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Methodology for Improving the Sustainability of Industrial Buildings via Matrix of Combinations Water and Carbon Footprint Assessment

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Abstract: In Spain, 90% of companies are small- or medium-sized and are usually located in industrial areas, in warehouses with particular characteristics. This paper presents a methodology for the environmental assessment of this type of construction with water and carbon footprint indicators. A database was developed for the identification of typologies and common construction elements based on a sample of 87 projects in the province of Seville. Based on this, the paper proposes a methodology for comparative analysis that merges the data obtained from the research survey with environmental and economic data. The work proposes a systematic classification of the construction units of industrial buildings in order to improve the sustainability of the decision-making process by introducing environmental information on construction materials and machinery. First, the most impactful elements were identified, and then the technical solutions were adjusted using solutions already in the sample of 87 industrial projects. Reductions of up to 74% in the carbon footprint and 54% of the water footprint were found, as well as 14% reduction in construction costs in the most favorable case.

Keywords: industrial construction; water footprint; carbon footprint; environmental analysis; cost assessment; sustainable construction; decision-making

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1. Introduction

Globally, 82 billion square meters of built environment is expected to be built and rebuilt by the year 2030, which represents about 60% of the total inventory of buildings in urban areas [1]. Such construction accounted for 39% of global energy-related emissions in 2017, of which, 28% were caused by operations or direct impact and 11% by materials or indirect impact. The decarbonization of the built environment is essential to achieve the 1.5 °C target of the Paris Agreement, both in terms of operational carbon and embodied carbon, which requires the assessment of the direct and indirect impact of the built environment [2]. The construction sector has a huge influence not only on CO_2 emissions but also on water consumption and treatment [3]. Optimizing energy and water consumption in buildings is an important step toward meeting the community's 2030 goals [4].

To achieve this, knowing which construction option would bring more benefits in terms of sustainability is essential for any construction project. Professionals in this industry must be able to easily assess different construction options in order to make the best decision for sustainability. Aside from the technical aspects, environmental and economic aspects should also be considered.

In the Spanish case, special interest should be given to an understudied sector: the construction of industrial buildings. Industrial activity represented 20% of the gross domestic product in 2019, and 46% more companies were created in 2021 compared to 2020. Notably, 90% of companies in Spain are medium or small, have less than 20 employees [5], and are located in industrial parks. It is important that they grow sustainably to reduce the direct impact of their exploitation and expansion—mainly due to their production of natural resources—via the emission of pollutants and generation of solid waste, as well as their indirect impacts, such as the construction of infrastructure, on the air, soil, and water [6].

The environmental impact of industrial buildings has been explored by several authors; the main indicator used has been the carbon footprint (CF). In Bilbao, Spain, researchers from the University of the Basque Country developed a model for the environmental analysis of industrial buildings, evaluating quantitative and qualitative aspects that are transformed into a standard unit according to the importance of each aspect [7]. Another model, which was developed by Italian researchers, evaluates the CF of four industrial buildings; it is sensitive to modifications in thermal insulation and service life [8]. Heravi et al. included in their model the three dimensions of sustainability—environmental, social, and economic—for the life cycle of petrochemical projects, highlighting the importance of the sustainability of industrial buildings in developing countries [9].

Other works have focused on the façade of industrial buildings, such as Opher et al., who environmentally studied [10] the conservation of the façade of a heritage industrial building in Toronto by evaluating the greenhouse gas emissions of the life cycle. Their study included cradle-to-grave life-cycle assessment (LCA) of materials, transportation, and construction activities, in addition to foreseeable emissions due to operational energy consumption. They concluded that the CF incorporated into the restoration project was offset by operational energy savings over a period of 3 to 13 years, depending on the energy sources used. Another study on industrial building façades developed an environmental and economic life-cycle analysis tool for a three-façade system in which laminated timber produced 80% fewer emissions compared to steel structures and sandwich panels [11].

Recently, the ARDITEC research group began developing a platform for open educational resources intended for university students, professors, researchers, and companies that want to acquire knowledge about the methods of estimating the environmental impact of industrial buildings [6]. These resources use other indicators in addition to CF, such as the water footprint (WF). CF and WF indicators are favorable environmental indicators for public tenders and regulation development aiming to improve the sustainability of the life cycle of buildings, as they promote messages that are simple and understandable for the general public [12].

The CF aims to determine greenhouse gas emissions from processes [13] and is based on LCA data. The indicator is expressed in kilograms of CO_2 equivalent [14], being calculated with the GHG Protocol and PAS 2050 methodologies. The CF indicator is related to the main objectives of the Kyoto Protocol, due to its ease of understanding by the non-specialized public and its simple application in environmental policy decision-making. However, reviews related to the use of the CF indicator in construction have detected that the results are not always comparable due to the lack of an international standard methodology, so studies have been carried out to establish emission scales in construction processes [15–17].

The WF footprint indicator was created to assess the total volume of fresh water used in the production of goods and services consumed by an individual or a community and is measured in m^3 [18]. WF considers the volume of fresh water used directly and indirectly. Indirect consumption, also known as virtual water, refers to water used in the manufacturing processes of production materials and equipment [19]. ISO 14,046 determines the requirements and guidelines necessary for the evaluation of products, processes, and organizations [20]. Buildings and their associated industry consume 30% of the freshwater available globally [21]. Therefore, the reduction of direct water footprint water consumption through more efficient systems, devices and appliances, and better treatment and recycling of wastewater is a major goal. Another large part of the consumption in the construction sector occurs indirectly through the production processes of materials and equipment, which is usually called indirect water or virtual water (VW) [22]. The materials consume water in their extraction and manufacture, waste management, and reuse. While this approach has received criticism, it cannot be ignored [23] given the substantial developments it has provided. Crawford and Pullen [24] studied the WF in residential buildings over a period of 50 years and concluded that VW in building materials is greater than direct household consumption. Other researchers have concentrated their effort on the VW assessment, for example, measuring it in the construction of a multi-story residential apartment in Kolkata, India [25]. In Beijing, researchers determined the total footprint of nine projects [26], while in Tehran, researchers measured the WF of six residential buildings [27].

In the case of buildings, WF can be analyzed from a global perspective using an input–output analysis of consumption in the country [28] or with models that evaluate the components of construction projects [26]. In keeping with a component-evaluation approach, the ARDITEC group uses the inventory of resources that is defined in the economic control of the projects [29].

In order to measure the impact of buildings, it is essential to design automated systems based on, for example, standardized databases of quantitative data collected from research and construction cost assessment [30]. The ARDITEC group also calculates the CF of buildings using cost databases and is developing a methodology based on an environmental budget perspective [31] while measuring all necessary resources across the life cycle of the building [32]. Similar cost databases such as ITeC [33] and CyPE [34] are available on the market.

These initiatives could facilitate, for example, the implementation of Spanish law LPSC_9/2017, which regulates public contracts and establishes a framework involving economic, environmental, and social criteria. They can also promote green public procurement via legislation for environmental policies related to climate change and the sustainable production and use of resources [35]. The main objective of this study was to optimize the design process with the use of new tools. To do so, it was necessary as a secondary objective to create a cost database for the construction of industrial buildings that is accompanied by environmental indicators, such as CF and WF, that facilitates design decisions, as a supporting tool for professionals in the field (architects, designers, constructors) or investors and beneficiaries. Therefore, it was necessary to define a standardized classification of work units to introduce product environmental information.

This paper proposes a method for the evaluation of industrial projects and the optimization of their design. A new database of industrial buildings characteristics that combines cost with environmental data optimizes the design process with an Excel tool that easily allows the selection of less impacting solutions. The tool is defined with data collected from 87 surveys that can be easily updated by adding more projects or new construction solutions with their corresponding cost and environmental information. For the validation of the new database and its methodology, four warehouses built in the province of Seville (Spain) were used to identify the potential of the tool. The tool is used with a budgetary structure, being a system with which the participants in the project are already familiar, so that a double analysis—economic and environmental—is possible.

2. Research Methodology

The research methodology of this work was divided into three phases: development, application, and validation of the model. In turn, sub-levels were established according to the order of execution of each of the tasks necessary to achieve the objectives, see Figure 1. The research phases and the corresponding activities are presented in the following sections.

In the first phase (model development), the research team conducted the activities shown in Figure 1 in parallel to create two databases, one with the project quantities (based on the surveys on the industrial buildings) and one with the economic and environmental costs of each stage and task of a construction project. These two databases were afterwards correlated to create an Excel tool that facilitates the determination of the total economic and environmental costs for different typologies of industrial buildings.

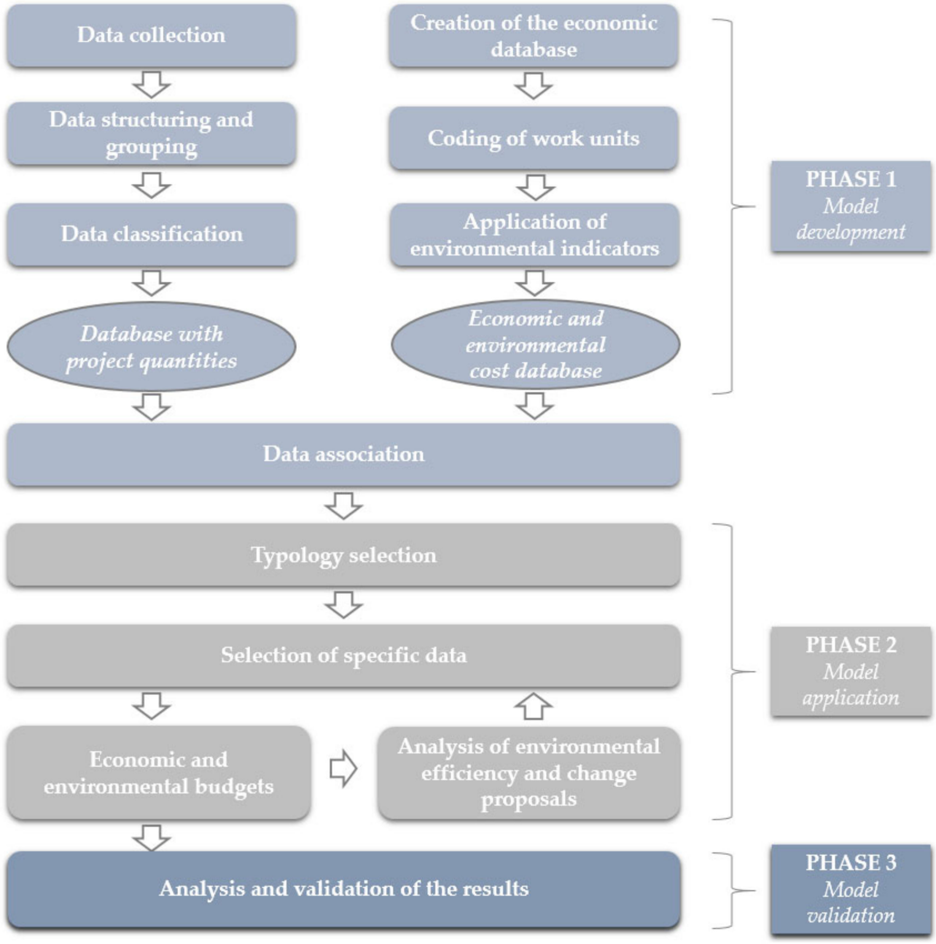


Figure 1. Methodology of the environmental and economic impact assessment model.

The second phase applied the model to four cases to test the validity of the model. These cases were chosen from the 22 different typologies identified as a result of the collection and processing of data from the surveys previously conducted.

Finally, the results obtained were compiled to show the financial and environmental impact of each construction element. To test the validity of the tool proposed, a scenario was chosen in which the original elements were fictionally replaced with others with less environmental and financial impact.

The paper proposes a methodology for creating a tool based on this database to support decision-making for sustainability. The final database is a dynamic object that can be updated in time with additional data about other industrial buildings to improve the quality of information offered, making it easier to find a project in the database that matches a given project.

2.1. Model Development

2.1.1. Project Quantities Database

The project quantities were collected in surveys in the province of Seville. The surveys included qualitative questions that correspond to the seven items in Table 1 and 56 quantitative questions listed in the column "concepts" of Appendix D.

The data were transformed into quantities of each construction element by floor area. In the next step, the data collected were analyzed, and the projects with similar characteristics were grouped and average values were calculated. The projects were classified according to the characteristics shown in Table 1: height, foundation type, structure type, and roof type.

Table 1. Identified typologies.

Type	Samples	Height (m)	Plants	Additional Floor	Foundation Type	Structure Type	Roof Type
1	4	5–7.5	1		Trenches	Metallic	Sloped
2	1	7.5–10	1		Trenches	Metallic	Sloped
3	12	7.5–10	1		Isolated footings	Metallic	Sloped
4	3	3.5–5	1		Isolated footings	Metallic	Sloped
5	43	5–7.5	1		Isolated footings	Metallic	Sloped
6	1	>10	1		Isolated footings	Metallic	Sloped
7	1	7.5–10	1	Mezzanine	Isolated footings	Metallic	Sloped
8	1	>10	2		Isolated footings	Metallic	Sloped and horizontal
9	1	7.5–10	2		Trenches	Concrete	Sloped and horizontal
10	1	5–7.5	1		Piles	Mixed	Sloped
11	1	7.5–10	1		Running ditches	Concrete	Sloped
12	2	7.5–10	1		Isolated footings	Concrete	Sloped
13	1	7.5–10	1	Basement + Mezzanine	Isolated footings	Metallic	Sloped
14	4	5–7.5	1	Mezzanine	Isolated footings	Metallic	Sloped
15	1	5–7.5	1	Mezzanine	Isolated footings—Trenches	Mixed	Sloped
16	2	>10	2		Piles	Concrete	Sloped
17	1	>10	2		Isolated footings	Metallic	Sloped
18	1	5–7.5	2		Isolated footings	Metallic	Sloped
19	3	7.5–10	2		Isolated footings	Metallic	Sloped
20	1	7.5–10	1	Mezzanine	Isolated footings	Metallic	Sloped and horizontal
21	1	7.5–10	2	Basement	Slabs	Metallic	Sloped
22	1	7.5–10	3		Isolated footings	Metallic	Sloped

2.1.2. Economic and Environmental Cost Database

Cost control of construction projects always takes place and is based on the coding of the work units. Classification systems have been defined in different regions or countries [36]. This codification is necessary in order to define the budget of construction projects, unify elements and tasks that normally always take place, and obtain the resources inventory. The same codification can be employed for the environmental assessment and its controls. In the present work, the construction options and costs were based on the coding in the Andalusia Construction Cost Database or ACCD [37], which we considered adequate for our objectives [38]. The structure of the ACCD is pyramidal: at its apex are the work phases, named chapters in the classification, which group the tasks by stage of execution of the project; for example, foundation, sewerage, structures, facilities, etc. At the next level are the unit costs that define units of work within the phases; the latter are formed by the basic costs (materials, labor, and machinery). The coding is alphanumeric, as shown in Figure 2, and the structure of the classification with an example of each level is displayed in Table 2. These follow the cost structure established by the Law on Public Sector Contracts and its implementing regulations to allocate direct costs to each unit of work [39]. We employed 140 construction solutions from the ACCD and created 16 new ones with the support of the online tool “Construction Cost Generator” [35] but powered by basic elements of the ACCD.

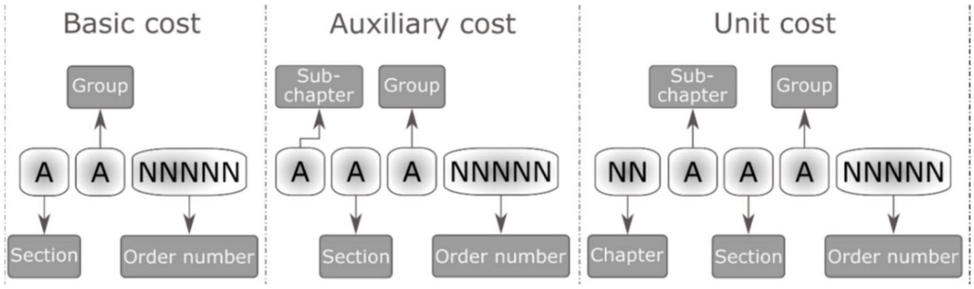


Figure 2. The classification and coding of the Andalusia Construction Cost Database; A stands for alphabetic letters, and N is for numbers.

Table 2. ACCD classification hierarchy.

Class Levels	Definitions
L1. Construction site	All the construction elements on a construction site
L2. Chapter	Main stages of a dwelling construction project. *e.g.,: **03**. Foundations.*
L3. Sub-Chapter	Chapter division. *e.g.,: 03**C**. Foundations.*
L4. Section	Sub-Chapter division. *e.g.,: 03C**P**. Foundation pile.*
L5. Group	Section division. *e.g.,: 03CP**S**. Foundation pile in-situ.*
L6. Unit Cost	Group division into unitary elements. *e.g.,: 03CPS**00007** m Concrete pile* in situ *with 65 cm diameter.*

In the next research phase, we distributed a questionnaire to the selected sample of 87 warehouses in Spain. The questions of the survey were grouped in two categories: fixed and multiple choice. The first category contained elements that did not usually have a wide variety of options in the sample, so they were assigned a single unit cost; see Table 3. The first column corresponds to the code in the ACCD and the second to its concept.

Table 3. Sections that contain only one unit cost in the sample.

ACCD Code	Concept
02EX	Excavations
02RR	Filled
03AX	Rebar
03HM	Concrete in mass
04EA	Manholes and wells
04VB	Downspouts
05AC	Hot-rolled steel
05AF	Cold rolled steel
05HA	Steel rebar
05HE	Formwork
05MX	Structural wood
06DX	Interior brickwork
06DY	Interior partition (distribution)

Table 3. *Cont.*

ACCD Code	Concept
08EC	Circuits
08ED	Derivations
08EL	Points of light
08EP	Grounding conductor
10CG	Plaster

The multiple-choice categories, in Table 4, have a code and a concept but were grouped into families of construction elements based on main characters, as shown in the fourth column, giving rise to the matrix of combinations.

Table 4. Sections with more than one unit cost option in the sample.

ACCD Code	Concept	Quantity	Construction Elements
10AA	Tiled	5	Façade Finishes
10AC	Plated	3	Façade Finishes
13EX	Exterior paintings	4	Façade Finishes
13IX	Interior paintings	4	Interior Finishes
12XX	Glazing	4	Glazing
09AX	Acoustic insulation	3	Acoustic Insulation—Walls and Acoustic Insulation—Floors
09TX	Thermal insulation	6	Thermal Insulation—Walls and Thermal Insulation—Floors
06LX	Exterior brick work	4	Masonry Façade
06PA	Prefabricated metal	1	Masonry Façade
06PH	Prefabricated concrete	3	Masonry Façade
10RX	Finishes and windowsills	7	Windowsill
10RX	Finishes and windowsills	8	Finishes
08CA	Air conditioning and hot water appliances	8	Air Conditioning Devices and Terminal Units
08FS	Sanitary appliances	4	Sanitary Appliances
08FF	Water piping	4	Water Pipes
08CC	Air conditioning ducts	4	Pipes
04EC	Collectors	2	Collectors
07HX	Horizontal covers	6	Horizontal Covers
07IX	Sloping roofs	8	Sloping Roofs
03EX	Formwork	2	Formwork
10CE	Plastered	2	Plastered—Façade and Plastered—Partitions
05WF	Reinforced concrete (structure)	2	Structure
10TX	Ceilings	5	False Ceilings
05FX	Forged	2	Forged
06BZ	Walls of concrete blocks	1	Walls
06LZ	Ceramic brick walls	1	Walls
03CP	Piles	1	Reinforced Concrete (Foundation)
03HA	Reinforced concrete	4	Reinforced Concrete (Foundation)
06LY	Interior brickwork	5	Partitions
11AX	Carpentry steel	3	Doors and Windows
11LX	Aluminium carpentry	4	Doors and Windows

Table 4. *Cont.*

ACCD Code	Concept	Quantity	Construction Elements
11MX	Wood carpentry	3	Doors and Windows
10SC	Ceramic flooring	9	Floors in Small Areas
10SN	Natural stone flooring	4	Floors in Small Areas
10SX	Low density continuous flooring	1	Floors in Big Areas
10SY	Medium density continuous flooring	1	Floors in Big Areas
10SZ	High density continuous flooring	1	Floors in Big Areas
08ET	Power outlets	3	Power Outlets
02TX	Transport	2	Transport (Elevators)

In the literature, environmental data are normally gathered per kg of material. However, the construction sector has traditional ways to measure and sell their materials. More specifically, while some materials are commercialized per kilogram or ton, others are sold by length, as is the case for door frames, per square meter for flooring or tiles, per cubic meter for concrete, etc. This required an additional tool in the Excel to determine the weight of the construction materials prior to making the environmental calculations. First, the original basic cost unit (m^2, m, thousands of units, t, m^3, etc.) was converted to m^3, which, together with the densities established in the Catalogue of Constructive Solutions of the Technical Building Code [40], determined the weight of each element. Table 5 shows an example of calculations for foundation piles, measured per meter of concrete pile, fabricated in situ, with 65 cm diameter. The quantities refer to the amount of basic element that is needed in one unit of pile per meter. The information in the column "Type" refers to the element nature, where MAT stands for construction materials and MAQ for machinery.

Table 5. Calculation of the basic elements that are part of the work unit of the foundation pile, with code 03CPS00007, which is measured per meter.

Type	ACCD Code Basic Cost	Quantity	Unit	Name	Basic Cost (€)	Cost in Unit (€/m)	WF in Basic ($m^3{}_{water}$/unit)	WF in Unit ($m^3{}_{water}$/m)	CF in Basic ($kgCO_2$ eq/unit)	CF in Unit ($kgCO_2$ eq/m)
MAT	CA00320	10.47	kg	Rebar steel b 500 s	0.81	8.48	0.027	0.283	1.457	15.251
MAT	CH80150	0.43	m^3	Concrete 30 Mpa resistance	64.61	27.59	5.144	2.196	344.353	147.039
MAQ	MC00100	0.03	h	Hammer compressor	6.35	0.19	0.236	0.007	4.960	0.149
MAT	MP00210	0.434	m	Pile perforation equipment (rent)	225.53	97.88	0.011	0.005	3.125	1.356
MAT	MP00600	1	u	Hammer repercussion tool	6.45	6.45	0.212	0.212	0.523	0.523
							TOTAL	2.703	TOTAL	164.318

Along with the defined weights, the coefficients of environmental impacts per kg were calculated through the Simapro LCA software [41], together with the Ecoinvent database [42], as follows:

$$I_{MAT} = (\Sigma i\ C_i \times U_{MAT}) + (U_{TRAN} \times C_i), \quad (1)$$

where:
I_{MAT} = environmental impact of building material ($kgCO_2eq/kg$, $m^3{}_{water}/kg$)
U_{MAT} = unit impact of manufacture per kg of material ($kgCO_2eq/kg$, $m^3{}_{water}/kg$)
U_{TRAN} = unit impact of transport per kg of material ($kgCO_2eq/kg$, $m^3{}_{water}/kg$)
C_i = consumption of building material i (kg).

The impact of construction machinery depends on its power and hours in operation, which determine the kWh consumed on site, and the corresponding CO_2 emissions [43].

The fuel consumption in liters is

$$V = (P \times T \times Y), \tag{2}$$

where P refers to the machine power (kW), T is the usage time (hours), and Y is the fuel consumed by the engine, depending on whether it is diesel or gasoline (l/kWh).

The fuel machinery impact is M_{COMB}, found by

$$M_{COMB} = V \times I_F \; (m^3{}_{water};\, tCO_2eq), \tag{3}$$

where I_F is the impact of fuel; diesel or gasoline ($m^3{}_{water}/l_{fuel}$; tCO_2eq/l_{fuel}).

For electrical machinery, the total kWh consumed is obtained by analyzing the engine power and the hours of use [44]. The CO_2 equivalent emissions generated in the production of one kWh is 0.248 $kgCO_2$/kWh in the Spanish electricity system [45], measured via the global-warming potential (GWP) of the various gases emitted. The WF of electric machinery uses the WF associated with the Spanish energy mix.

In the present work, 156 unit costs were employed and their environmental impacts were determined.

2.1.3. Data Association

The data obtained from the project quantities were merged with the cost database (economic and environmental) to generate an Excel tool for calculating the total economic and environmental costs of 22 different industrial building typologies. The tool allows changing construction solutions among the ones in the database to make economic and environmental comparisons, helping the user to make a decision regarding the most sustainable option.

In the event that a project does not contain in its survey all quantities, the average of the typology to which it belongs is used. In case the typology is formed by a single project, the general average is employed.

2.2. Model Application—Case Studies

The 87 projects were grouped in 22 typologies described in Table 1, where the second column indicates the sample size in each typology. The 22 are represented in Appendices A–C, in which the cost, carbon footprint, and water footprint, respectively, are illustrated using a scale of colors that are most intense for the highest values. In all typologies, the impact of hot-rolled steel structures and reinforced concrete stood out. The impact of masonry impact is also significant when using block walls.

Four projects with different combinations of stand-out characteristics were used for the validation of the model proposed, and four projects were chosen to show the potential of the tool. The projects had different floor areas, were with and without basement, metal or reinforced concrete structures, and four different foundations: slabs (PL), insulated footings (PZ), trenches (PC), and piles (PP) that correspond to typologies 21, 8, 9, and 16, respectively. The most relevant characteristics of the projects studied can be seen in Table 6, and the quantity survey is summarized in Appendix D.

Table 6. Characteristics of the projects.

Features/Projects	PL	PZ	PC	PP
Floor area (m^2)	1535	12838	312	8896
Typology	21	8	9	16
Height from floor to ceiling (m)	7.5–10	>10	7.5–10	>10
Number of floors	2	2	2	2
Additional floor	Basement	-	-	-
Foundation type	Concrete slab	Isolated footing	Trenches	Piles
Structure type	Metallic	Metallic	Concrete	Concrete

Other construction elements commonly used as solutions among the samples include:

1. Land conditioning: land transport, maximum distance 5 km, loading with mechanical means
2. Foundations: wooden formwork
3. Sanitation: buried collector with polyethylene pipe 200 mm
4. Structures: prestressed beams, ceramic vault
5. Façade: masonry with prefabricated alveolar panels of prestressed concrete and walls of reinforced concrete blocks, 50 × 20 × 25 cm. Interior partitions of double hollow brick 9 cm thick
6. Roofs: cement tiles
7. Installations: VRF inverter unit with roof terminal, black steel pipes of diameter 3/8″, PE-X water pipes with diameter 25 mm and 2.5 mm thick, bathroom appliances: stainless steel sink with drainer, vitrified porcelain toilet, and pedestal sink 0.60 m × 0.50 m
8. Insulation: acoustic 40 mm rigid fiberglass panel partitions, 40 mm fiberglass-insulated floors, 30 mm projected polyurethane thermal insulation façade, and floors with 20 mm rigid panels of expanded polystyrene
9. Finishes: cementitious paint on exterior, synthetic enamel paint in interior. Industrial flooring with high mechanical and chemical resistance and flooring in small areas with 30 × 30 cm ceramic tiles. Ceilings with plaster plates, with a removable system and exposed lattice. Ceramic tile sill of 14 × 28 cm. Other finishes with 14 × 28 cm ceramic tiles;
10. Carpentry and security: sliding stainless-steel windows (1.50–3 m^2). Galvanized steel folding doors (1.50–3 m^2);
11. Glazing: glazing double-panel and low-emissivity windows of 4 mm and 6 mm thickness

The cost and environmental data for the evaluation of the 87 projects were last consulted in 2021.

3. Results and Discussions

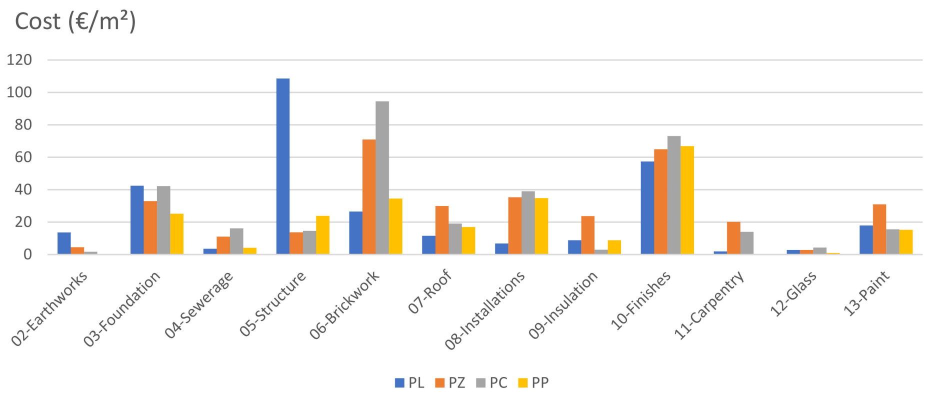
The measurements of the construction elements corresponding to each project generated the results in Table 7. The CF obtained, ~230–340 $kgCO_2eq/m^2$, is within the ranges defined by Chastas et al. (130–1350 $kgCO_2eq/m^2$) [17], or those calculated by De Wolf (200–500 $kgCO_2eq/m^2$) [46]. The results obtained by Solis et al. are higher (~570–880 $kgCO_2eq/m^2$) [47], since they evaluate housing and its urbanization. Differences in methodologies between studies make it difficult to compare their results [48].

Table 7. Total calculations of the four projects; m^2 means built-up area.

Project	PL	PZ	PC	PP
Project cost (€/m^2)	301.88	340.83	337.19	232.00
Water footprint ($m^3{}_{water}/m^2$)	12.15	8.60	10.85	6.12
Total carbon footprint ($kgCO_2eq/m^2$)	657.86	348.34	433.61	199.68
Hours of labor (h/m^2)	1.12	0.56	0.40	0.26
Operator hours of machines (h/m^2)	5.06	5.26	4.89	3.87

The WF range of industrial buildings, ~6–12 $m_{water}{}^3/m^2$ per floor area, is similar to that seen in the construction of streets and gardens, 2.6–7.3 $m_{water}{}^3/m^2$ [25]. However, the range is lower than those of other authors who evaluate construction projects of greater complexity. For example, in Calcutta, India, the WF of the construction of a multi-story residential apartment building with steel and reinforced concrete structure was reported to be 27 $m_{water}{}^3/m^2$ per floor area [27] and 18.76 $m_{water}{}^3/m^2$ [49]. Similarly, in China, researchers determined the WF of several building constructions to be 20.83 $m_{water}{}^3/m^2$ [50] and 26.6 $m_{water}{}^3/m^2$ [26]. In Spain, the WF of the complete life cycle of single-family dwellings is 27 m_{water}^3/m^2 which includes the direct water consumption of the occupants [50].

Looking in detail at each project, as can be seen in Figure 3, the PL project had high impact in the structures and foundation sections, which was due to the large amount of steel and concrete used. This is similar to the results obtained in an evaluation of housing construction in Spain [46]. Masonry was in the third place for CF, also due to the high consumption of steel and concrete, in this case, in the plates on the façade. The coatings also stand out: in particular, their WF is notable, which is due to the production of the main ceramic flooring.



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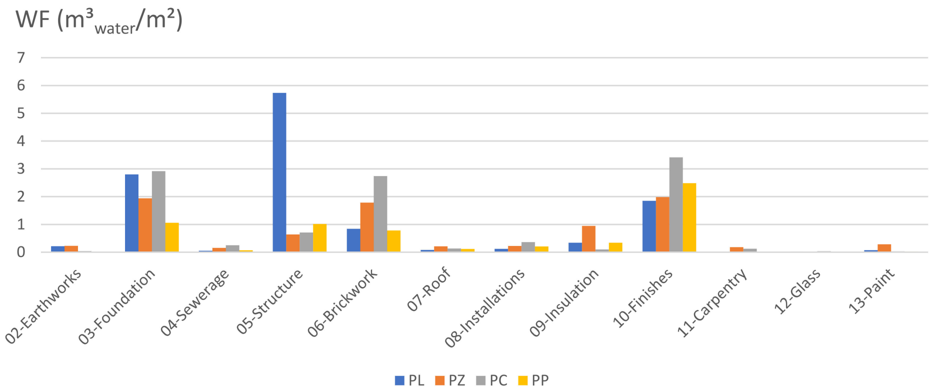
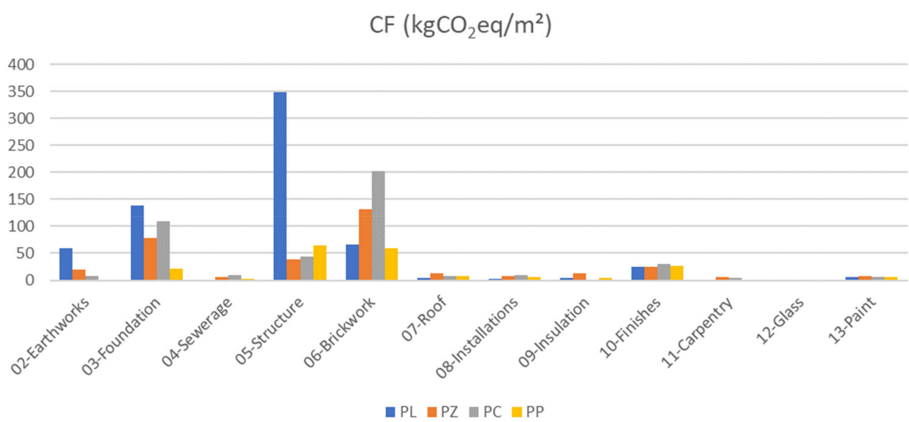


(**b**)



(**c**)

Figure 3. (**a**) Cost, (**b**) water footprint, and (**c**) carbon footprint of projects per chapter in the budget and by floor area. The studied projects are characterized based on the foundations type: PL—with slabs, PZ—with insulated footings, PC—with trenches, and PP—with piles.

In the four projects, the highest values were always focused on the foundations, structures, masonry, and cladding chapters. The basic elements that mostly influenced the impact were structural steel, brick/concrete work, and the type of floor placed.

Table 8 shows the chapters that represented the majority of the financial and environmental impacts of each typology studied; the impact of each typology is marked with a color (green for cost, blue for WF and red for CF) and the darker the color, the greater the impact of the respective typology within the respective chapter on cost, WF and CF. These few elements represented more than 50% of all impacts:

- The project with pile foundation (typology 16) had the lowest environmental and financial impacts due to its type of foundation, which had less reinforcement and concrete.
- The foundation projects of isolated footings (typology 8) and trenches (typology 9) had the highest costs per constructed area. However, this was not due to their foundation, but because their walls were made of concrete blocks requiring high labor consumption. As for WF, the biggest impact was from ceramics, sills, and flooring. The total CF was focused on elements that carry concrete and steel, especially in the foundation with reinforced concrete.
- The slab-type foundation project (typology 21) had reinforced concretes in the foundation and structure, in addition to hot-rolled steel elements. These elements were responsible for generating the highest environmental impact in both WF and CF among the four projects studied. As for the economic aspect, this project had the second lowest cost per m^2, because of little brick/block work in the walls.

Table 8. Impacts by constructed area of costs, water footprint, and carbon footprint. The "%TOTAL" represents the percentage of the impact of the items listed in the table with respect to all items in the projects.

		Cost (€/m^2)				Water Footprint (m$^3_{water}$/m^2)				Carbon Footprint (kgCO$_2$eq/m^2)			
Chapter	**ELEMENT/ TYPOLOGY**	PL	PZ	PC	PP	PL	PZ	PC	PP	PL	PZ	PC	PP
03-FOUNDATIONS	Rebar	5.56	8.28	8.63	0.19	0.13	0.19	0.20	0.00	6.83	10.17	10.61	0.24
	Piles	0.00	0.00	0.00	19.79	0.00	0.00	0.00	0.32	0.00	0.00	0.00	19.72
	Formwork	4.47	4.47	7.59	4.47	0.69	0.69	1.18	0.69	−1.14	−1.14	−1.93	−1.14
	Reinforced concrete (foundation)	1.72	1.85	1.30	0.68	0.09	0.10	0.07	0.04	6.32	6.79	4.79	2.48
	Bulk concrete	27.50	2.33	2.24	0.00	1.01	0.09	0.08	0.00	35.51	3.01	2.89	0.00
05-STRUCTURES	Hot-rolled steel	16.53	6.20	5.96	9.34	0.61	0.23	0.22	0.34	37.02	13.88	13.34	20.91
	Forged steel	0.00	0.00	0.00	6.18	0.00	0.00	0.00	0.14	0.00	0.00	0.00	7.59
	Rebar	64.54	5.15	6.39	8.30	4.12	0.33	0.41	0.53	275.72	22.00	27.32	35.48
	Reinforced concrete (structure)	5.20	38.78	38.78	21.26	0.07	0.51	0.51	0.28	5.07	37.83	37.83	20.74
06-MASONRY	Walls of concrete blocks	0.44	0.30	1.10	0.00	0.00	0.00	0.01	0.00	0.56	0.38	1.41	0.00
	Partition walls	3.06	1.53	0.94	1.53	0.04	0.02	0.01	0.02	6.74	3.37	2.08	3.37
	Interior brickwork	17.81	30.35	53.69	11.71	0.73	1.24	2.20	0.48	53.17	90.60	160.27	34.95
	Precast concrete	0.00	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00
10-COATINGS	Finishes	3.46	2.04	2.04	2.04	0.15	0.09	0.09	0.09	4.64	2.73	2.73	2.73
	Floors	52.58	61.16	64.24	61.16	1.13	1.27	1.33	1.27	21.16	22.62	23.66	22.62
	Ceilings	2.09	1.07	0.26	1.07	0.01	0.01	0.00	0.01	0.87	0.45	0.11	0.45
	Finishes and windowsills	2.73	2.73	8.03	4.66	0.71	0.71	2.08	1.21	2.27	2.27	6.69	3.88
	% TOTAL	77.8%	53.6%	66.5%	78.9%	92.5%	73.9%	90.1%	95.4%	87.6%	78.7%	89.0%	97.0%

Not all building materials on a construction site can be easily replaced, but it is possible that some changes in construction solutions can significantly improve environmental efficiency. For example, minimizing the amount of ceramic usage in building materials or reducing concrete consumption.

To demonstrate how the decision process could be improved, for the cases studied using the Excel tool created, the following scenario was proposed: the original elements were replaced with the ones displayed in Table 9.

Table 9. New construction solutions with lower impact.

Category	New/Original Solution	Difference		
		WF ($m^3{}_{water}/m^2$)	**CF ($kgCO_2eq/m^2$)**	**Cost (€/m^2)**
Partitions	Brick partition with mortar/9-cm-thick double hollow brick partition	−0.096	−16.24	−2.91
Masonry façade	9-cm-thick double hollow brick partition/precast concrete	−0.72	−36.07	−8.55
Thermal insulation—walls	Walls insulation of semi-rigid panel fibreglass, 60 mm thick/Walls insulation of projected polyurethane, 30 mm thick	−0.354	−3.047	2.08
Floors in small sup.	Continuous 7-mm-thick pavement with mortar/30 × 30 cm porcelain floor tiles with adhesive	−0.709	−19.43	1.01
Main floors	Continuous 7-mm-thick pavement with mortar/highly resistant ceramic pavement	−1.165	−15.92	−41.64
Doors	Metallic door with frame of 70 mm × 40 mm/galvanized steel door	0	−23.76	40.03
Windows	Wood pine window (width: 1.50 to 3 m^2)/aluminum window	−0.187	−26.94	−26.10
Façade finishes	Anti-corrosive, antioxidant paint/cementitious paint for exterior	0	−6.092	−11.48
Interior finishes	Anti-corrosive, antioxidant paint/synthetic paint for metallic surfaces	−0.094	−0.304	−0.67

The total reduction in impacts is illustrated in Figure 4. The project with the least reduction of environmental and financial impacts was project PL (typology 21). This was because the values of the slab had not been altered, which largely controls the total impacts, and it was the only project with a basement.

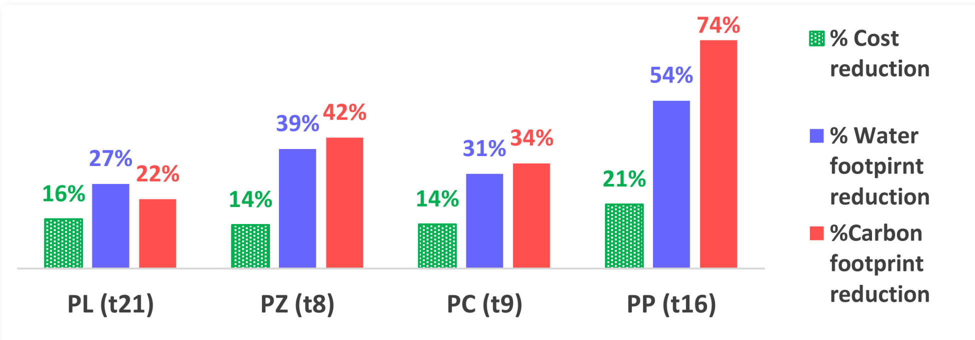


Figure 4. Impact generated in each project after the change in the construction solutions.

Here, the main elements that controlled the impacts for evaluating the complete life cycle of the buildings remained the same as in another study by the authors [44], which focused on social housing. This needs to be tested in future work with industrial buildings.

The model has been developed for Spain, but the methodology can be adapted to other countries, following the same steps described in the methodology: preparation of cost control data such as systematic classification of construction works in the region of evaluation, quantity surveying in order to obtain the resources inventory, calculating the material weights, and finally, applying regionally specific environmental data.

4. Conclusions

The present work created a new database for industrial buildings that combines cost and environmental data. The design process can be optimized by an Excel tool that easily allows the selection of less impactful solutions for the building design. The tool was defined with data from 87 surveys but can be easily updated by adding more projects or adding new construction solutions with their corresponding cost and environmental information.

The present work also aimed to develop a methodology for the evaluation of industrial buildings in terms of sustainability. The methodology eases and improves the decision-making process for identifying optimum solutions in construction or renovation projects for this type of building. It uses the water footprint and the carbon footprint as indicators for environmental assessment and the costs for economic assessment. Aside from its utility in the decision-making process, the methodology also has implications for regulatory formulation.

The authors used Simapro software to obtain the environmental data and Excel to combine the cost data, the quantity surveys, and the environmental information. It is possible to use the created Excel tool to automatically change design assumptions and quickly adjust input data, e.g., changing costs.

The present work has shown that it is possible to define a systematic classification and cost database for the construction of industrial buildings based on the systematic classification system of cost control. The cost database created has been equipped with environmental indicators such as the carbon and water footprint.

To validate and test the new database, measurements from 87 industrial buildings constructed in the province of Seville were used. Data were collected in field work through simplified quantity surveying.

The combination of project data and the new cost database made it necessary to create a tool that automates the information collected and its combinations in order to identify patterns in the construction solutions with the greatest impact.

In the sample evaluated, four chapters of the project budget control the impacts: foundations, structures, masonry, and coatings. Changes in the construction solutions of these could lead to savings of up to 74% of the carbon footprint or 54% of the water footprint in the cases studied. This type of analysis and comparison can be easily performed by interested parties (such as designers, architects, constructors, beneficiaries) in order to check the benefits of the available solutions and to choose the optimum solution for the project.

One advantage of the tool developed is its usability and accessibility, as a large group of people have access to and know Excel. Moreover using the tool may make people more aware of the impact that their decisions have on the sustainability of the project. Even a small change in a construction solution can lead to significant benefits for the environmental and financial aspects. On the other hand, this tool is not generally applicable, but it can be successfully used for industrial buildings in Spain and in other European countries with similar climate conditions.

In the long term, the objectives of this paper are aimed at designing a model that allows national and international adaptations and applications. In this way, the present work contributes to making the design of buildings with low environmental impact more efficient. A future line of research is to analyze the life cycle and its recycling, reuse, or rehabilitation potential with circular economy indicators. Another line is to expand the sample and add artificial intelligence tools to optimize design and construction.

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Appendix A. Matrix of Carbon Footprint per Budget Classification, Dark Colors Represent Higher Impacts

Chapter	Work Unit/Project	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Average
02-Earthworks	Excavations																							0.972
	Filled																							0.381
	Transport																							7.936
03-Foundations	Rebar																							5.365
	Piles																							1.173
	Formwork																							–1.167
	Reinforced concrete																							111.782
	Concrete																							23.221
04-Sewerage	Manholes and wells																							3.924
	Collectors																							1.354
	Downspouts																							0.351
05-Structures	Hot-rolled steel																							52.840
	Cold rolled steel																							1.233
	Forged steel																							15.676
	Steel Rebar																							0.584
	Formwork																							–0.053
	Reinforced concrete																							250.261
	Structural wood																							–0.010
06-Brick work	Walls Blocks																							32.405
	Partition (chamber)																							0.064
	Partition (walls)																							0.499
	Int. Brick work																							3.503
	Precast concrete																							92.186
07-Roofs	Pitched roof																							10.023
08-Installations	A/C and DHW																							1.655
	A/C ducts																							0.103
	Circuits																							0.214
	Derivations																							0.090
	Points of light																							0.104
	Power outlets																							0.250
	Grounding conductor																							0.305
	Water pipes																							0.183
	Sanitary appliances																							3.496
09-Insulation	Acoustic insulation																							0.338
	Thermal Insulation																							4.906
10-Finishes	Plastered																							0.184
	Ceramic flooring																							2.444
	Light screeds																							19.053
	Ceilings																							0.500
	Windowsills																							2.458
11-Carpentry and security	Steel bar																							3.852
12-Glass	Glazing																							0.752
13-Paints	Exterior																							4.657
	Interior																							3.212

Appendix B. Matrix of Water Footprint per Budget Classification, Dark Colors Represent Higher Impacts

Chapter	Work Unit/Project	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Average
02-Earthworks	Excavations																							3.51×10^{-3}
	Filled																							3.27×10^{-2}
	Transport																							2.87×10^{-2}
03-Foundations	Rebar																							9.95×10^{-2}
	Piles																							1.93×10^{-2}
	Formwork																							7.10×10^{-1}
	Reinforced concrete																							1.71
	Concrete																							3.47×10^{-1}
04-Sewerage	Manholes and wells																							3.61×10^{-2}
	Collectors																							6.64×10^{-2}
	Downspouts																							6.10×10^{-2}
05-Structures	Hot-rolled steel																							1.50
	Cold rolled steel																							3.50×10^{-2}
	Forged steel																							2.57×10^{-1}
	Steel Rebar																							1.08×10^{-2}
	Formwork																							2.89×10^{-2}
	Reinforced concrete																							3.74
	Structural wood																							5.84×10^{-3}
06-Brick work	Walls Blocks																							4.41×10^{-1}
	Partition (chamber)																							3.96×10^{-4}
	Partition (walls)																							3.23×10^{-3}
	Int. Brick work																							2.17×10^{-2}
	Precast concrete																							1.27
07-Roofs	Pitched roof																							1.56×10^{-1}
08-Installations	A/C and DHW																							4.41×10^{-2}
	A/C ducts																							3.72×10^{-3}
	Circuits																							3.29×10^{-2}
	Derivations																							1.40×10^{-2}
	Points of light																							1.46×10^{-2}
	Power outlets																							3.64×10^{-2}
	Grounding conductor																							2.77×10^{-2}
	Water pipes																							4.68×10^{-3}
	Sanitary appliances																							8.75×10^{-2}
09-Insulation	Acoustic insulation																							8.93×10^{-3}
	Thermal Insulation																							3.44×10^{-1}
10-Finishes	Plastered																							3.30×10^{-3}
	Ceramic flooring																							7.73×10^{-2}
	Light screeds																							1.13
	Ceilings																							8.00×10^{-3}
	Windowsills																							7.63×10^{-1}
11-Carpentry and security	Steel bar																							1.10×10^{-1}
12-Glass	Glazing																							3.13×10^{-2}
13-Paints	Exterior																							1.81×10^{-2}
	Interior																							3.49×10^{-1}

Appendix C. Matrix of Cost Impact per Budget Classification, Dark Colors Represent Higher Impacts

Chapter	Work Unit/Project	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Average
02-Earthworks	Excavations																							0.37
	Filled																							0.08
	Transport																							1.68
03-Foundations	Rebar																							4.37
	Piles																							1.18
	Formwork																							4.58
	Reinforced concrete																							30.12
	Concrete																							6.32
04-Sewerage	Manholes and wells																							4.85
	Collectors																							3.82
	Downspouts																							1.62
05-Structures	Hot-rolled steel																							40.92
	Cold rolled steel																							1.49
	Forged steel																							7.00
	Steel Rebar																							0.48
	Formwork																							0.09
	Reinforced concrete																							58.58
	Structural wood																							0.05
06-Brick work	Walls Blocks																							33.22
	Partition (chamber)																							0.03
	Partition (walls)																							0.39
	Int. Brick work																							1.59
	Precast concrete																							30.88
07-Roofs	Pitched roof																							22.49
08-Installations	A/C and DHW																							24.72
	A/C ducts																							0.49
	Circuits																							0.77
	Derivations																							0.25
	Points of light																							0.39
	Power outlets																							1.15
	Grounding conductor																							2.32
	Water pipes																							0.69
	Sanitary appliances																							2.68
09-Insulation	Acoustic insulation																							0.70
	Thermal Insulation																							8.42
10-Finishes	Plastered																							0.43
	Ceramic flooring																							1.82
	Light screeds																							56.65
	Ceilings																							1.20
	Windowsills																							2.95
11-Carpentry and security	Steel bar																							12.28
12-Glass	Glazing																							3.98
13-Paints	Exterior																							12.32
	Interior																							21.42

Appendix D. Quantities of Work Units in the Four Typologies. U Refers to the Unit of Measurement of the Basic Element

Code	Concept	Unit	PL	PZ	PC	PP
02EX	Excavations	m^3	2.9621	0.8927	0.3736	0.0700
02RR	Filled	m^3	0.0000	0.4750	0.0386	0.0100
02TX	Transport	m^3	7.4052	2.2318	0.9340	0.0638
03AX	Rebar	kg	4.2974	6.4032	6.6761	0.1500
03CP	Piles	m	0.1085	0.1085	0.1085	0.2400
03EX	Formwork	m^2	0.2854	0.2854	0.9682	0.2854
03HA	Reinforced concrete	m^3	0.8542	0.2956	0.2498	0.0902
03HM	Concrete in mass	m^3	0.0255	0.0274	0.0193	0.0100
04EA	Manholes and wells	or	0.0039	0.0169	0.0385	0.0100
04EC	Collectors	m	0.1898	0.5212	0.3758	0.0800
04VB	Downspouts	m	0.0000	0.0000	0.1155	0.0400
05AC	Hot-rolled steel	kg	16.8300	1.4283	1.3716	0.0000
05AF	Cold rolled steel	kg	0.0000	0.0000	0.0000	0.0000
05FX	Forged	m^2	1.1686	0.2191	0.4212	0.6600
05HA	Steel rebar	m^2	0.0000	0.0000	0.0000	4.7800
05HE	Formwork	m^2	0.0000	0.0000	0.0000	0.0000
05WF	Reinforced concrete	m^3	0.3886	0.0620	0.0770	0.1000
05MX	Structural wood	m^3	0.0000	0.0000	0.0000	0.0000
06BZ	Walls blocks	m^2	0.2178	0.8125	0.8125	0.4454
06DX	Partition (chamber)	m^2	0.0000	0.0000	0.0000	0.0000
06DY	Partition (walls)	m^2	0.0414	0.0280	0.1033	0.0000
06LX	Ext. brick work	m^2	0.2178	0.2994	0.2994	0.2994
06LY	Int. brick work	m^2	0.4512	0.1129	0.1392	0.1129
06LZ	Brick walls	m^2	0.9877	0.9877	0.9877	0.9877
06PA	Prefabricated metal	m^2	0.6070	0.8238	0.6070	1.2000
06PH	Prefabricated concrete	m^2	1.6124	2.7474	4.8602	1.0600
07HX	Horizontal covers	m^2	0.0905	0.0905	0.1424	0.0905
07IX	Sloping roofs	m^2	0.9934	2.5710	1.6400	1.4600
08CA	A/C and DHW	unit	0.0001	0.0021	0.0021	0.0021
08CC	A/C ducts	m	0.0416	0.0416	0.0416	0.0416
08EC	Circuits	m	0.0000	0.0000	0.2792	0.0000
08ED	Derivations	m	0.0000	0.0000	0.0000	0.0000
08EL	Points of light	unit	0.0000	0.0000	0.0513	0.0000
08ET	Power outlets	unit	0.0286	0.0286	0.0256	0.0286
08EP	Grounding conductor	m	0.1021	0.1021	0.1021	0.1021
08FF	Water piles	m	0.0777	0.0777	0.1604	0.0777
08FS	Sanitary appliances	unit	0.0104	0.0208	0.0320	0.0088
09AX	Acoustic insulation	m^2	0.0740	0.0740	0.0740	0.0740
09TX	Thermal insulation	m^2	0.6441	3.6304	0.3592	0.6441
10AA	Tiled	m^2	0.1132	0.0962	0.2280	0.0962
10AC	Plated	m^2	0.1260	0.5399	0.3462	0.5399
10CE	Plastered	m^2	0.6510	1.3421	1.3421	1.3421
10CG	Trim	m^2	0.0000	0.0000	0.0691	0.0000
10SC	Ceramic flooring	m^2	0.3894	0.1148	0.1148	0.1148
10SN	Natural stone flooring	m^2	0.1182	0.1182	0.4100	0.1182
10SX	Light screeds	m^2	0.8623	0.8623	0.8623	0.8623
10SY	Light heavy rigs	m^2	0.9358	2.8566	0.9358	1.3400
10SZ	Heavy screeds	m^2	1.6268	0.9790	2.0600	0.9790
10TX	False ceilings	m^2	0.3042	0.0778	0.0382	0.0778
10RX	Finishes	m	0.0768	0.0768	0.4520	0.1312

Code	Concept	Unit	PL	PZ	PC	PP
11AX	Carpentry steel	m^2	0.0242	0.2488	0.1734	0.0036
11LX	Aluminium carpentry	m^2	0.0424	0.0330	0.1436	0.0800
11MX	Wood carpentry	m^2	0.0160	0.0128	0.0128	0.0128
12XX	Glazing	m^2	0.0567	0.0567	0.1738	0.0400
13EX	Exterior paintings	m^2	0.8193	0.8193	0.8193	0.8193
13IX	Interior paintings	m^2	0.7844	2.1344	0.1382	0.0383

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