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HERRAMIENTA PARA LA ESTIMACIÓN DE COSTES ECONÓMICOS Y AMBIENTALES EN EL CICLO DE VIDA DE EDIFICIOS RESIDENCIALES. FASE DE CONSTRUCCIÓN

A TOOL FOR ESTIMATING ECONOMIC AND ENVIRONMENTAL COSTS IN THE LIFE CYCLE OF RESIDENTIAL BUILDINGS: THE CONSTRUCTION STAGE.

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RESUMEN

Este trabajo presenta una herramienta para predecir los impactos económicos y ambientales del ciclo de vida de edificios de tipo residencial en fase de diseño, partiendo de un proyecto arquitectónico, del presupuesto del proyecto, de las bases de costes de la construcción, en particular, las de Andalucía y del indicador huella ecológica. La herramienta propone alternativas en el uso de recursos (materiales, mano de obra y maquinaria) y sistemas constructivos, pudiendo formar parte en la toma de decisiones para mejorar el impacto del ciclo de vida del edificio. Se analiza un caso concreto de edificio residencial de diez plantas sobre rasante y se obtienen los recursos empleados y su impacto económico y ambiental a nivel global y de forma pormenorizada, según las fases del proyecto. Los materiales son el recurso de mayor importancia y, específicamente, el hormigón o el cerámico son los que producen mayor impacto. Se realiza un análisis de sensibilidad, en el que se proponen diferentes alternativas de materiales para una solución constructiva y se obtienen los datos para decidir la opción más viable económica y ambientalmente. La herramienta es de fácil manejo para el usuario y puede ser base para la certificación de edificios y el desarrollo de valores estándares a emplear en políticas gubernamentales.

Palabras clave
herramienta, ciclo de vida del edificio, impacto económico, impacto ambiental, huella ecológica, bases de costes de la construcción, edificios residenciales.

ABSTRACT

This article presents a tool to predict the economic and environmental impacts of the life cycle of residential buildings in the design phase based on an architectural project; the project's budget; construction costs databases, in particular those of Andalucía, Spain; and the ecological footprint indicator. The tool proposes alternatives in resource use (materials, manpower and machinery) and construction systems, as these can be used in decision making to improve the impact of the building's life cycle. The case of a specific ten-floor residential building is analyzed, including the resources used and their general and specific economic and environmental impacts according to the stages of the project. The materials were found to be the resource of greatest importance, with the concrete or ceramic in particular producing the greatest impact. A sensitivity analysis was carried out in which different material alternatives were proposed for a building solution, and data was obtained to decide on the most economically and environmentally viable option. The tool is easy to use and can be the basis for building certification and the development of standard values for use in government policies.

Keywords
tool, building life cycle, economic impact, environmental impact, ecological footprint, construction cost databases, residential buildings.

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INTRODUCTION

The knowledge resulting from the large number of studies on the environmental impact is finally reflected in the generation of calculation tools, normally addressed to the environmental certification of buildings. The development of this type of tools has been reinforced in recent years due to the need to create environmental policies for buildings that allow measuring that sustainability. Currently, there are a number of tools in Spain created from research projects that calculate the carbon footprint of buildings. LEED y BREEAM are the most widely used international instruments and in Spain they are managed by the Spain Green Building Council («SpainGBC VERDE tool website Available online» 2018) and BREEAM Spain («BREEAM.ES website Available online» 2018), respectively. They evaluate several aspects in order to obtain a final score, such as the CO2 emissions generated by the manufacture of the construction materials used and the energy consumed in the operational phase of the building. At a national level, SpainGBC VERDE presents the tool that assigns the highest percentage of points (~ 25%) to greenhouse gas emissions. On the other hand, there are the energy certification tools, such as CE3, CE3X, CERMA («Ministry of energy tourism and digital agenda, energy efficiency certification of buildings (Ministry of energy, tourism and digital agenda, Energy efficiency certification of buildings)» 2018) and the unified LIDER-CALENER («Spain MPW Unified Tool LIDER-CALENER Available online» 2018), developed by Spanish associations and universities. There are also several more specialized platforms that allow the detailed calculation of CO2 emissions of the resources, depending on the ratio of amounts defined by a project, such as the BEDEC cost database ("ITeC BEDEC website Available online" 2013) , developed by the Institute of Tecnología de la Construcción de Cataluña and whose environmental data come from the Ecoinvent ACV database (Ecoinvent center 2016), known, in turn, as one of the most complete at European level [63] and for its integration with the Simapro ACV software («PRé Sustainability SimaPro 8 Available online» 2018).

To determine the environmental impact, various methodologies can be applied to the construction sector; currently, the tendency is to use the simplest ones. Thus, the ecological footprints (HE, by its initials in Spanish) (Wackernagel and Rees, 1996) and the carbon one (HC, by its initials in Spanish) (Weidema *et al.*, 2008) are the most used ones: the results they produce are understandable by the non-scientific society and are easy to apply for decision-making and environmental policies (Bare et al. 2000). The indicator HE is increasingly used to quantify the growth of cities and control their effects, and more and more researchers are developing models for it (Lu and Chen, 2017; Yang and Hu, 2018). In this sense studies by Destacan Bastianoni *et al.* (2007), Li and Cheng (2010), Solís Guzmán, Marrero and Ramírez de Arellano (2013) and Teng and Wu (2014) are outsatnding, they have selected the HE indicator to evaluate the peculiarities of the construction sector.

Some authors evaluate the materials used in the construction of buildings through indicators that generally follow the methodology of ACV (S. Lasvaux, Schiopu, J. Chevalier 2012; «UNE-EN ISO 14020 Environmental labels and declarations - General principles» 2002; F. García-Erviti, J. Armengot-Paradinas 2015), as well as the CO2 or energy emissions of the building's life span (CVE) (Chau, Leung and Ng, 2015) (the conclusions of the phases usually match). The construction phase is concentrated in a short period of time (1-2 years); however, the decisions made during this phase influence to a large extent the results for the rest of the CVE. The operation phase is usually responsible for 80% to 90% of the CO2 emissions generated during the CVE (Radhi and Sharples, 2013), and almost 60% of which is caused by the demand of energy for heating and air conditioning (You et al., 2011). This paper presents a tool to assess the economic and environmental impact in the CVE, focused on the phases of manufacturing materials and construction, based on the data of the project budget, the construction cost basis and HE indicator. The tool is intended to be robust, flexible and easy to use, so that the indicator HE can be included in the certification of buildings, since none of the certification instruments is considered.

In order to obtain the economic impact in question, the construction cost bases are used, which use Construction Information Classification Systems (SCIC, by its initials in Spanish) (Marrero and Ramírez de Arellano Agudo, 2010). In Spain, there are several construction cost bases, generally developed according to the autonomous communities, such as PREOC in Madrid, ITEC in Catalonia, PRECIOCENTRO in Guadalajara or BCCA in Andalusia. The tool proposed here uses the Andalusian one (BCCA), which has a stable, flexible and consolidated structure. The strength of the SCIC and the BCCA lies in the fact that they are capable of dividing a complex unit into parts, such as the construction of a building, and then adding them and forming the total. Other authors carry out the ACV and the analysis of the cost of the life cycle (CCV), and, from both, they make a complete study of the building. Recently, various tools and websites are being developed with this approach of economic and environmental analysis (Khan et al. 2018; Sesana and Salvalai 2013; Vasquez Palacios and Quesada Molina 2017) highlighting the importance of its use in the design phase to project more efficient buildings according to the economic and environmental impact, and demystifying the cost increase of a more ecological building. Islam, Jollands and Setunge (2015), for example, perform a review evaluating and comparing the ACV and CCV of residential buildings, and to afterwards apply that analysis to a case in Australia. For this purpose, they use the Ecoinvent database (Ecoinvent Centre, 2016), the Simapro program (PRé Sustainability SimaPro 8 Available online, 2018) and an Australian construction cost base, which is not available openly and free of charge (Rawlinson, 2009). When they finish, they emphasize the importance of both analyzes, as well as the clear definition of limits and hypotheses. The building typology, the technologies used and the climate are also determining factors.

This document explains, in the first place, the functioning of the proposed tool, according to the inventory analysis and the impact evaluation. Next, it is applied to a specific case: a residential building of ten floors above ground. Finally, the results and conclusions obtained are exposed according to the different proposed analyzes, which serve for the decision making in the design phase of the building and to define strategies around the improvement of the economic and environmental impacts.

METHODOLOGY

To explain the development and operation of the cost evaluation tool, the buildings' ACV methodology is followed (UNE-EN ISO 14040 Environmental management — Life cycle assessment — Principles and framework 2006; UNE-EN ISO 14044 Environmental management — Life cycle assessment — Requirements and guidelines, 2006): definition of objectives and scope of application, analysis of inventory, evaluation of impacts and interpretation of results.

In the present investigation the initial methodology of HE for the evaluation of housing construction developed by Solís-Guzmán, Marrero and Ramírez de Arellano (2013) and by González-Vallejo, Marrero and Solís-Guzmán (2015) is updated. The main difference with respect to the initial methodology is that the impacts produced by the resources (materials, manpower, machinery, electricity and water) are calculated using the CO2 emissions directly instead of the incorporated energy data (MJ). In the case of construction and demolition waste (RCD, by its initials in Spanish), transportation to the recycling plant is included, for which material transport assumptions are included. The mobility of workers is eliminated by adapting to the LCA life cycle cost standards (UNE-EN ISO 14020 Environmental labels and declarations - General principles, 2002). For the impact produced by workers' food, the methodology of GFN is employed (Lazarus et al., 2014). For municipal solid waste (RSU, by its initials in Spanish), the data per person per year in the country under study and the corresponding emissions are applied, instead of making assumptions about the type of RSU generated at the construction site. In order to obtain the energy consumption in the work, empirical data are used. Finally, the impact of water is assumed to be generated by the energy needed for its supply (previously it was counted as HE of forests and now it is HE of energy). In addition, the methodology has been refined and systematized, which allows the development of eco-efficient construction standards capable of achieving sustainability certification.

DEFINITION OF OBJECTIVES AND SCOPE OF APPLICATION

The main objective is to obtain a tool to predict the economic and environmental impacts of CVE in the design phase, proposing alternatives for improvement in resource management: greener materials, more efficient machinery, optimization of labor and planning of RCD generated.

As secondary objectives, it is proposed that the developed tool be used to quantify resources, waste and emissions generated and to evaluate the project in detail from the design phase.

The tool focuses on residential buildings, in the phases of extraction and manufacturing of materials and in the construction of the building. It is considered that the plot is ready to execute the work, so that the urbanization works are not counted. Provisional installations for water, sanitation and electricity connections will be taken into account. It includes the transport of the material from the factory to the construction site and from the construction and demolition waste (RCD) to the management plant. In the construction phase, the impact of workers is evaluated according to the consumption of food and the production of solid urban waste (RSU), the impact produced by the machinery used, powered by electricity or fuel, the consumption of electricity and water during the work and the surface occupied. The impacts according to the HE indicator are accounted for per year.

Likewise, the impacts produced by the resources included in the budget for material execution of the work (PEM) or direct costs (CD), as well as those from general data or indirect costs (CI), which are those resources of the work evaluated not attributed to a specific task (crane, scaffolding, construction technicians, etc.); and the data of temporary facilities such as the connections of facilities, work stands and consumption of resources (energy, water and personnel) associated to them are included (Marrero and Ramírez de Arellano Agudo, 2010).

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Project selection					
Characteristics	Options				
No. of floors above ground:	1	2	3	4	5 or more
No. of floors below ground:	0		1		2
Foundation:	Isolated footings		Continuous trench	Reinforced slab	Pile
Structure:	Load-bearing walls of brick factory			Reinforced concrete	
Cover:	Horizontal			Sloped	
Use on the ground floor:	Housings			Commercial buildings	

Table 1. Selection of project typology in the tool according to typology and main characteristics. Source: González-Vallejo et al. (2015).

INVENTORY ANALYSIS

- At this point, all energy flows and incoming and outgoing materials of the system are quantified throughout their useful life, which are extracted from or emitted to the environment, for which the budget of each project based on of the construction cost bases is used.
- Construction cost base: Used to draft the PEM budget of the project, which includes a detailed study of resources used and the analysis of the inventory proposed in the ACV to determine the impacts of the building. The BCCA (Consejería de Fomento y Vivienda 2016), whose structure and systematic classification organizes prices and their decompositions into resources of materials, labor and machinery (Marrero and Ramírez de Arellano Agudo, 2010; Ramírez de Arellano Agudo, 2004), which is used as the basis of the model developed by the tool.

Building project: The tool has a database of more than one hundred projects (Ramírez de Arellano Agudo, 1988), which are updated to current regulations (CTE (Ministerio de Vivienda de España, 2006; Gobierno de España, 2008) and RCD) and whose main characteristics are presented in Table 1. It is the first data selection proposed in the tool.

Measurements of the project: To define the project and estimate its impact, it is necessary to quantify the resources used based on the measurements defining the budget. The tool proposes a Qi type measurement, obtained thanks to statistical methods (Ramírez de Arellano Agudo, 1988) depending on the types of projects (González-Vallejo, Marrero and Solís-Guzmán, 2015). They are organized according to the systematic classification of the BCCA, as defined in Table 2, in chapters, sub-chapters, sections, groups and simple unit prices, grouped according to similar characteristics. The chapters are the first level of the classification (02 Excavations, 03 Foundations, 04 Sanitation, etc.) which, in turn, are subdivided into sub-chapters (in the case of chapter 04: 04C, hanging networks, 04E, buried networks, etc.); then, in sections (in the case of 04E: 04EA, boxes, 04EC, collectors, 04B, downspouts, etc.); and, finally, in groups (in the case of 04EC: 04ECF. Fiber cement collectors; 04ECH. Concrete collectors; 04ECP. PVC collectors, etc.), which are the ones that include the simple unit prices (PUS, by its initials in Spanish) (in the case of 04ECH: 04ECH90002. m. Concrete buried collector of diameter 200 mm with overhangs, in the earth). PUS are made by, in turn, by auxiliary prices (PA, by its initials in Spanish) and basic prices (PB, by its initials in Spanish), which are those corresponding to the labor, materials and machinery necessary to execute such PUS (Consejería de Fomento y Vivienda, 2016).

For the update of the projects, new Q_i for air conditioning are calculated (in chapter 08. Installations: 08CA u, HVAC and 08CR devices, m² Radiators), solar energy (08N: accumulators, load-bearing structures and solar collectors) and management of waste (chapter 17), included in Table 2.

One of the novelties of the tool is the one of introducing a series of deployable to define constructive systems, materials or type of machinery to employ, in function of the options posed, as it is specified in Table 2.

In order to obtain the specific measurement of the project to be evaluated, the real area of the case study is applied to each Q_i and, thus, obtain the quantities of the total resources needed (Q), according to equation 1:

$$Q = Q_i \cdot S \qquad (1)$$

Where:
Q: total measurement of a project item
Q_i: unit measurement of each item (u/m²) (unit of measurement of the item/m² of constructed area)
S: Project surface

Each Qi is associated to a simple unit price (PUS), from which the total resources will be obtained, based on the decomposition in PB and PA, which are collected to calculate each of the partial footprints that make up the total HE. Each resource produces one or several impacts, which are added to calculate the total environmental impact of the project. On the other hand, to define the economic impact, the PB is applied to each resource, then the PB and PA summation is made and, in this case, the unit price of item -04ECH90002 is obtained in this case - and, when applying the project surface, the total of the PUS for that project. Finally, adding all the items (PUS) results in the total budget, as shown in Figure 1.

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STRUCTURE OF THE PROJECT MEASUREMENT			
Code	Unit	Concept	Deployable options
CHAPTER 02		EXCAVATIONS	
02E	m^3	Excavations	Shovel
			Backhoe
02R	m^3	Fillings	Manual means
			Mechanical means
02T	m^3	Earth transportation	Manual means
			Mechanical means
CHAPTER 03		FOUNDATIONS	
03A	kg	Reinforcement	-
03P	m	Piles	-
03E	m^2	Formworks	Wood
			Metal
03HA	m^3	Concrete reinforced footings	Manual pouring
			Crane pouring
			Pump pouring
03HM	m^3	Mass concrete	-
03H	m^3	Bnad concrete	-
CHAPTER 04		SANITATION	
04A	u	Boxes	In situ (brick factory)
			Prefabricated
04C	m	Collectors	PVC
			Concrete
			Fibre cement
04B	m	Downspouts	PVC
			Zinc
			Steel
			Galvanized steel
CHAPTER 05		STRUCTURES	
05AE	kg	Steel metal structures	-
05F	m^2	Forged	Cement hollow brick
			Ceramic hollow brick
05HA	kg	Reinforcement	-
05HE	m^2	Formworks	Wood
			Metal
05HA	m^3	Reinforced concrete	-
CHAPTER 06		MASONRY	
06FB	m^2	Block factories	-
06DC	m^2	Partition distribution (chambers)	-
06DT	m^2	Partition distribution (partitions)	-
06LE	m^2	Exterior brick factories	-
06LI	m^2	Interior brick factories	-

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CHAPTER 07		COVERS	
07H	m²	Horizontal covers	Transitable
			Not passable
07I	m²	Sloping covers	Ceramic tile
			Cement mortar tile
CHAPTER 08		FACILITIES	
08CA	u	Air conditioning equipment	-
08CC	m	Conduits	-
08CR	m²	Radiators	-
08EC	m	Circuits	-
08ED	m	Lines and bypass	Under tube: PVC
			In brick factory
08EL	u	Points of light	-
08ET	u	Plug	-
08EP	m	Earthing conductor	-
08FC	m	Hot water pipes	Copper
			Galvanized steel
08FD	u	Drains	-
08FF	m	Cold wáter pipes	Copper
			Galvanized steel
08FG	u	Faucets	-
08FS	u	Sanitary Appliances	Porcelain
			Steel
08FT	u	Water heaters/Heaters	Electric
			Gas
08NA	u	Accumulators	-
08NE	u	Support structures	-
08NO	u	Solar collectors	-
08NP	m	Primary circuit	-
CHAPTER 09		INSULATIONS	
09A	m²	Acoustic insulation	Glass fiber
			Polystyrene
			Polyethylene
			High density synthetic
09T	m²	Thermal insulation	Glass fiber
			Polyurethane
			Polystyrene
			Mineral wool

CHAPTER 10		LINING	
10AA	m²	Tiled	With adhesive
			With mortar
10AC	m²	Plated	Artificial stone
			Limestone
			Granite
			Marble
10CE	m²	Plastered	-
10CG	m²	Garrisoned	Cast
			Plaster
10S	m²	Pavement	Ceramic
			Stoneware
			Hydraulic tile
			Wood deck
			Marble
			Limestone
			Granite
			Terrazzo
10SS	m²	Floors	-
10T	m²	Roofs	Fixing with rods
			Metallic fastening
10R	m	Finishes	Limestone
			Wood
			Ceramic tile
			Marble
CHAPTER 11		CARPENTRY AND SECURITY AND PROTECTION ELEMENTS	
11CA	m²	Steel carpentry	-
11CL	m²	Light carpentry	-
11M	m²	Wood carpentry	-
11MA	m²	Wardrobe	-
11MP	m²	Wooden doors	-
11B	m²	Railings	Steel
			Anodized aluminum
11P	m²	Blinds	-
11R	m²	Grilles	-
CHAPTER 12		GLASS	
12A	m²	Glazing	-
CHAPTER 13		PAINTS	
13PE	m²	Exterior paints	Smooth elastomer
			With limestone
13PI	m²	Interior paints	Smooth plastic
			With plain plastic

CHAPTER 17		WASTE MANAGEMENT	
17AH	t	Iron and Steel	-
17HA	m³	Aggregates and natural stones	-
17HC	m³	Ceramic	-
17HH	m³	Concrete, cement and lime	-
17MM	t	Wood	-
17MP	t	Plastic and synthetic	-
17RR	m³	Mixed waste	-

Table 2. Definition of the project: Systematic classification according to criteria of the BCCA and options of the tool to select type of resources or construction systems. Source: González-Vallejo (2017).

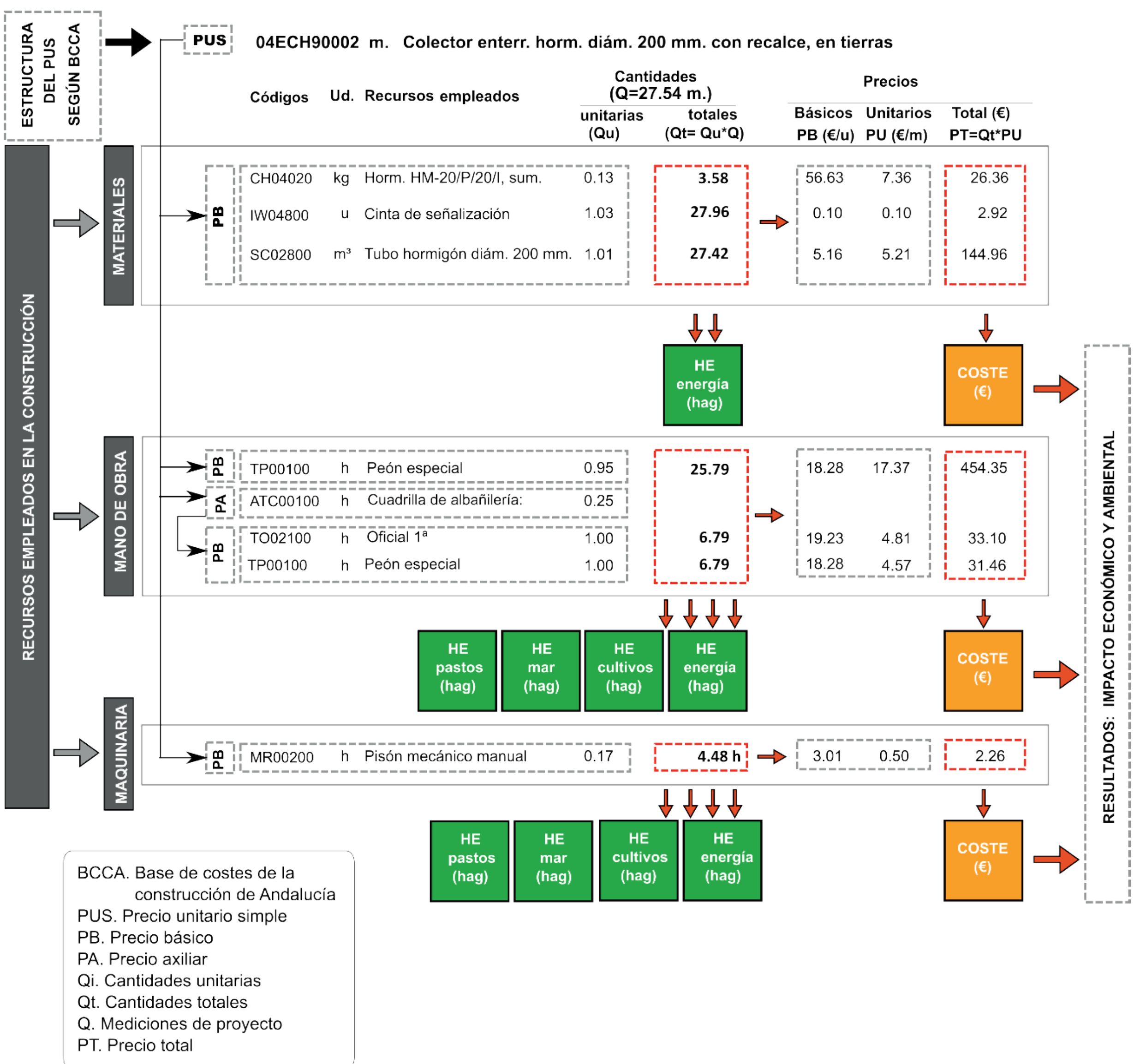

Figure 1. Internal operation of the tool to obtain resources and to define the impacts. Source: González-Vallejo, Muñoz-Sanguinetti and Marrero (2019).

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IMPACT EVALUATION

A classification and evaluation of the results of the inventory is made, relating their results to observable environmental effects through a set of categories of impacts (HE, CO_2 emissions). The developed tool evaluates the environmental impacts through the HE and HC indicators, following the HE methodology (Lazarus et al., 2014; Mancini et al., 2016) updated by the Global Footprint Network (GFN), 2014) and applied to construction (Solís-Guzmán, Marrero and Ramírez de Arellano, 2013, González-Vallejo, Marrero and Solís-Guzmán, 2015). This method has been implemented to the different phases of the building's CV (Alba-Rodríguez et al., 2017; Martínez-Rocamora, Solís-Guzmán and Marrero 2017; González-Vallejo et al., 2015a) and it is summarized below:

- HE methodology for construction of buildings

As defined at the beginning of the work, the HE methodology has been updated to adapt to the ACV criteria (UNE-EN ISO 14040 Environmental management, 2006) and the GFN (Global Footprint Network, 2014).

The methodology defines the sources of impacts of the resources and energy consumption of the CV of the building, defining each one of the partial footprints that they produce. Illustrated in Table 3 there are the equivalence factors of each type of productive land and absorption of CO2 emissions specific to the HE methodology (Lazarus et al., 2014), which are used in each of the partial footprints.

Electricity and water consumed on site: in the estimation of electricity consumption, the expected consumption data C_{me} for the work is needed.

The sources of impacts are: for electricity according to the calculation of the CI (Equation 2): workhouses, lighting, machinery and facilities testing (Freire Guerrero and Marrero 2015). Likewise, CO_2 emissions of electricity (CO_2/kW) that depend on the energy mix of the country of study are required. For water, the impact generated by the energy used in infrastructures necessary for water to reach the point of consumption is considered, which is estimated according to equation 3.

The footprint produced is of energy and is calculated according to expression 2:

$$HE_{me} = C_{me} \cdot E_{elect} \cdot \left(\frac{1-A_o}{A_b}\right) \cdot FE_{ac} \quad (2)$$

Where:
HE_{me}: HE of electricity (hag/año) C_{me}: electricity consumption (kWh)
E_{elec}: Electricity emission factor: Spain (0.000248 tCO_2/kWh) (REE. Red Eléctrica Española, 2015)

Symbol	Description
A_b:	Forest absorption factor (3.59 t CO_2/ha/year)
A_o	Reduction of emissions by CO_2 absorption of the oceans 0.28 (28%)
FE_b	Equivalence factor of forests (1,26 hag/ha)
FE_{ac}	Earth equivalence factor of carbon absorption (1.26 hag/ham)
FE_s	Equivalence factor of consumed surface (1,26 hag/ha)

Table 3. Specific factors of the HE methodology (Global Footprint Network (GFN), 2014).

In order to determine the impact produced by water, the consumption of it (C_{agua}) calculated according to the type of project is needed (m³ of water/m² constructed) (González-Vallejo, Marrero and Solís-Guzmán 2015).

The water footprint is considered, therefore, estimated energy footprint according to equation 3:

$$HE_{agua} = C_{agua} \cdot IE_{agua} \cdot E_{elect} \cdot \left(\frac{1-A_o}{A_b}\right) \cdot FE_{ac} \quad (3)$$

Where:
C_{agua}: water consumption (m³)
IE_{agua}: energy intensity for water consumption (0.44 kWh/m³) (EMASESA, 2005).

Consumed surface: The surface used by the building is needed which is obtained from the general data of the work. The footprint that it produces corresponds to the occupied surface and its impact is calculated from the expression 4:

$$HE_{sup} = S \cdot FE_s \quad (4)$$

Where:
HE_{sup}: HE of the consumed surface (hag/year) S: Consumed surface (ha)

Materials: the consumption data of budget materials expressed in kg (from the densities) are necessary.
The sources of impact are:

<u>Manufacture and extraction of materials</u> (equation 5), with specific calculation for wood (Eq.6).

<u>Transport of materials and RCD</u>, from the factory to the construction site and from the construction site to the management plant, respectively (EQ.7). The quantities of materials and RCD generated that are going to be

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transported are required, as well as the distances of the journeys.

The partial footprints they produce are: energy in all cases, and forests in the case of wood.

The manufacture of materials is defined in equation 5:

$$HE_{mat} = \sum_i (C_{mi} \cdot Fe_{mi}) \cdot \left(\frac{1-A_b}{A_f}\right) \cdot FE_{ac} \quad (5)$$

Where:
HE_{mat}: HE of material manufacturing (hag/year) C_{mi}: Material consumption i (kg)
Fe_{mi}: Material emission factor i (kg CO_2/kg) (Ecoinvent Centre, 2016)

The extraction and transformation of the wood is calculated according to equation 6. The productivity of the wood materials (Pmad) is 0.98 m³/ham, except for the chip panels, which is 1.28 m³/ham (Kitzes *et al.*, 2009).

$$HE_{mad} = \sum \left(\frac{C_{madi}}{P_{madi}}\right) \cdot FE_b \quad (6)$$

Where:
HE : HE of wooden materials (hag/year) mad
Cmadi: Wood consumption i per year (t o m3/year)
Pmad: wood productivity i (m3 ó t/ha) (Kitzes et al., 2009)

For the transport of materials and RCD equation 7 is used and the round-trip distances of the vehicle are considered.

$$HE_{tr} = \sum \left(\frac{P_{mi}}{V_{cam}} \cdot D_m\right) \cdot C_{cam} \cdot E_g \cdot \left(\frac{1-A_b}{A_b}\right) \cdot FE_{ac} \quad (7)$$

Where:
P_{mi}: Weight of material consumption i (t/year)
D_m: average distance (km), considering 500 km (Andalusia) and 15 km, for materials and RCD, respectively.
V_{cam}: capacity of the truck (t)
C_{cam}: truck consumption (l/100 km)
E_g: fuel (gasoil) emission factor of trucks or machinery i, (0.0026 tCO_2/l)

In the case of RCD transport (equation 4), Pmi is the amount of RCD generated and is obtained by applying the percentage of residue (Solís-Guzmán et al., 2009) to the amount of material used.

Manpower: The amount of manpower quantity data is required as budget hours. The sources of impact are:

- Feeding. Food consumption is required, extracted from the World Food and Agriculture Organization of the United Nations (FAO) (Organization of the United Nations 2014). To obtain the consumption of each country, the food produced, imported and exported is taken into account: Spain consumes 3.86 kg of food/person/day. For each of them the impact they produce is calculated: both the energy needed for its manufacture and the productive land from which they come (farming, sea or pasture), applying equation 8, according to the methodology of the GFN (Global Footprint Network , 2014; Borucke et al., 2013). Thus, the impact of the food consumed per person / year in the country of study is obtained, totally and partially, in the case of Spain, the HE_{alimC} generated is 1.43 hag/person/year. To apply it to the workforce (HE_{alim}) expression 9 is used in each type of footprint.
- Generated Urban Solid Waste (RSU, by its initials in Spanish). Once the RSU/person/year consumption of the country is available, the amount generated per hour is calculated and the impact is obtained according to expression 10.

The partial footprints produced are: energy, in both cases, and crops, sea and pastures in food.

To obtain the footprint of food consumption, the expression 8 is used:

$$HE_{alimC} = HE_{alimP} + HE_{alimI} - HE_{alimE} \quad (8)$$

Where:
HE_{alimC}; HE_{alimP}; HE_{alimE}; HE_{alimI}: HE Of consumption, production, export and import of food in the country of study.

The impact of food consumption on site is obtained with the expression 9:

$$HE_{alim} = \frac{H_t}{H_d} \cdot F_{Calim} \cdot \frac{HE_{alimC}}{D} \quad (9)$$

Where:
HE_{alim}: HE of total food consumption of manpower (hag/year)
HE_{alimC}: HE of the food consumed per person per year according to the categories of partial HE i (hag/person/year) F_{calim}: factor consumption of food on site, 0.61, corresponding to breakfast and lunch on the total food eaten daily by an adult in Spain (61%) (Moreno Rojas *et al.*, 2015)
H_d: hours per working day (8h/day).
H_t: Total hours worked by manpower annually (h/year)
D: days per year (365)

The impact of the RSU is calculated according to the expression 10:

$$HE_{RSU} = H_t \cdot G_{RSU} \cdot E_{RSU} \cdot \left(\frac{1-A_o}{A_f}\right) \cdot FE_{ac} \quad (10)$$

Where:
HE_{RSU}: HE of RSU (hag/año)
E_{RSU}: Emission factor of the RSU (0.244 tCO_2/t) (European Environment Agency, 2013)
G_{RSU}: RSU generated per hour (0.000077 t/h) (EUROSTAT, 2015)

Machinery: the data of the quantity of machinery used from the budget in hours is needed.

The sources of impacts are: the fuel (gasoline or gas oil) or the electricity with which the machinery is supplied; and it is calculated, according to equation 11 and equation 2, respectively (Freire Guerrero y Marrero 2015).

In both cases the engine performance data are necessary to obtain the liters of fuel (equation 12) or the kW of electricity (equation 13), in addition to the emissions of fuel and electricity, according to the country's energy mix study. The partial footprint they produce is of energy.

The impact of the fuel machinery is calculated with expressions 11 and 12:

$$HE_{mc} = C_{comb} \cdot E_g \cdot \left(\frac{1-A_o}{A_b}\right) \cdot FE_{ac} \quad (11)$$

Where:
HE_{mc}: HE of fuel consumption (diesel) for machinery (hag /year)
E_g: Fuel emission factor (diesel) of trucks or machinery i, (0.0026 tCO_2/l)
C_{comb}: Truck consumption (l/100 km)

$$C_{comb} = P \cdot T_u \cdot R \quad (12)$$

Where:
P: Engine power of machinery (kW)
T_u: Time of use of the machinery in the construction works (h)
R: performance of diesel or gasoline engine (l/kWh): 0.15-0.20 diesel o 0.30-0.40 gasoline.

To calculate the impact of the electrical machinery we use expression 2, where Cme is the consumption of the machinery calculated according to equation 13:

$$C_{me} = P \cdot T_U \quad (13)$$

CONCEPT	Deployable
CHAPTER 02. EXCAVATIONS	
Excavations	Shovel
Fillings	Mechanical means
Earth transportation	Mechanical means
CHAPTER 03. FOUNDATIONS	
Formworks	Wood
Concrete reinforced footings	Crane poured
CHAPTER 04. SANITATION	
Boxes	In situ
Collectors	PVC
Downspouts	PVC
CHAPTER 05. STRUCTURES	
Forged	Ceramic hollow brick
Formworks	Wood
CHAPTER 07. Covers	
Horizontal covers	Passable
Sloping covers	Ceramic tile
CHAPTER 08. FACILITIES	
Lines and bypass	PVC
Hot water pipes	Copper
Cold water pipes	Copper
Sanitary Appliances	Porcelain
Water heaters/heaters	Electric
CHAPTER 09. INSULATIONS	
Acoustic insulation	Polyethylene
Thermal insulation	Polyurethane
CHAPTER 10. LININGS	
Tiled	With adhesive
Plated	Limestone
Plastered	Plaster
Floors	Ceramic
Roofs	Metal fastening
Finishes	Limestone
CHAPTER 11. CARPENTRY AND SAFETY AND PROTECTION ELEMENTS	
Railings	Steel
CHAPTER 13. PAINTS	
Exterior paints	Smooth elastomer
Interior paints	Smooth plastic

Table 4. Options of deployants selected for the case study. Source: González-Vallejo (2017).

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CASE STUDY

The typology studied here corresponds to one of ten floors above ground, with a basement, a foundation with insulated footings, a reinforced concrete structure, a flat roof and houses on the ground floor. The building has a square floor plan and four homes per floor. The space of each house is divided into kitchen, living room, two bedrooms and two bathrooms, plus the distribution aisles, which adds a useful area of 72 m^2.

The rest of construction characteristics are defined in Table 4, where the selected options of materials, construction systems and machinery are indicated.

RESULTS

PROJECT RESOURCES

The resources needed for the construction of the project are shown in Table 5.

- Materials: They are classified into families and Table 5 includes those of greater weight and impact. The most important materials are, first, concrete, followed by ceramics and aggregates. Steel has very little presence in weight.

- Manpower: Here we consider the one that handles the fuel and electric machinery, in addition to the labor coming from the CIs, which is of great importance since it corresponds to half the manpower of the project, according to Table 5.

- Machinery: The performance of all the fuel machinery used is 0.20 l/kWh, to obtain the total fuel consumption (liters), which is 4.66 l/m². The electrical machinery consumes 1.72 kWh/m², as shown in Table 5. The equipment coming from the CI corresponds to: crane, telescopic handler, lifting platform, hoists, concrete mixer and cutter; all of great magnitude in the project as they represent more than 71.13% of the total machinery required.

TOTAL ECOLOGICAL FOOTPRINT AND PARTIAL FOOTPRINTS

Table 6 includes the HE values according to the sources of impact and the types of footprints per unit of constructed area. The partial footprint that produces the greatest impact is that of energy and, in particular, the manufacture of materials. The results of the total HE of the proposed study case can be

Resources of the work	Quantity	Percentages
Materials	kg/m²	(%)
Steel	18,37	0,99
Aggregates	241,14	12,95
Cement	28,56	1,53
Ceramic	379,65	20,38
Concrete	1112,22	59,71
Paint	3,76	0,20
Total materials	1783,70	95,76
Manpower	(h/m²)	(%)
CD	8,65	48,36
CD Fuel for machinery	0,12	0,66
CD Electric machinery	0,17	0,97
CI	8,94	50,00
Total manpower	17,88	100,00
Machinery	(h/m²)	(%)
CD Fuel	0,12	11,70
CD Electric	0,17	17,17
CI Electric	0,72	71,13
Total machinery	1,01	100,00
RCD	t/m²	(%)
Total metal	2,23	0,18
Total aggregates and natural stones	29,45	2,39
Total ceramic	274,73	22,32
Total Wood	9,53	0,77
Total plastic and synthetic	1,21	0,10
Total concrete, cement and limes	873,13	70,95
Total mix	40,42	3,28
Total RCD	1230,70	100,00
Food	food kg /m²	-
Total food	3,04	-
RSU	t/m²	-
Total RSU	7,95E-04	-
Electricity	kWh/m²	%
Workhouses	4,33	62,47
Lighting work and facilities testing	2,60	37,53
Total electricity	6,93	100,00
Water	m³/m²	-
Total water	0,0677	-
Used surface	Used surface m²/constructed surface m²	-
Total used surface	0.01	-

Table 5. Quantification and percentage of project resources. Source: González-Vallejo (2017).

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Impact	Type of footprint (hag/m²)					
	Energy	Forests	Pastures	Sea	Crops	Consumed surface
Fuel machinery	3,06E-03	-	5,36E-06	8,57E-06	2,01E-06	-
Electric machinery	1,11E-04	-	7,86E-06	1,26E-05	2,94E-05	-
Manpower food	2,14E-04	-	4,95E-04	7,92E-04	1,85E-03	-
Manpower RSU	4,90E-05	-	-	-	-	-
Manufacturing materials	8,00E-02	2,92E-02	-	-	-	-
Transportation of materials	2,91E-03	-	-	-	-	-
Materials RCD	2,35E-05	-	-	-	-	-
Water	1,87E-06	-	-	-	-	-
Electricity	4,34E-04	-	-	-	-	-
Direct occupation	-	-	-	-	-	2,28E-05
HE total (hag/m²)	0,12					
HE partial (hag/m²)	0,09	2,92E-02	5,09E-04	8,13E-04	1,89E-03	2,28E-05

Table 6. Total ecological footprint and partial footprints. Source: González-Vallejo (2017).

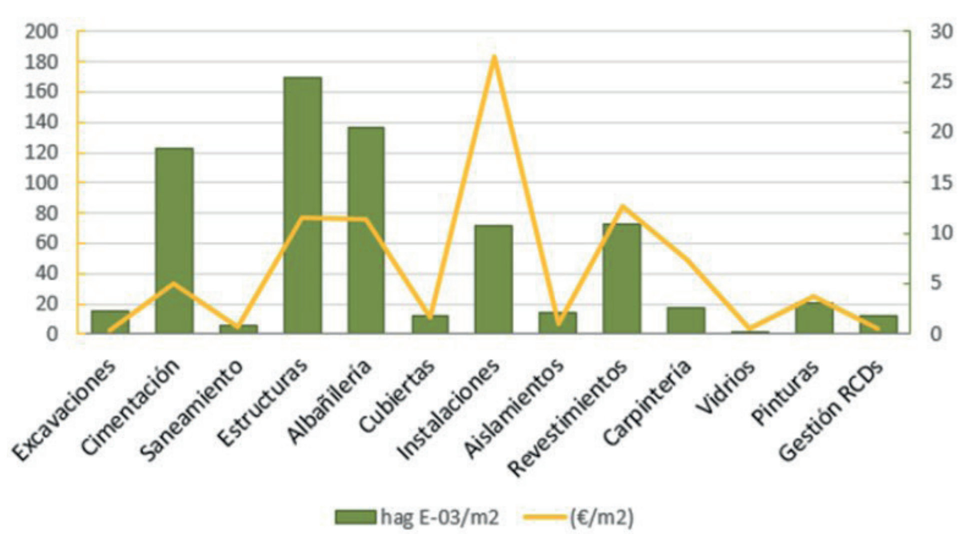

Figure 2. Comparison of economic and environmental impact. Breakdown by project chapters according to the criteria of the BCCA. Source: González-Vallejo (2017).

compared with the previously published results for buildings of the same type evaluated with the initial methodology, for which the impact on 0.235 hag / m² is quantified (González-Vallejo, Marrero and Solís -Guzmán, 2015) and in 0,237 hag/m² (González-Vallejo *et al.*, 2015).

ANALYSIS OF THE ECONOMIC AND ENVIRONMENTAL IMPACT

In this part of the work, a comparison is made between the economic and environmental impact of the entire project (Figure 2) and is broken down into the chapters according to the systematic classification of the BCCA.

It is observed, therefore, that there is no coincidence between the chapters with the largest footprint and those with the highest PEM, with the facilities being the largest chapter, followed by linings and, thirdly, the structures and masonry. However, the phases with the greatest environmental impact are: structures, masonry and foundations.

The total PEM of the project is 500.01 €/m² and has an HE of 0.12 hag/m², and the HE corresponding only to resources (materials, manpower and machinery) is 0.10 hag/m². In other words, the environmental impact of the project corresponds 83% to resources and 17% to electricity, water and surface consumed.

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05HA	m3. Reinforced concrete: 05HHJ00003. m3. Concrete to reinforce HA-25/P/20/IIa in beams (according to BCCA)						
			Quantity		Price	Cost (€)	Total
Code	Unit	Decomposed	Units	Total	€	80,01	96.368,97 €
MATERIALS							
CH02920	m3	Concrete HA-25/P/20/IIa, supplied	1,03	1221,10	60,26	60,26	73.583,30 €
MANPOWER							
TO02100	h	First official bricklayer	0,20	244,22	19,23	3,85	4.696,34 €
TP00100	h	Special laborer	0,60	732,66	18,28	10,97	13.392,99 €
MACHINERY							
MV00100	h	Vibrator	0,30	244,22	19,23	3,85	4.696,34 €

Table 7. Example of quantification of resources in the tool. Chapter 05 of structures, reinforced concrete beams. Source: González-Vallejo (2017).

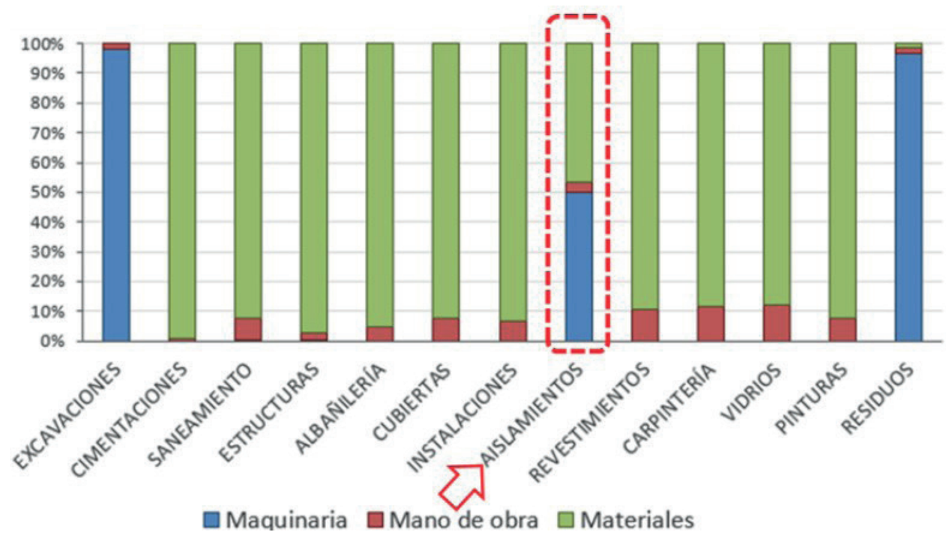

Figure 3. Decomposition in project resources: materials, manpower and machinery. Breakdown by project chapters and BCCA. Source: González-Vallejo (2017).

Families	Unit	Percentage.	HE	Percentage	Cost	Percentage
Of materials	Emission ($kgCO_2/m^2$)	Of total emissions (%)	energy (hag/m^2)	of HE materials (%)	of materials (€/m²)	of the cost (%)
Steel	44,70	14,12	1,13E-02	10,80	72,46 €	29,73
Aggregates	0,48	0,15	1,22E-04	0,12	0,93 €	0,38
Cement	21,89	6,92	5,53E-03	5,29	2,68 €	1,10
Ceramic	96,02	30,34	2,43E-02	23,20	31,59 €	12,96
Copper	5,56	1,76	1,41E-03	1,34	35,24 €	14,46
Concrete	122,98	38,85	3,11E-02	29,71	32,06 €	13,16
Wood	-18,04	-5,70	2,00E-02	19,16	15,42 €	6,33
Paint	12,42	3,92	3,14E-03	3,00	10,38 €	4,26
Total	286,02	90,36	9,69E-02	92,63	200,78 €	82,39
Total of the project	316,52	100	1,05E-01	100	243,71 €	100

Table 8. Families of materials with the greatest impact on the project. Source: González-Vallejo (2017).

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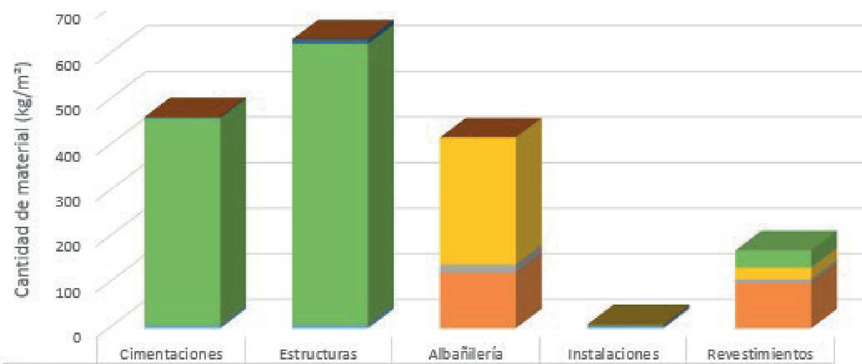

	Cimentaciones	Estructuras	Albañilería	Instalaciones	Revestimientos
PVC				2,28	
Porcelana				1,54	
Pintura	0,06	0,26	0,09		
Madera	2,30	10,00			
Hormigón	454,40	616,38		0,22	37,26
Cobre				1,79	
Cerámico			278,08		26,05
Cemento			17,99		7,67
Áridos			121,95		99,67
Acero	6,17	6,81		3,53	

Figure 4. Materials used (kg/m²) in the chapters with the greatest impact of the project. Source: González-Vallejo (2017).

DETAILED ANALYSIS OF RESOURCES

Table 7 exemplifies the quantification of resources in the tool's database to determine the impacts, according to data extracted from the BCCA. Each resource produces one or several impacts, as reflected in Figure 1.

After studying the importance of resources (materials, manpower and machinery) in each chapter (Figure 3), it is noticed that the use of materials predominates, with the exception of the excavation and RCD management phases where the use of machinery and, to a lesser extent, labor (in all cases). Unlike the rest of the activities, in insulation, 50% of the resources used correspond to machinery, 45% to materials and 5% to manpower. Next, the materials and machinery are analyzed in greater detail, as they are the resources that define the impacts of the project.

Machinery: In excavations, loader and dump truck are used; in the insulation of facades, the electrical machinery (compressor to project) used to place the thermal insulation of projected polyurethane. In the management of RCD, front loader, backhoe loader, dump truck and tilting mechanical trolley for internal transport are used. The impact can be reduced by using more efficient machinery with better performance. In the insulation work it is possible to try other alternatives of materials that do not need machinery and check if, in this way, the impact decreases.

Materials: To the extent that materials are responsible, in almost all chapters, for 90% of the impact, they are analyzed at the project level and, in particular, in each chapter, to determine where the impacts come from.
The project consumes a total of 1862.61 kg/m² of materials, which produces emissions of 316,52 kgCO_2/m².
The HE of materials is 0,011 hag/m², being 0,08 hag/m² HE of energy and 0,03 hag/m² HE of forests (wood).

Next, the families with the greatest impact are selected and the CO2 emissions, the HE and the cost are analyzed, including the percentages over the totals (Table 8). It should be noted that ceramic and concrete materials represent the most significant in weight, in addition to a high economic and environmental impact. Steel has great importance in weight and lower environmental impact in relation to the rest of the materials; however it is the one that generates the greatest economic impact. On the other hand, wood stands out for its large amount of HE, contrary to its CO2 emissions, which are negative. Regarding the economic impact, steel, copper, concrete and ceramics are the most expensive materials.

The chapters of greater impact are: foundations, structures, masonry, facilities and linings (Figure 4).

In structure and foundation materials with greater weight and impact (kg / m²) are used, due to the presence of concrete, followed by masonry, which uses mostly ceramic material. Aggregates are also used in large quantities, in some phases, such as masonry and linings, but as they are natural elements they have much less impact. In facilities and linings, the impacts are more distributed due to the great variety of items and

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materials that include these phases, however, they have a high cost, being effectively the two chapters of greater economic impact.

PROPOSALS TO IMPROVE THE ECONOMIC AND ENVIRONMENTAL IMPACT OF THE PROJECT

To check the sensitivity of the tool, it is proposed to change the thermal insulation material of the facades in the project of the case study. The proposals according to the data of the BCCA are: projected polyurethane, initially proposed insulation (PUS 09TPP90037), fiberglass (PUS 09TPP00110) and mineral wool (PUS 09TPP90221). In Figure 5, we observe how resources vary according to the type of insulation. The new options do not use machinery and the impact is mainly produced by the material and, to a lesser extent, by the manpower.

The economic and environmental impact of the three proposals is analyzed and the comparison is made in Figure 5. Fiberglass insulation is the most viable option from the economic and environmental point of view and the initial projected polyurethane proposal is the worst, since it produces greater economic and environmental impact.

CONCLUSIONS

Starting from the budget of the case study and the methodology of the HE indicator, the economic and environmental impacts are estimated, and it is inferred that the tool is very relevant for its use in the design phase of buildings. The conclusions indicated below, related to the case study, would be applicable to any building that is evaluated from these criteria of economy and sustainability.

Thus, it is possible to determine the project phases with the greatest economic and environmental impact for the case study that, in general terms, are: excavations, foundations, structures, masonry, facilities and linings; in which, however, their level of economic impact does not usually coincide with the environmental impact, which forces decisions to be made in this regard. Therefore, in the design stage, the impacts of these phases and the materials used must be quantified in detail, and other solutions with a lower environmental impact can be proposed and decide whether to change them even if they have a higher cost. The concrete and ceramic materials are those that have greater weight in the total of the project, both being those that produce greater impact, which should be taken into account in the design of the building and try to reduce their use or use more environmentally friendly alternatives such as concrete recycling or ceramics involving more efficient manufacturing energy sources (pellets, for example).

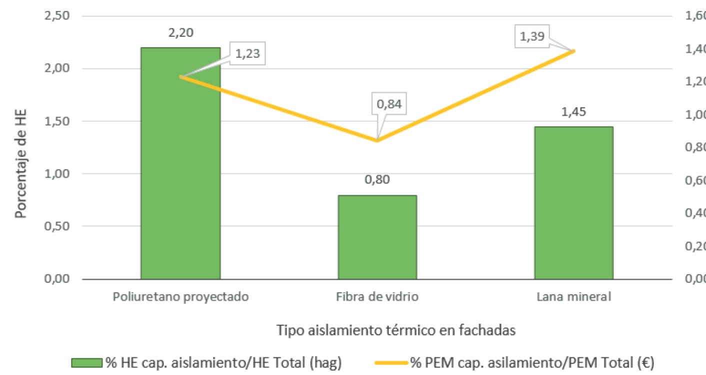

Figure 5. Economic and environmental comparison of the insulation chapter on the total project. Source: González-Vallejo (2017).

The steel has little presence in weight and, nevertheless, its impact is very high, so that the overall impact of the project would be equally improved if we chose recycled steel.

The results of HE, according to the current methodology, are lower when compared with those obtained in buildings with similar characteristics of previous investigations. This is mainly due to the update in the calculation of energy in the manufacture of materials, consumption of energy and water, and the impact produced by manpower.

Therefore, the sensitivity of the tool in terms of the different material alternatives is demonstrated and also that fiberglass is the most suitable insulation. This study would be completed analyzing the operation phase of the building with each of the three alternatives and thus have the vision of the complete ACV and be able to make the best decision.

The tool proposed here includes the construction characteristics most used in Spain, in recent years for residential buildings; the methodology is replicable and, given its versatility, allows its expansion including traditional materials from other climates, new more sustainable proposals, in addition to other types of foundations, metal or wood structures, different types of facades and finishes, etc.

The tool is very flexible in terms of the possibility of expansion and inclusion of new types, construction systems and materials, and easy to use for the user. The use of the BCCA provides a stable and robust system that guarantees its viability and favors such flexibility. It is considered that it is an essential instrument in the decision-making when preparing a project from the design phase, since it allows to study different alternatives of resources and construction systems, according to economic and environmental points of view.

Regarding the weaknesses, the difficulty of access to some of the specific information of the HE indicator is considered, such as consumption data, or specific emissions of materials, energy or water resources, for the construction sector of each country.

In future research, building typologies and resource alternatives, structural systems and proposed construction details can be expanded, and other environmental analyzes, such as embodied energy or the water footprint, can be included. In addition, the data used can be applied to energy certification tools and thus determine the impact of the operation phase of the building, completing the ACV, to facilitate decision making in the design phase with a view to improving the impact levels of the CVE. Likewise, it can be connected with BIM tools, which would facilitate the obtaining of project data.

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