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Life Cycle Assessment of Industrial Building Construction and Recovery Potential. Case Studies in Seville

Madelyn Marrero , Cristina Rivero-Camacho, Alejandro Martínez-Rocamora * ,
María Desirée Alba-Rodríguez and Jaime Solís-Guzmán

ArDiTec Research Group, Department of Architectural Constructions II, Higher Technical School of Building Engineering, Universidad de Sevilla, Av. Reina Mercedes 4-a, 41012 Seville, Spain; madelyn@us.es (M.M.); crivero1@us.es (C.R.-C.); malba2@us.es (M.D.A.-R.); jaimesolis@us.es (J.S.-G.)
* Correspondence: rocamora@us.es

Abstract: In Spain, most businesses are medium to small size enterprises, representing 90% of the total, but there is a lack of studies of the types of building this sector uses. The main objective of this paper is to present a method for the evaluation of small industrial construction projects to facilitate the introduction of eco-efficient solutions. For this, it is necessary to identify the most representative buildings and the aspects of these which have the most environmental impact. A methodology in place for the evaluation of dwelling construction is adapted, for the first time, to evaluate industrial buildings. The construction solutions characterized are those traditionally used in the sector, as identified through 87 surveys. A standardized classification of work units is proposed to enable the use of environmental product information, such as eco-labels and/or EPD, and LCA databases. The carbon footprint (CF) and water footprint (WF) are the indicators selected because of their straightforward message. Finally, a comparative analysis is performed showing the high recycling potential of concrete and cement which, along with metals and aggregates, control the impact in terms of CF. With respect to the WF indicator, plastic substitute aggregates are among the materials with the greatest impact.

Keywords: recycling potential; industrial building; carbon footprint; water footprint; life cycle analysis

1. Introduction

The building sector contributes between 30 and 40% of the total CO_2 emissions generated by society (European Parliament–Council of the European Union 2018). Regulation 305/2011 concerning construction products promotes the assessment of the sustainable use of resources and the environmental impact of construction sites, and where available, recommends that environmental product declarations should be used. There are international standards in place to quantify these impacts by means of life-cycle assessment (LCA) (UNE-EN ISO 14040:2006; UNE-EN ISO 14044:2006; UNE-EN 15978:2012), environmental labels (UNE-EN ISO 14020:2002; UNE-EN ISO 14025:2006; UNE-EN 15804:2012; UNE-EN ISO 14021:2017), and the assessment of building life cycles (UNE-EN ISO 14001:2015; ISO 15686-5:2017). In the case of Spain, Royal Decree 187/2011 recognizes environmental product declarations (EPD) or Type III ecological labels in accordance with standard UNE-EN ISO 14025.

Sustainable urban development [1] is mainly focused on climate change and resource conservation, which can be applied to building construction, starting with material production and transport and continuing through construction activities and usage. Developers play a crucial role in change of the sector since they control purchasing and commissioning of construction products, and can lead environmental awareness, requiring ready access to environmental information [2].

1.1. Industrial Building Assessment

The assessment of the environmental impact of industrial buildings and prefabricated building elements has been explored by several authors, and a variety of indicators including carbon footprint, embodied energy or waste reduction have been reported. For example, researchers from the Basque Country in Spain proposed a method for the environmental analysis of industrial buildings through an integrated value model for sustainable assessment (MIVES) [3,4]. According to the authors, industrial buildings have been overlooked in life cycle analysis (LCA) studies which usually focus on residential and office buildings. Their approach follows an analytic hierarchical process (AHP) where several quantitative and qualitative aspects of the building are evaluated, transformed into a standard unit, and weighted according to the importance of each aspect. Bonamente and Cotana [5] conducted a systematic LCA of four prefabricated industrial buildings in Italy considering carbon footprint and primary energy consumption in a cradle-to-grave approach. Their calculation model was especially sensitive to modifications of the thermal insulation and expected service life as these influenced the embodied energy and carbon footprint of the construction phase, but more significantly the energy consumption during the use phase. Floor area and the foundation type had a lower influence on the results. Moreover, Tulevech et al. [6] carried out a LCA of a low-energy industrial building and a multi-scenario analysis that revealed significant energy-saving potential through a combination of recycling strategies and the installation of a rooftop PV system, which enabled zero life-cycle energy demand to be achieved.

Regarding the analysis of existing industrial buildings, Opher et al. [7] studied the life-cycle GHG emissions of the restoration of a heritage industrial building in Toronto, Canada, with particular interest in considering restrictions on the design related to the conservation of the building's external aesthetics. Their analysis included a cradle-to-grave LCA of construction materials, transport, and construction activities for the restoration process, as well as the foreseeable emissions due to operational energy consumption. The results showed that the embodied carbon footprint of the restoration project would be balanced by savings in operational energy within 3 to 13 years, depending on the energy sources used for heating, cooling, and lighting. Shubbar et al. [8] explored the potential energy savings of retrofitting an existing industrial building in Liverpool, UK, using IESVE (integrated environmental solutions virtual environment) software. They determined that installing wall and floor insulation could reduce energy consumption and carbon footprint by 56%, which could be further improved by using PV panels.

Heravi et al. [9] highlighted the importance of the sustainability of industrial buildings in developing countries given their need for growth in industrial areas. In their study, they designed a holistic evaluation model of sustainability indicators including the environmental, social, and economic dimensions through the entire life cycle of petrochemical projects. Finally, they evaluated the correlation between variables and between the three dimensions of sustainability. Similarly, Židoniene and Kruopiene [10] proposed another life cycle assessment and environmental impact assessment framework for industrial buildings and applied it to a case study of an insulation materials production plant, enabling a 40% decrease of impact on human health and a 20% saving of primary resources compared to the initial situation.

In some instances, LCA studies focus on building systems or elements instead of complete buildings. For instance, Kovacic et al. [11] developed a life-cycle environmental and economic analysis tool to support decision-making on façade systems for industrial buildings. Through the assessment of three façade systems, they determined that the substantial differences in construction costs became less significant after 35 years of service life. Regarding the environmental dimension, cross-laminated timber was predicted to produce 80% less emissions than steel-liner tray and sandwich panels. Švajlenka et al. [12] analyzed the environmental impact of different construction systems of buildings for agricultural production through a cradle-to-gate LCA method. Again, wood-based systems obtained the best results in comparison to steel- and reinforced-concrete-based solutions. Aye et al. [13]

analyzed the life-cycle greenhouse gas (GHG) emissions and energy consumption of prefabricated reusable building modules. The assessment of an 8-storey building revealed that a steel-structured prefabricated system could reduce material consumption by up to 78% compared to a conventional concrete system, while this resulted in a 50% increase in embodied energy. The authors highlighted the benefits of reusing these materials for reduction of both the space needed for landfill and the requirement for primary resources. This reuse of materials produced significant embodied energy savings for the construction of a new system (81% for steel and 69% for timber systems over concrete), as well as reduction in the consumption of primary material resources. In terms of WF, plastics are the most important category, followed by wooden materials, even though both materials are not significant in terms of weight.

Regarding construction and demolition waste, Begum et al. [14] compared conventional and industrialized building systems in terms of waste generation and recycling potential. The study revealed that prefabrication resulted in significant reduction in waste generation, while the rates of reused and recycled waste materials were relatively higher than in conventional construction. The waste reduction potential of prefabricated elements was also explored by Jaillon et al. [15] through a survey of experienced professionals and several case studies of residential buildings in Hong Kong, and by Li et al. [16], who developed a calculation model for the benefits of prefabrication in construction where they integrated all waste handling activities, and validated it through a case study in Shenzhen, China. Furthermore, the latter showed that granting subsidies to promote the use of prefabrication was a more effective strategy than increasing taxes on waste generation. Recently, Lu et al. [17] carried out a new quantitative analysis to re-evaluate the effects of prefabrication on the minimization of construction and demolition waste based on big data obtained from 114 high-rise building projects in Hong Kong, mostly residential, with 85 of them applying prefabrication and 29 conventional construction. Their study revealed that prefabrication could reduce waste generation by 15.38% compared to conventional construction, with precast windows and walls playing a major role in this. Finally, Mah et al. [18] estimated that moving to prefabricated industrial building systems would reduce the impact on landfill of construction and demolition waste by 98.1%, while continuing with the business-as-usual landfilling model from now to 2025 would increase this impact by 20.2%.

1.2. Life Cycle Assessment of Architectural Projects and Construction Materials

At the material manufacturing level, environmental product declarations (EPDs) incorporate the LCA inventory of products and assess the use and efficiency of material resources [19]. This information can be employed as a contracting criterion [20,21], as described in the Spanish Law of Public Sector Contracts (LPSC) [22], which establishes a contracts framework that includes economic, environmental and social criteria. The green public procurement concept was also incorporated into Spanish legislation in 2019 with environmental policies related to climate change, resource use, and sustainable production and consumption [23]. The latter establishes sustainability requirements for transport, road construction, design and construction of offices, food, etc.

In Spain, there are tools in place for the assessment of projects, such as BREEAM (Building Research Establishment Environmental Assessment Methodology) [24] and LEED (Leadership in Energy and Environmental Design) [25]. Other available tools are ECOMETRO (carbon footprint metric in construction) [26], BEDEC cost database (database of construction cost in Catalunya) [27], SOFIAS (Software for a Sustainable Architecture) tool [28], and E2CO2Cero (embodied energy and zero CO_2 tool) [29], which calculate CO_2 emissions through the project bill of quantities. However, these are not generally employed in Spain, mainly due to the expertise needed for their management and their expensive implementation due to user license payments. Open data can be employed for LCA information, such as free access construction cost databases and EPDs, which can reduce the assessment costs. There are also opportunities to include other indicators, apart from the

calculation of CO_2 emissions, and to identify those activities that actually control a variety of impacts [30].

In Spain, most businesses are medium to small size enterprises located in industrial buildings. These buildings are usually small [31], with less than 20 employees. For example, in 2014, according to the last report available by the National Institute of Statistics of Spain, these represented 90% of the total number of enterprises. Despite this high representation of small industrial buildings in this sector, very few studies have focused on determining their environmental impact.

1.3. The Proposal

The present paper presents a methodology for the evaluation of industrial construction projects in Spain. For this, it is necessary to identify the most representative buildings and the most impacting elements of the projects. A methodology that evaluates urbanization, gardens and dwelling construction is adapted, for the first time, for the assessment of industrial buildings. The constructive solutions are those traditionally used in the sector, as identified through surveys. A standardized classification of work units is proposed to introduce the environmental product information. The carbon footprint (CF), water footprint (WF), the generation of construction and demolition waste (CDW) and its recyclability potential are the indicators selected because of their straightforward message. Finally, in the province of Seville, a comparative analysis of the most characteristic industrial building typologies, identified from an 87-buildings sample of industrial projects, is performed.

2. Materials and Methods

As can be seen in Figure 1, the methodology commences with the collection of accessible and generic data from construction cost and LCA databases. This information can be tailored to the project specifics, the project bill of quantities and environmental product information, such as that obtained for the specific materials and products from eco-labels, self-declarations and EPDs. Each element that is part of the project budget is assessed in terms of WF and CF, generating an "environmental budget", similar to that previously defined for the calculation of the ecological footprint [32]. These two environmental impacts have also been assessed in other type of projects [33] and in CDW management [34]. Finally, surveys are defined that include a new classification of works and construction characteristics in the province of Seville, and three representative projects are fully evaluated.

2.1. Work Units Classification

The automation of data and its processing constitute advances in information technology (IT) that provide major advantages. The most representative classification systems of construction information, in order of publication, are: MasterFormat [35], CI/SfB [36], the Standard Method of Measurement of Civil Engineering [37], Uniformat [38], and Uniclass [39]. In Spain, the construction classification systems are related to cost control and are region specific, such as the Institute of Construction Technology of Catalonia [27] and the Andalusian Construction Cost Database (ACCD) [40].

The ACCD [41], published from 1986 to the present, is a database classification [40] with a pyramidal structure (see Figure 2). The base of the pyramid is supplier costs which represents the actual market. The next ascending level is basic costs (BC), which are of three types, materials, labor and machinery. The next higher level, the auxiliary costs (AC) are combinations of BC, while work units are represented above this by unit costs (UC) composed of BC and/or AC. UC are grouped in chapters corresponding to the stages of the construction process, such as earthworks, foundation, structure, etc. At the top of the pyramid are the costs that are not part of the activities of the construction site, including industrial profit, taxes, and overheads.
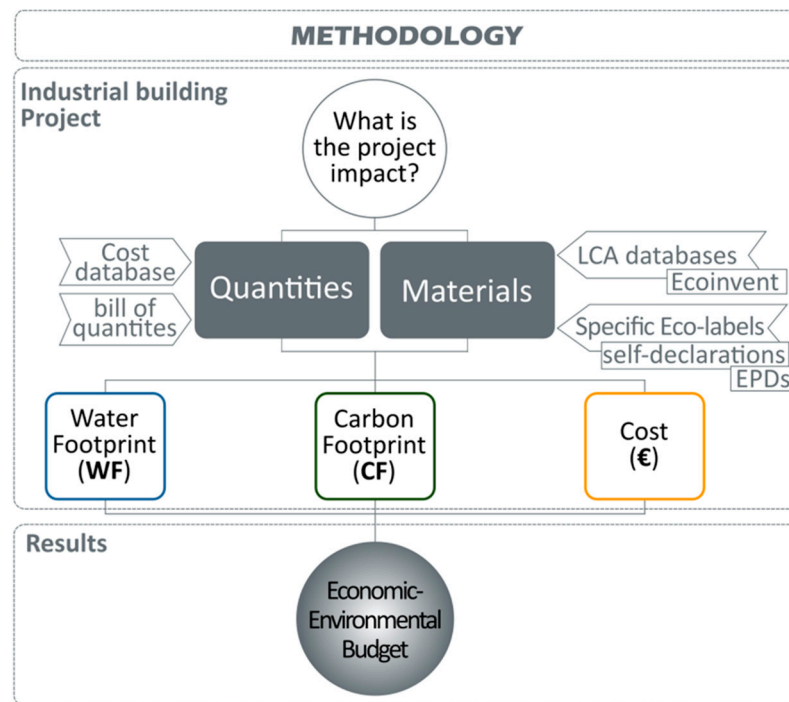
Figure 1. Methodology for the inclusion of the WF (m^3_{water}) and CF (tCO_2eq) in the green assessment of industrial projects.
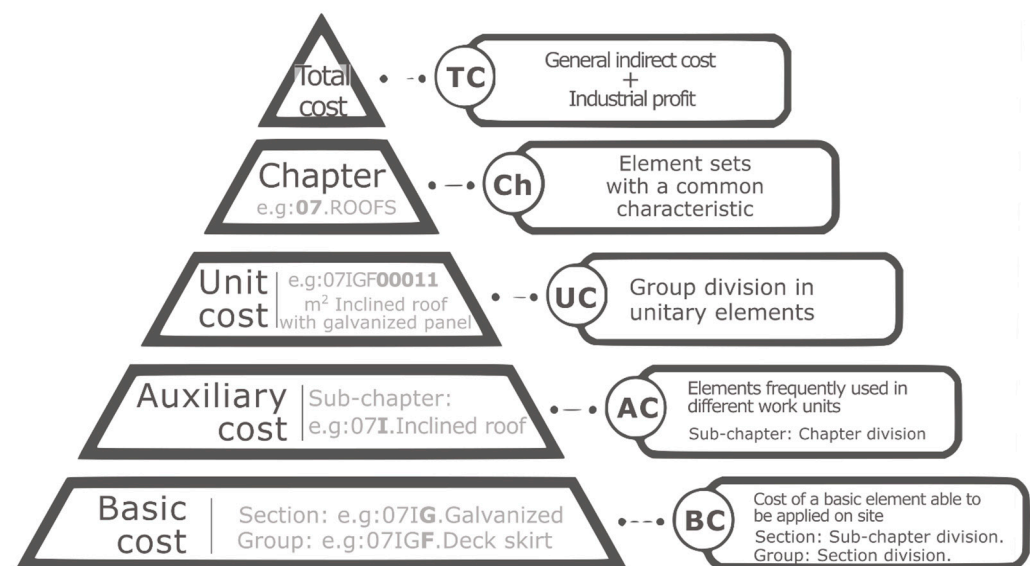

Figure 2. Hierarchical pyramid of the ACCD (adapted from [42]).

2.2. Environmental Analysis

Several tools and calculation models are available to determine the environmental impact of construction. These can be based on multi-variable analysis, such as the ecological footprint, energy, CML, or Eco-indicator, or use one indicator, such as CF or WF [43]. The CF indicator is commonly used in construction work assessment [44–46], and improvements have taken place in the definition of CO_2 ranges in manufacturing [47]. The WF, another indicator with a straightforward message [48,49], is defined by the water footprint network [50] and determines the amount of water consumed in the production of goods, employing the standard calculation methodology [51] and using *The Water Footprint As-*

sessment Manual [52]. The combination of indicators has produced interesting comparative results in previous work by the authors [33,34].

CF and WF information can be obtained from LCA databases of construction products [53] and EPDs (www.eco-platform.org/ accessed on 15 December 2021) [54]. The consumption of natural resources on site is mainly due to energy consumption by machinery (fuel or electricity), and construction material expenditure (e.g., during manufacture, transport, and commissioning).

Machinery

The machinery environmental impact is due to the energy consumption during its operation on the construction site (differentiating between fuel and electrical energy). Fuel consumption depends on the engine power and working hours, differentiating between diesel and petrol. The CO_2 generated by one liter of fuel is used [55] as an emission factor in Equation (1). The CO_2 emissions corresponding to the Spanish electrical system [56] are used for electrical machinery on site (see Equation (2)). The WF of electricity consumption is obtained from the embodied water in energy generation according to LCA databases.

Building materials

The environmental impact of materials, following a cradle-to-gate model, can be obtained from EPDs or LCA databases. Their transport to the construction site depends on the type of products [32]: for concrete, the truck capacity is 24,000 kg and 20 km trip and for the other products it is 2000 kg and 250 km trip. The diesel consumption is 26 L/100 km and its emissions are 2.62×10^{-3} tCO$_2$/L [57]. The diesel embodied water is 1.26 m^3/L, and the electric mix embodied energy is 3.6 MJ/kWh in Spain (see Equations (1) and (2)).

The volume of each construction element is determined using technical data and commercial product descriptions as BC have typical measurement units in the market (m^3, m^2, meters, tons, thousands of units, etc.) not always expressed in kg or m^3. Once the volume is calculated, the elements' densities, according to the *Catalogue of Construction Solutions of the Technical Building Code* [58] and the *Spanish Technical Building Code* [59] are used to calculate the mass, as shown in Table 1.

Table 1. Weight calculation of basic construction elements.

ACCDCode	Cost (€)	Unit	Description	Volume (m^3)			Density (kg/m^3)	Weight (kg)	Source
				X	Y	Z			
AG00100	10.86	m^3	Gravel	1.00	1.00	1.00	1784.00	1784.000	[58]
CA80030	3.78	kg	Steel triangular section mesh	1.00	1.00	1.00	1.00	1.000	[58]
CH80200	157.08	m^3	Light concrete-25 N/mm^2	1.00	1.00	1.00	2 549.25	2549.250	[59]
FB80200	2.14	u	Concrete block 50 × 20 × 25 cm	0.50	0.20	0.25	900.00	22.500	[58]
IE02600	4.43	m	Copper wire 1 × 16 mm^2 H07V-K(AS)	1.00	16.00	10^{-6}	880.00	0.0141	[58]
PA00500	1.71	Kg	Acrylic paint	1.00	1.00	1.00	1.00	1.000	[58]
QP00800	3.99	m	Sheet flashing for sandwich panel. Polyester	1.00	0.50	0.005	1140.00	2.085	[59]
QP02000	22.70	m^2	Sandwich panel 30 mm polyester	1.00	1.00	0.03	1223.64	36.709	[59]
RA00300	0.17	u	Soft solid color tile 15 × 15 cm	0.15	0.15	0.01	2300.00	0.518	[58]
WW00300	0.55	u	Special small material	0.10	0.005	0.005	8004.65	0.020	[59]

The LCA data is obtained from the Ecoinvent database [60], which was established by the Swiss Centre for Life Cycle Inventories and applied in Simapro. It is chosen because it combines several databases of construction materials [53]. Finally, BC are grouped into "environmental families". The environmental impact of machinery is obtained by applying Equations (1) and (2) depending on the energy source of each machine, while that of construction materials is obtained through Equation (3).

$$IM_{COMB} = P \times TU \times Per \times IU_{COMB}, \tag{1}$$

where P: power of the engine (kW); TU: time of use (h); Per: performance as liters of diesel or petrol consumed per unit of engine power (l/kWh); and IU_{COMB}: unit impact of diesel or petrol (MJ/L, tCO_2eq/L, m^3_{water}/L) [61].

$$IM_{ELEC} = P \times TU \times IU_{ELEC}, \tag{2}$$

where IU_{ELEC}: unit impact of electric mix (MJ/kWh, tCO_2eq/kWh, m^3_{water}/kWh) [50,62].

$$I_{MAT} = (\Sigma i \, Cm_i \times IU_{MAT}) + (IU_{TRAN} \times Cm_i), \tag{3}$$

where IU_{MAT}: unit impact of manufacturing per kg of material (MJ/kg, tCO_2eq/kg, m^3_{water}/kg); IU_{TRAN}: unit impact of transport per kg of material (MJ/kg, tCO_2eq/kg, m^3_{water}/kg); and Cm_i: consumption of construction material *i* (kg).

The life cycle inventory (LCI) for the CF of each material, is obtained using the IPCC 100 yr methodology, which isolates CO_2 and other GHGs in tCO_2eq/kg. Calculation of the WF is based on the work of Hoekstra et al. [51,52,63], that represents the direct and indirect consumption in m^3_{water}/kg. Figure 3 summarizes the methodology, which combines the construction cost systematic classification of the work with the environmental impact.
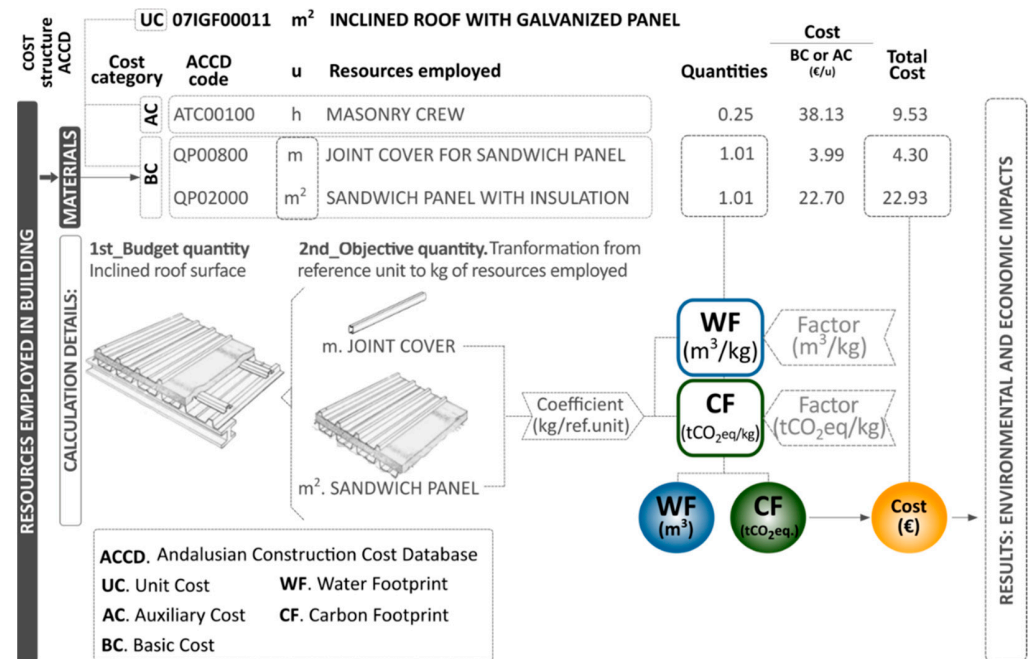

Figure 3. The industrial building unit is transformed into environmental impact per work unit.

Construction and demolition waste (CDW)

The construction materials that generate waste due to losses, cuts, damaged pieces, demolition and three transformation coefficients [64] are defined for calculation, as expressed in Equation (4):

$$QRi = Qi \times CRi \times CCi \times CTi, \tag{4}$$

where QR_i: amount of waste generated by element or material i; Qi: quantity of material i in project; CRi: percentage of the original element wasted; CC_i: conversion factor of the units of the original element or product to the units of waste (t, m^3, kg, or unit); and CT_i: considers the change in volume of material i when it is transformed into waste (Figure 4).

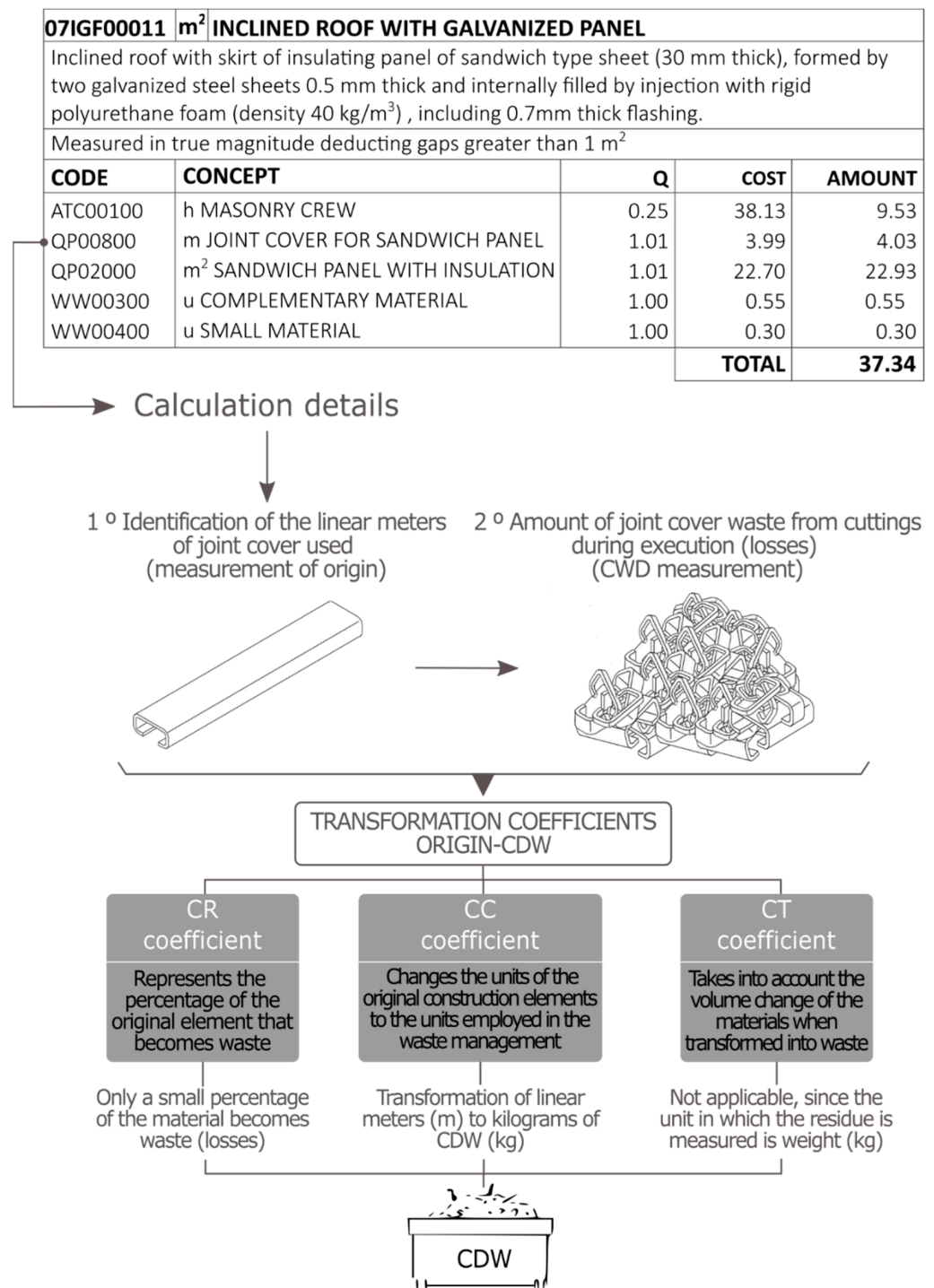| 07IGF00011	m² INCLINED ROOF WITH GALVANIZED PANEL			
Inclined roof with skirt of insulating panel of sandwich type sheet (30 mm thick), formed by two galvanized steel sheets 0.5 mm thick and internally filled by injection with rigid polyurethane foam (density 40 kg/m³) , including 0.7mm thick flashing.				
Measured in true magnitude deducting gaps greater than 1 m²				
CODE	**CONCEPT**	**Q**	**COST**	**AMOUNT**
ATC00100	h MASONRY CREW	0.25	38.13	9.53
QP00800	m JOINT COVER FOR SANDWICH PANEL	1.01	3.99	4.03
QP02000	m² SANDWICH PANEL WITH INSULATION	1.01	22.70	22.93
WW00300	u COMPLEMENTARY MATERIAL	1.00	0.55	0.55
WW00400	u SMALL MATERIAL	1.00	0.30	0.30
			TOTAL	**37.34**

Figure 4. Example of unit cost of chapter roof and the calculation of CDW using the transformation coefficients.

Table 2 shows examples of these coefficients used in the construction of industrial buildings. This methodology has been explained more fully by Marrero et al. [65]. For example, for joint cover (Figure 4), the CR coefficient is 0.01 because only 1% is lost due to cuttings during the execution; CC is equal to 2.00 because the unit of measurement of the element is its length in meters, and one meter of cover weights 2 kg; finally, CT is equal to 1.00 as this coefficient considers the change in volume of the material from the origin to its destination as waste, but in this case the unit of waste management is also kilograms. The

CDW management cost is obtained by applying the corresponding cost in the ACCD for each type of waste depending on its destination/treatment.

Table 2. Transformation coefficients for an industrial building construction (examples defined in the present work).

Constructive Element	Waste Origin	Waste Generated	CR	CC	CT
Sandwich panel for cover	Sandwich panel	Losses	0.01	0.367	1.00
	Wooden	Packaging	0.05	9.380	1.00
	Plastic	Packaging	1.00	0.006	1.00
Steel (kg)	Steel	Losses	0.01	0.001	1.00
Paint (kg)	Container	Packaging	1.00	0.035	1.00
	Wooden	Packaging	0.05	0.00025	1.00
	Plastic	Packaging	1.00	1.28×10^{-5}	1.00
Lighting circuit (m)	Copper	Losses	0.05	0.829	1.00
	Wood	Packaging	0.05	0.001	1.00
Earth excavation (m^3)	Soil	Excavation	1.00	1.000	1.25
Join cover of roof	Plastic	Losses	0.01	2.000	1.00
High-density polyethylene water pipe	HDPE	Losses	0.05	0.00213	1.00
	Sand	Losses	0.01	0.065	1.00
Reinforced concrete	Concrete	Losses	0.05	1.000	1.00

3. Case Studies

3.1. RecoverIND Project

Access to and assessment of environmental information can be achieved through teaching tools for technicians, engineers and architects. The main objective of the European project RecoverIND, funded in the Erasmus+ 2020 call, is the transfer of knowledge, through the implementation of training tools at professional, vocational and higher education levels, on the use of new technologies that allow the rapid acquisition of data in the sector, with a wide range of applications in the construction industry, renovation and energy efficiency of buildings. Another important objective of the project is to facilitate the evaluation of industrial buildings' life cycle and identify better economic or environmental alternatives. The project is developing an open educational resources (OER) platform for students, teachers, researchers, and enterprises, to gain knowledge on environmental impact estimation methods. The main page of the official website shown in Figure 5 [66]. The circle represents the main objective to be tackle by RecoverIND, clockwise from top: teaching innovation, industry, material transport, construction, waste management, recycling potential and digitalization in the life cycle of industrial buildings. In this connection, the present article explores a simple methodology for the environmental assessment of industrial buildings. In the next sections, the evaluation of the sustainability of industrial budlings, using case studies, and tools in place for the assessment are presented.
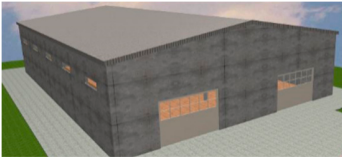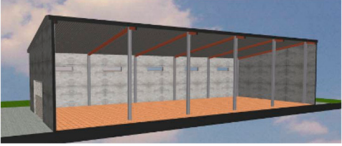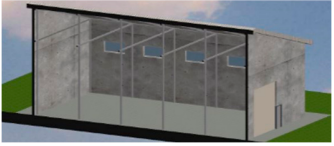
3.2. Actual Projects

The case studies belong to Los Alcores, a supra-municipal entity that includes Seville capital and municipalities in Los Alcores area. Among its responsibilities is the management of CDW. It serves a population of approximately one million inhabitants. A statistical study was carried out to typologically assess the industrial buildings.

The study comprised the following:

1. Classification of industrial buildings based on specific construction criteria of the buildings. This included the following as the most important aspects: (industrial) use, number of floors, foundation, structure, roof, roof support, envelope, height and wall-to-wall width.

2. Performing the survey. The surveys were carried out to obtain the characteristics and quantities (Q) of work. Each survey was divided into two parts: the first was aimed at identifying the project according to the typology and the period in which it was carried out; the second collected the values of each of the different concepts into which each system is divided. This was organized according to a new classification model based on the ACCD [41], which can be found in Table A1 in Appendix A. Based on the economic budget, the survey gathered data on the amount of each construction element (in its corresponding unit) per m^2 of floor area (see Table 3).

3. Analysis of the construction typologies of industrial buildings. The survey study was carried out in three municipalities of Los Alcores. A total of 87 industrial buildings were studied, 28 in Alcalá, 29 in Carmona and 30 in Mairena del Alcor.

4. Obtaining average statistical values of each construction element per m^2 of floor area for the identified as most representative building typologies. These average values are obtained from the interquartile range of 75%, to eliminate discordant extreme values.

Table 3. Description of case studies.

	Project N1	Project N2	Project N3
LOCALIZATION			
Municipality	Carmona	Alcalá de Guadaira	Mairena del Alcor
Plastic	Seville	Seville	Seville
Community	Los Alcores	Los Alcores	Los Alcores
DIMENSIONS			
Floor area (m^2)	673.88	464.45	787.90
Number of floors	1	1	1
Total height of building (m)	7.90	8.84	7.50
Total width of building (m)	20.00	10.00	30.10
CONSTRUCTIVE FEATURES	Heavy slab, continuous trench, metal structure, heavy enclosure executed on site with concrete blocks and sloping sheet metal in roof.	Heavy slab, insulated footing, concrete structure, precast enclosure, and sloping roof with sandwich panel.	Semi-heavy slab, piles, metal structure, precast enclosure, and sloping roof with precast panels.
IMAGES			
Exterior			
Interior			

The most representative typologies were: typology 1 (one floor, precast enclosure and heavy slab), with 15 buildings analyzed; typology 2 (one floor, precast enclosure and semi-heavy slab), with 29 buildings; and typology 3 (one floor, in-situ enclosure and heavy slab), with 15 buildings. For these three typologies, three projects were selected belonging to each municipality. Their basic characteristics (floor area, type of structure, façade, concrete slab, height from floor to ceiling and wall-to-wall width) are listed in Table 3 and their projects' bills of quantities can be found in Table 4. All projects have one floor, concrete pads foundation, and sloped roof with portico support.

Figure 5. Homepage with the RecoverIND website menu for teaching tools [66].

Table 4. Bills of quantities of the three case studies according to the systematic classification defined in Table A1.

Code	Unit	Description	N1	N2	N3
02		EARTH WORK			
02EX	m^3	Open excavation	0.09	1.17	0.10
02RR	m^3	Refilling and compacting			0.00
02TX	m^3	Transport	0.11	0.22	0.13
03		FOUNDATION			
03AX	kg	Rebars	15.70	0.65	3.99
03EX	m^2	Formwork		0.36	
03HA	m^3	Reinforced concrete	0.07	0.11	0.09
03HM	m^3	Bulk concrete	0.01	0.17	0.01
04		SEWAGE			
04EA	u	Manholes and pits	0.01	0.03	0.01
04EC	m	Underground pipeline	0.12	0.16	0.04
04VB	m	Vertical pipelines	0.08	0.08	0.02
05		STRUCTURE			
05AC	kg	Hot rolled steel		4.11	19.55
05AF	Kg	Cold rolled steel			5.66
05FX	m^2	Concrete slab		1.03	
05HA	kg	Steel rebar			0.69
06		BRICK WORK			
06BZ	m^2	Wall made of concrete blocks			0.61
06PH	m^2	Precast concrete	1.28	2.19	
07		ROOF			
07IX	m^2	Sloping roof	0.79	0.93	0.93

Table 4. *Cont.*

Code	Unit	Description	N1	N2	N3
08		INSTALLATIONS			
08EC	m	Electric circuits	0.09		0.35
08ED	m	Electric bypass	0.06	0.01	
08EL	u	Lights	0.01		0.07
08ET	u	Electric socket	0.02		0.05
08EP	m	Grounding conductor	0.00	0.38	
08FF	m	Water pipes		0.01	0.10
08FS	u	Bathroom sanitary ware	0.00	0.01	
10		FINISHES			
10AA	m^2	Tiles	0.02		
10SC	m^2	Ceramic floor	0.00		
10SY	m^2	Medium weight floor	0.99		
10SZ	m^2	High weight floor		1.00	0.20
10RX	m	Windowsill			0.02
11		CARPENTRY AND SAFETY			
11AX	m^2	Steel	0.00	0.07	0.03
11LX	m^2	Aluminium		0.07	0.07
12		GLASS AND POLYESTER			
12XX	m^2	Glass			0.03
13		PAINT			
13EX	m^2	Exterior			0.02
13IX	m^2	Interior		0.15	

4. Results and Discussion

Table 5 shows the results obtained from the evaluation material consumption for the case studies. The project construction units and its quantities are grouped by families of materials according to their nature; the family of concrete and cement, used in the foundation and enclosures, having the highest consumption in terms of weight. The next families in terms of weight are aggregates and stones, used in the preparation of mortars and for the improvement of soil, and metals and alloys consumed in the structure, roof and installations. The most important families are similar to the ones employed in dwelling construction in Spain [67], except for the use of bricks and ceramic materials which are typical of the residential sector.

Table 5. Weight of construction materials consumed in the case studies grouped by family.

Material Family	N1 (kg)	N1 (kg/m^2)	N2 (kg)	N2 (kg/m^2)	N3 (kg)	N3 (kg/m^2)
Concrete and cement	927,550	1177.2	739,335	1591.8	952,434	1413.3
Ceramic and bricks	9776	12.4	5763	12.4	8361	12.4
Wood	3990	5.0	3342	7.1	2533	3.7
Metals and alloys	41,755	52.9	16,865	36.3	32,788	48.6
Plastics	2649	3.3	4079	8.7	3166	4.6
Water	6007	7.6	5885	12.6	3137	4.6
Aggregates and stones	271,077	344.0	181,726	391.2	209,129	310.3
Others	36,223	45.9	25546	55.0	36,808	54.6
TOTAL	1,299,031	1648.7	982,543	2115.5	1,248,359	1.852.5

Table 6 shows the results obtained from the environmental evaluation of the case studies. Since the N3 project was originally designed with a concrete block enclosure, a low percentage of recyclability can be obtained. For this reason, it was decided to evaluate the same project replacing the facade with precast concrete (as in cases N1 and N2). The results obtained show that not only is it possible to double the percentage of recyclability of the

project, but also to reduce its environmental and economic impact. The labor required for the assembly of the prefabricated façade is reduced; however, more hours of machinery are required.

Table 6. Economic and environmental evaluation of the case studies.

Project	N1	N2	N3 (Concrete Block)	N3 (Precast Concrete)
Budget (€)	181,623	137,964	208,182	190,879
Cost per floor area (€/m^2)	230.52	297.05	308.93	283.25
Carbon footprint (tCO$_2$eq)	271.36	204.043	234.949	232,442
Carbon footprint (tCO$_2$eq/m^2)	0.34	0.44	0.349	0.35
Water footprint (m^3)	8423	6778	7407	7,62
Water footprint (m^3/m^2)	10.69	14.60	10.992	11.30
CDW (t total)	39,399	29,79	37,870	34,39
CDW (t total/m^2)	50.01	64.15	56.198	50.97
% Recyclability of raw materials	64.15	64.12	34.89	64,31
% Recyclability of CDW	49.88	49.19	49.58	49,37
Total working hours	3618	2972	3336	3095
Total machine working hours	354.72	383.35	148.74	208.35

In terms of WF, plastics are the most important family, followed by wooden materials, even though these are not the most consumed. The CF of concrete and cement is the highest, followed by metals and alloys, both being also the most consumed families.

Solís-Guzmán et al. [46] observed that dwelling construction on average generates 600 kgCO$_2$eq/m^2 of floor area, double that of industrial buildings. In addition, the cost obtained in that study (800 €/m^2) was triple the results for the industrial case studies analyzed here. Ruiz-Perez et al. [30], determined the carbon footprint of two urbanization projects during the renovation of a city street with gardens. Their footprint was 141.2 and 256.5 kgCO$_2$eq/m^2 of street area, respectively. The project costs were also calculated as 88.9 and 205.3 €/m^2 of street area, respectively. Thus, the results obtained for the studied industrial buildings were of the same magnitude and not significantly different from these. Compared to the results from Bonamente et al. [5], where the carbon footprint of the construction phase was between 252 and 468 kgCO$_2$eq/m^2 for the four case studies they analyzed, those from the present study fall under that range, which can be explained by differences in the calculation method. Regarding the weight of materials consumption, several studies by Scheuer et al. [68], Kofoworola and Gheewala [69] and Tulevech et al. [6] have reported similar values for office, institutional and industrial buildings.

It is also of note that, in the case of dwelling construction, a standardized cost database was employed with all the representative data from social housing construction, while for that of urbanization and gardening, only the work classification system was available from open-source databases, but it was necessary to create new construction work units specifically for the two projects studied. In the case of industrial building construction, construction cost databases are not available, so it was necessary to adapt the classification system of dwelling construction to industrial buildings. Many similarities were found in several work units, such as those related to the building's installations, but others needed to be created anew.

In Table 6, the recyclability criteria are established as follows: concrete and cement (70% in dry assembly and 40% in wet solutions), ceramics and bricks (20%), wood (30%), metals (100%), plastics (0%), water (0%), aggregates and stones (50% in dry assembly and 30% in wet solutions), excavated soil is 80%, and other materials (10%). The total percentage of recyclability is obtained by dividing the total weight of recyclable materials or CDW by the total weight consumed or generated, respectively.

Another way of putting together the information is by chapters in the project budget, which represent stages in the construction work. As can be seen in Figure 6, the chapter of structures is the most impacting, followed by foundation, making these stages of the

execution of the project crucial for controlling the environmental impact in terms of CF. The execution of the installations is shown to be an important factor regarding the WF indicator.
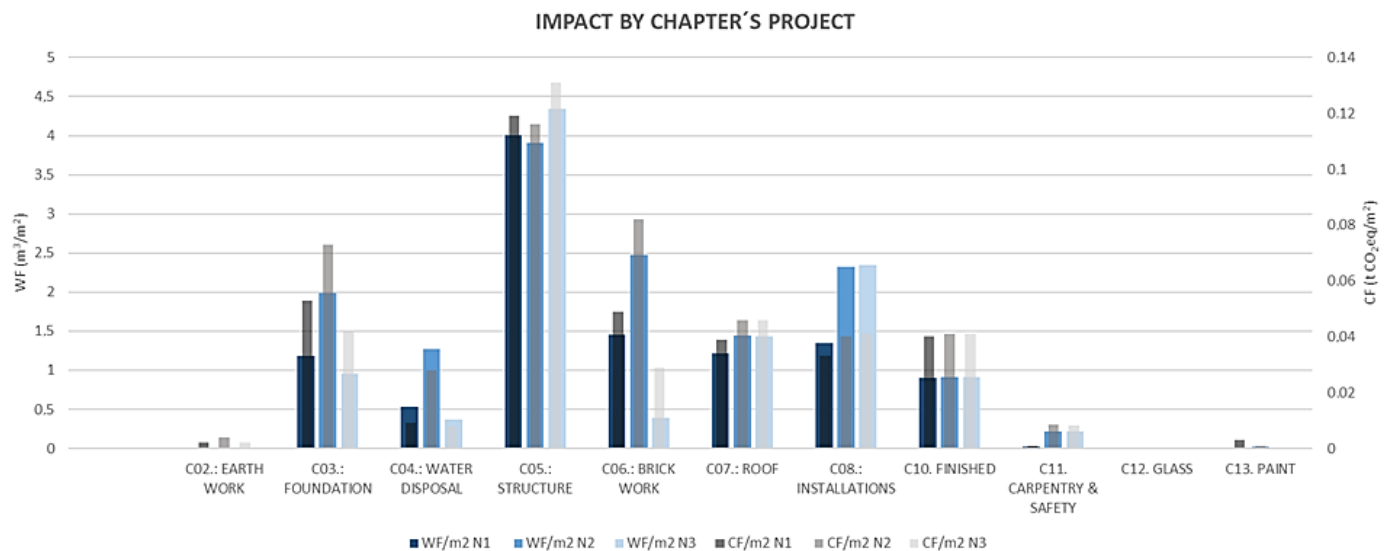

Figure 6. Carbon and water footprint of case studies per chapter of the classification system.

In Figure 7, these impacts are represented in percentages, clearly showing that almost half of the CF is caused by use of concrete and cement, and that the WF is controlled in a similar way by three families: concrete and cement, wood and plastics, representing about 70% of the total.

The CDW generated by the three projects is presented by family in Table 7. As expected, the most consumed materials are also the ones that generate most of the waste, specifically the family of concrete and cement. This family has a high recycling potential, and elements can be reused if carefully extracted. The next family in importance is aggregates and stones, inert materials that can be recycled if not mixed with other materials. In Spain, since 2008, efforts have been made to recycle these by introducing recycled aggregates usage and control in the Code of Structural Concrete [70], but still less than 10% is used in new concrete, while the rest is mainly used as land refill [71]. However, recycled concrete can replace elements in construction that are less restrictive, such as cycling tracks, trench filling and electric shaft foundations [72]. In these applications it has been shown that in-situ recycling of concrete can generate significant savings [65].

Table 7. Weight of CDW in the case studies grouped by material family.

| Material Family	N1 (kg)	N1 (kg/m^2)	N2 (kg)	N2 (kg/m^2)	N3 (kg)	N3 (kg/m^2)
Concrete and cement	27,826.514	35.317	22,180.058	47.756	28,573.022	42.401
Ceramic and bricks	586.596	0.745	345.785	0.745	501.707	0.745
Wood	199.542	0.253	167.103	0.360	126.687	0.188
Metals and alloys	1252.661	1.590	505.958	1.089	983.653	1.460
Plastics	132.464	0.168	203.986	0.439	158.304	0.235
Water	147.337	0.187	173.704	0.374	148.927	0.221
Aggregates and stones	8132.319	10.322	5451.782	11.738	6273.879	9.310
Others	1086.720	1.379	766.389	1.650	9.310	1.639
TOTAL	39,364.153	49.961	29,794.765	64.151	36,775.490	56.198
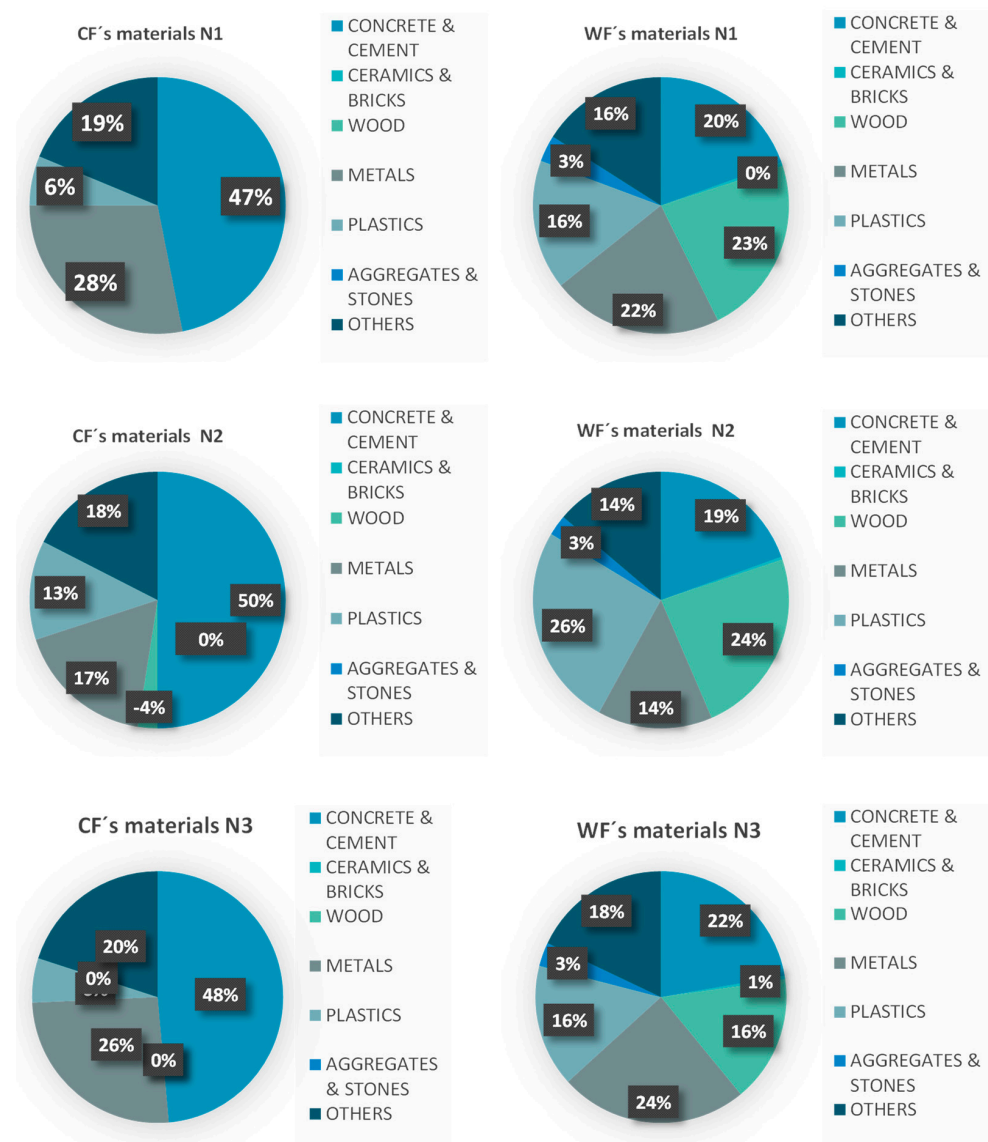
Figure 7. Carbon and water footprint of case studies by material family.

5. Conclusions

A structured and straightforward methodology is proposed for the evaluation of industrial buildings construction. The analysis starts with the evaluation of typical or most representative constructions in the area of study. A survey is proposed for the data collection based on construction cost classification. All this allows an easy comparison with other types of buildings. However, the most consumed material is not always the most impacting. That is the case for stones and aggregates in terms of CF. Furthermore, materials with a low consumption, such as the plastics family, has a high WF. The most impacting materials in both CF and WF indicators are cement and concrete, as expected. The second most impacting is the family of metals and alloys, used not only in the structure but also in the roof and installations.

The waste generated in the projects is also calculated. This is mainly inert material, such as concrete and cement or aggregates and stones. The non-hazardous materials employed have a high recycling or reuse potential, which is the case for metallic roofs and structure.

Due to the identified high recycling potential, it is recommended that future research includes evaluation of the building's life cycle and its recycling/reusing potential, since

these buildings have a short service life of 35 years according to Spanish legislation. The assessment can also be implemented in future work in building information modeling.

Appendix A

Table A1. New classification model for industrial building projects based on the ACCD.

Code	Unit	Description
02		EARTH WORK
02EX	m^3	Open excavation
02RR	m^3	Refilling and compacting
02TX	m^3	Transport
03		FOUNDATION
03AX	kg	Rebars
03CP	m	Piles
03EX	m^2	Formwork
03HA	m^3	Reinforced concrete
03HM	m^3	Bulk concrete
04		SEWAGE
04EA	u	Manholes and pits
04EC	m	Underground pipeline
04VB	m	Vertical pipelines
05		STRUCTURE
05AC	kg	Hot rolled steel
05AF	Kg	Cold rolled steel
05FX	m^2	Concrete slab
05HA	kg	Steel rebar
05HE	m^2	Formwork
05HH	m^3	Reinforced concrete
05MX	m^3	Structure wood
06		BRICK WORK
06BZ	m^2	Wall made of concrete blocks
06DX	m^2	Chamber wall made with bricks
06DY	m^2	Partitions made with bricks
06LX	m^2	Brick exterior wall
06LY	m^2	Brick interior wall
06LZ	m^2	Masonry walls
06PA	m^2	Metal precast
06PH	m^2	Precast concrete

Table A1. *Cont.*

Code	Unit	Description
07		ROOF
07HX	m^2	Horizontal roof
07IX	m^2	Sloping roof
08		INSTALLATIONS
08CA	u	Air conditioning and hot water
08CC	m	Air conditioning ducts
08EC	m	Electric circuits
08ED	m	Electric bypass
08EL	u	Lights
08ET	u	Electric socket
08EP	m	Grounding conductor
08FF	m	Water pipes
08FS	u	Bathroom sanitary ware
09		INSULATION
09AX	m^2	Acoustic
09TX	m^2	Thermal
10		FINISHES
10AA	m^2	Tiles
10AC	m^2	Front plates
10CE	m^2	Continuous
10CG	m^2	Continuous light weight
10SC	m^2	Ceramic floor
10SN	m^2	Natural stone floor
10SX	m^2	Light weight floor
10SY	m^2	Medium weight floor
10SZ	m^2	High weight floor
10TX	m^2	Ceiling
10RX	m	Windowsill
11		CARPENTRY AND SAFETY
11AX	m^2	Steel
11LX	m^2	Aluminum
11MX	m^2	Wood
12		GLASS AND POLYESTER
12XX	m^2	Glass
13		PAINT
13EX	m^2	Exterior
13IX	m^2	Interior

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