. 2016) and contains the environmental impacts of various materials, elements and processes during each life cycle stage.

According to ISO 14044 (UNE-EN ISO 14044 2006), LCIA can be used to evaluate the performance and environmental impact of a project based on a functional unit. This study focuses on the analysis of the following impact indicators:

- cumulative energy demand, CED [TJ]; and
- global warming potential, GWP 100, CML 2001 [Ton CO_2-Eq].

Table 4 displays the unitary environmental impact values for the CED and GWP impact indicators obtained from the Ecoinvent database.

Table 4
Inventory of materials used and corresponding names in Ecoinvent database; unitary values for GWP and CED.

Component	ID	Name (Ecoinvent)	Units	GWP 100a GLO kg CO_2-Eq CML 2001 climate change Mean value	GLO MJ-Eq CED
Steel	1141	Reinforced steel, at plant	kg	1.34	20.94
Aluminium	1054	Aluminium, primary, at plant	kg	11.59	200.67
Timber	2448	Glued laminated timber, outdoor use, at plant	m^3	-592.80	17471.40
Concrete	504	Concrete, normal, at plant	m^3	265.22	1447.23
Paint for steel	1674	Polyester resin, unsaturated, at plant	kg	7.03	123.57
Wood preservative	1682	Wood preservative, organic salt, Cr-free, at plant	kg	2.94	72.59
Wood paint	1667	Acrylic dispersion, 65% in H_2O, at plant	kg	1.99	1.99
Transport 16 t	1940	Transport, 16 t lorry	tkm	0.32	5.27
Transport 32 t	1943	Transport, 32 t lorry	tkm	0.17	2.81
Electricity	698	Electricity mix, Spain (construction)	kWh	0.50	10.90
Diesel	559	Diesel, consumed in building machinery	MJ	0.09	1.38
Recycling of steel	2156	Disposal, building, reinforcement steel, to recycling	kg	0.06	0.86
Recycling of aluminium	2215	Disposal, aluminium, 0% water, to sanitary landfill	kg	0.02	0.55
Wood, final disposal	2052	Disposal, building, waste wood, untreated, to final disposal	kg	0.01	0.20
Concrete, final disposal	2149	Disposal, building, concrete, not reinforced, to sorting plant	kg	0.01	0.32

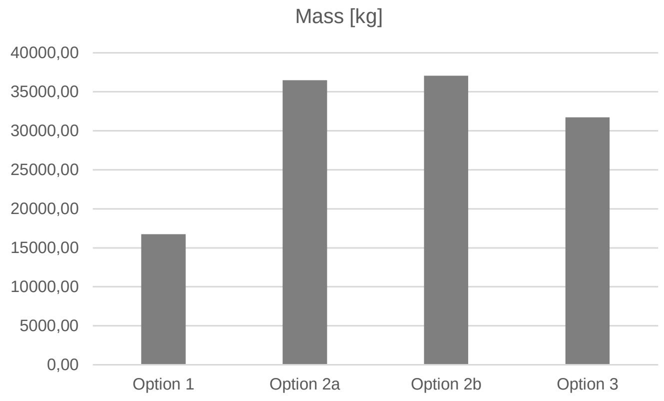

Fig. 7. Masses of building systems.

3. Results

The masses of the building systems were analysed (Fig. 7) to establish a direct relationship between the mass and environmental impact of each building system. The mass results relating to the building systems are displayed in kilograms. The total floor area was not taken into account in this study, as it was the same for all options analysed.

The results of the analysis of the mass of each structural system demonstrate that the lightest building is option 1, namely the aluminium structure (54.14%, 54.86% and 47.26% lighter than options 2a, 2b and 3, respectively), while option 2b, namely the wooden painted structure, is the heaviest building system (54.86%, 1.56% and 14.40% heavier than options 1, 2a and 3, respectively).

The results obtained in the impact categories and during the assessed life cycle stages are outlined below.

CED

From a global point of view, considering all life cycle stages in the CED impact category, the results indicate that option 2b, namely the wooden painted structure, produces the highest environmental impact (24.73%, 4.26% and 18.24% higher than options 1, 2a and 3, respectively) (Fig. 8). Furthermore, it is the heaviest building system.

In contrast, option 1, namely the aluminium structure, produces the lowest environmental impact (generating 21.38%, 24.73% and 7.94% lower environmental impact than options 2a, 2b and 3 respectively). Moreover, it is the lightest option.

In the CED impact category, the environmental impact of option 3, namely the steel structure, is similar to that of option 1, namely the aluminium structure, but lower than that of the wooden structures of options 2a and 2b. The similarity to the impact results of option 1 is owing to the lightweight and quick assembly/disassembly building system of option 3. In contrast, the difference between the environmental impact produced by option 3 and those of options 2a and 2b is owing to the design (geometry and construction process), minimising both the materiality and assembly/disassembly processes during the assembly stage.

During the production stage, option 2b, namely the wooden painted structure, produces the highest environmental impact (7.08%, 1.03% and 7.45% higher than options 1, 2a and 3, respectively). This is owing to the protective paint used on the laminated timber elements involved in this option. Furthermore, during this stage, option 3 produces the lowest environmental impact, although it is close to that of option 1 (option 3 produces 0.40% less than that of option 1).

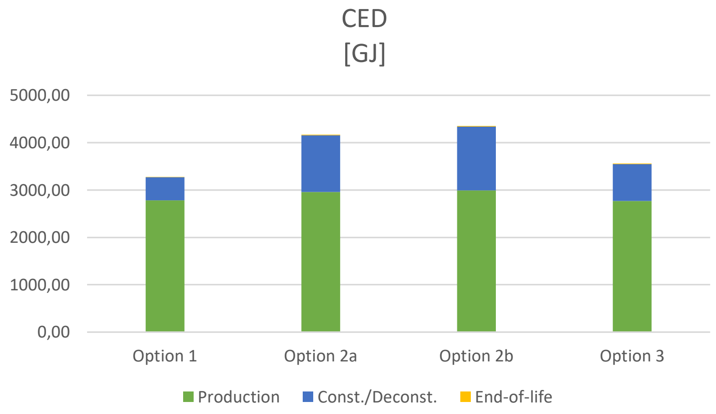

Fig. 8. CED Impact.

Table 5
Values of environmental impact produced by case studies.
CED.

	Option 1	Option 2a	Option 2b	Option 3
Production (GJ) A1-A3	2779.09	2960.08	2991.00	2768.05
Construction/Deconstruction (GJ) A4-A5	489.97	1193.93	1348.73	776.17
End-of-life (GJ) C1-C4	9.05	15.48	15.48	16.61
Total (GJ)	3278.11	4169.49	4355.21	3560.83
Total floor area (m^2)	168.00	168.00	168.00	168.00
Total/Total floor area (GJ/m^2)	19.51	24.82	25.92	21.19

In relation to the other building systems, option 3 generates 6.49% less than option 2a and 7.45% less than option 2b. Option 3 generates the lowest environmental impact owing to the design, as indicated above.

For the construction/deconstruction stage, option 2b is the structural system that produces the highest environmental impact (63.67%, 11.48% and 42.45% higher than options 1, 2a and 3, respectively), while building system 1 generates the lowest environmental impact (58.86%, 63.67% and 36.87% lower than options 2a, 2b and 3, respectively). The size and light weight of the elements constituting option 1 minimise the auxiliary resources used during the assembly and disassembly processes. Therefore, option 1 generates the lowest environmental impact during the assembly/disassembly stage. Option 3 incorporates large elements, which require additional auxiliary resources but generate the lowest environmental impact during the production stage, owing to their design. Even so, the environmental impact of option 3 is lower than that of options 2a and 2b.

For the end-of-life stage, option 3 produces the highest environmental impact. In all case studies, the results obtained are very similar for this stage, as the analysed building systems are reusable and minimise the environmental impact at the end-of-life stage. The variation in the results depends mainly on the mass and quantity of material used for each option.

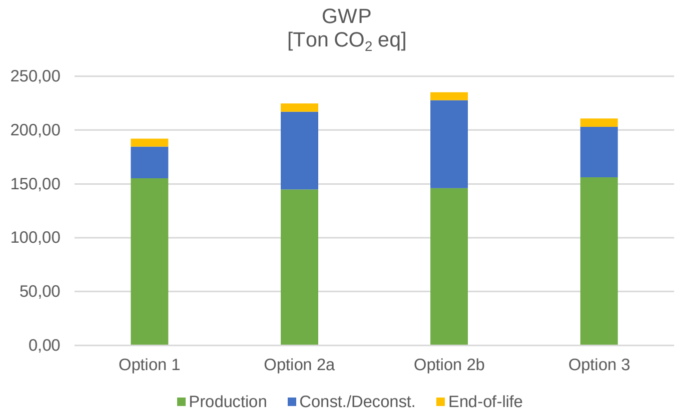

Table 6
Values of environmental impact produced by case studies.
GWP.

	Option 1	Option 2a	Option 2b	Option 3
Production (Ton CO$_2$ eq) A1-A3	155.18	144.80	145.96	156.05
Construction/Deconstruction (Ton CO$_2$ eq) A4-A5	29.58	72.26	81.66	46.91
End-of-life (Ton CO$_2$ eq) C1-C4	7.28	7.64	7.64	7.71
Total (Ton CO$_2$ eq)	192.04	224.70	235.25	210.66
Total floor area (m^2)	168.00	168.00	168.00	168.00
Total/Total floor area (Ton CO$_2$ eq/m^2)	1.14	1.34	1.40	1.25

GWP)

The global results obtained in the GWP impact category indicate that option 2b, namely the wooden painted structure, produces the highest environmental impact in the sum of the life cycle stages (generating 18.37%, 4.49% and 10.45% higher environmental impact than options 1, 2a and 3, respectively) (Fig. 9). Moreover, it is the heaviest construction system.

However, option 1, namely the aluminium structure, produces the lowest environmental impact in the sum of the life cycle stages assessed (generating 14.53%, 18.37% and 8.84% lower environmental impact than options 2a, 2b and 3, respectively). As with the impact category above, the environmental impact results for building system 3 are similar to option 1. Furthermore, option 3, namely the steel structure, produces an environmental impact similar to those of 2a and 2b, owing to its geometric design.

The results from the production stage demonstrate that option 3 produces the highest environmental impact, albeit with a similar result to that of option 1 (producing 0.55%, 7.21% and 6.47% higher environmental impact than options 1, 2a and 2b, respectively). During this stage, option 2a produces the lowest environmental impact (6.69%, 0.79% and 7.21% lower than options 1, 2b and 3, respectively), although the results obtained are very similar for all options. Although the building systems constructed from wooden elements produce the lowest environmental impact, there is almost no difference with respect to the environmental impact of options 1 and 3, which are composed of metallic elements.

During the construction/deconstruction stage, option 2b produces the highest environmental impact (63.77%, 11.51% and 42.56% greater than options 1, 2b and 3, respectively). In contrast, building system 1 produces the lowest environmental impact (59.06%, 63.77% and 36.93% lower than options 2a, 2b and 3, respectively). As in the previous impact category, the size of the elements forming each option determines the environmental impact generated by the structural systems during the construction/deconstruction stage. In this manner, option 1 is composed of smaller elements and is the lightest construction system, minimising the auxiliary resources used in assembly and disassembly, thereby generating the lowest environmental impact.

During the end-of-life stage, all options produce similar results. Option 3 generates the highest environmental impact, while option 1 generates the lowest. The results obtained from each structural system are similar, as the systems are reversible and minimise the environmental impact during the end-of-life stage. The variation in the results is owing to the mass and amount of material used for each option.

4. Discussion

Despite the growing body of literature, LCA is a relatively new concept in construction decision-making (Cabeza et al. 2014; Pineda et al. 2017). Limited research is available focusing on the use of LCA for the selection of constructive systems in protected heritage interventions. This study presents a methodology for decision-making during the project phase, based on proposing constructive systems (compatible with the heritage environment and the functional problem to be solved) that are lightweight, quick to assemble, reversible and recyclable, and can be evaluated by means of LCA. In the absence of reference values, a standard system has been used as a reference option. As a result, innovative solutions adapted to the heritage environment can be proposed and their environmental impact assessed in relation to the standard solutions.

In the literature, there are articles indicating that light, quick assembly and reversible systems tend to reduce the environmental impact (Wadel & Cuchí 2010). The use of LCA as a decision-making tool during the project phase can tangibly determine the impact of each proposed option. Therefore, this article contributes to proposals for accurate constructive systems that can be used for reversible heritage interventions, by presenting an original LCA-based methodology for their selection.

Given that the options for construction models in conventional buildings are significantly more open and dispersed, it is more difficult to propose a methodology correctly establishing reference values for the interpretation of results (Mohammadi & South 2017). In contrast, in simple building structures in heritage environments, we find that a close relationship exists between the constructive parameters, namely the material used, geometry and design considerations, and the environmental impact of individual options. Moreover, the proposed methodology allows for decision-making from an environmental perspective in this type of building structure.

As the results demonstrate, although the proposed options have been designed following the same strategies, namely lightness, quick assembly, reversibility and recyclability, there are obvious differences in the environmental impact that they produce. This is owing to the use of different materials and geometries in each of the compared architectural designs. Therefore, the applied LCA methodology has allowed us to select the most suitable option for each case study.

In this case, the results indicate that option 1, the aluminium option, is the most efficient in terms of environmental impact, producing the lowest impact during the sum of the life cycle stages. Option 3, the steel structure option, exhibits the second best results in terms of environmental impact. Options 2a, the wooden unpainted option, and particularly 2b, the wooden painted option, present the worst results considering the entire life cycle stages.

The results also demonstrate that the environmental impact during the product stage (A1 to A3) depends mainly on the mass used by the structure, and secondly on the main building material. Therefore, the lightest option, namely option 1 (the aluminium structure), is superior in terms of the impact relating to embodied energy (CED). This is always true when very little difference exists in the impact produced by the building materials considered; for example, the lower impact produced by options 2a and 2b (wooden structures) in terms of GWP compared to the other options. As indicated by the results, this occurs mainly because the wood-related GWP impact is much lower (-1.32 kg CO_2 eq/kg) than the aluminium-related impact (11.59 kg CO_2 eq/kg) according to the database considered (see Table 4).

Regarding the obtained results, it should be clarified that in traditional construction systems, an uncertainty analysis is necessary to prove the LCA validity, given the numerous materials and processes involved (Blengini & Di Carlo 2010; Hong et al. 2016). In the case of industrialised building systems, the degree of uncertainty is low owing to the tight control of elements and processes related to the life cycle stages (García-Martínez 2010); therefore, these results are assumed to be valid for our proposal.

The mass of the elements constituting up the building structure is also a decisive factor in the construction stage-related impacts (A4 and A5). According to the results, in the categories considered, the resulting impact is almost proportional to the mass of the building components. This is because, according to the methodology applied, mass is an important parameter in both the transport stage (A4) and construction stage (A5). Moreover, during the end-of-life stage (C1 to C4), the main differences are determined by the mass of the structural components, given that the end-of-life processes provide very similar results for impact (see Table 4). Therefore, in this type of construction, a greater correlation is observed between lightness and low impact.

During the construction stage, energy use is reduced slightly in the assembly/installation process (A4) in the case of quick-assembly structures. This is owing to the optimisation of the time and resources employed during the installation. Nevertheless, the procedure used in this research for establishing the process units in this stage, namely electricity and diesel consumption, are linked to the volume of building materials mobilised during the installation (Kellenberger 2004).

Reversibility and reusability are the third parameter used in the design of the studied options. This criterion has been considered a “sine qua non” condition in all three options. This feature allows each structure to be assembled and disassembled, providing the durability of the building components. The impact of a single-use structure would be the equivalent of multiplying the results obtained by the number of cycles of potential installation/uninstallation.

Relevant information is provided for the decision-making process, allowing architects and engineers to select the option best suited to the requirements. In this case, option 3 (steel structure) was selected (Fig. 3), owing to the need for a stage front with no support.

5. Conclusions

In this paper, LCA has been highlighted as a potential decision-making tool for selecting the most suitable architectural solution to be constructed at a heritage site. This was assessed by means of a comparative LCA study of three building options.

In heritage interventions, several variables should be taken into account apart from environmental impact, in order to select the most suitable construction option. This paper demonstrates that the applied methodology can be used to identify the most appropriate building system for intervention in a case study on a specific heritage site, from design and environmental perspectives.

The analysis of the case study requirements led to the proposal of three appropriate building systems based on the same design strategies. The use of LCA has made it possible to quantify the environmental impact of the building systems during the production (A1 to A3), construction/deconstruction (A4 and A5) and end-of-life (C1 to C4) stages.

The results demonstrate that environmental impact is directly proportional to the mass. Thus, the lightest model produces the lowest environmental impact; that is, the standard aluminium structural system of option 1. The environmental impact of option 3, based on a specific steel design, is close to that of option 1 (the CED and GWP impact indicators of option 3 produce only 7.94% and 8.84% higher impact, respectively, than option 1). Moreover, the results

Fig. 10. Building system (option 3).

demonstrate the reduction in impact owing to the quick assembly and reversibility. Nevertheless, further research is required in this regard.

In the case study, given an architectural requirement (the need to minimise the support at the stage front), option 3 was finally selected and used biannually from 2011 (Fig. 10). The applied methodology meant that, in addition to the functional, aesthetic and technical requirements, it was also possible to take environmental requirements into account during the decision-making process for design solutions in the heritage intervention.

In order to improve the proposed methodology, the following future research is required.

- More accurate procedures for quantifying the unit processes taking part in the construction stage (A5) should be established.
- Uncertainty analysis should be considered in future studies; for example, with a sensitivity study based on the Monte Carlo simulation method (Blengini & Di Carlo 2010).
- The data compilation process in the life cycle inventory is time and resource consuming. The development of tools for building information modelling and LCA in architectural heritage interventions is also required. These tools may be of assistance in calculating the environmental impact values during the early design process stages.

Acknowledgements

The authors would like to thank architect Santiago Bermejo Oroz for kindly providing the data on the applied case study and building systems, as well as the Provincial Government of Seville

Department of Citizenship, Participation and Culture for supporting us for more than five years and promoting architecture based on the integration of heritage.

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~~Reviewers' comments:~~

~~Reviewer #2: The Authors have been given much opportunity to improve the quality of this manuscript including the English language. However, although the Authors respond that they have professionally edited the language of the manuscript, the language and writing style of the manuscript is still not of a high quality with some grammatical errors. Hence, I may highly suspect that the Authors are using a low quality professional editing service. The following are some language problems present in the manuscript:~~
~~- In Discussion section, line 38: "Moreover, the methodology proposed methodology allows..."~~
~~- In Discussion section, line 59: "As results show, t occurs mainly because....". Do you mean "this occurs ...." or "t occurs.."?~~

~~Thus, I leave the decision to request for further revision or reject the manuscript to the Editor.~~

Con formato: Justificado, Espacio Después: 0 pto, Interlineado: Mínimo 5 pto, No dividir palabras