Methodology for Determining the Carbon Footprint of the Construction of Residential Buildings

J. Solís-Guzmán, A. Martínez-Rocamora and M. Marrero

Abstract With the increasing activity in the building sector in the last decade, construction has become a major consumer of natural resources. This resource consumption has been traditionally accounted for through life cycle assessment and similar approaches. In this chapter, a methodology to apply the carbon footprint indicator to a building project is proposed in order to predict the emissions generated by the construction work. The methodology takes into account the resources used and the waste generated. Thus, a number of factors involved in the calculations are first defined, followed by the methodology to determine the carbon footprint for each of the elements into which it is divided (i.e., energy, water, food, mobility, construction materials, and waste). Finally, the methodology is applied to a case study corresponding to the urbanization and building construction of a representative building type in Andalusia (Spain) when the building is in the planning stage.

Keywords Carbon footprint · Emissions · Construction · Building · Resources · Consumption · Waste

1 Introduction

Within the industrial sector, construction activity, including its associated industries, is the largest consumer of natural resources such as timber, minerals, water, and energy. In the European Union, the construction of buildings consumes 40 % of the total consumption of materials, 40 % of primary energy, and generates 40 % of the total waste, making it particularly responsible for the ongoing deterioration of

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S. S. Muthu, *Assessment of Carbon Footprint in Different Industrial Sectors, Volume 1*, EcoProduction, DOI: 10.1007/978-981-4560-41-2_3,

the environment due to the expansion of urban land (Baño Nieva and Vigil-Escalera del Pozo 2005). Therefore, in the pursuit of improving the environmental performance of buildings, it is necessary to assess this through indicators, so that the weight of the environmental impacts can be qualified and quantified throughout their life cycle, from the extraction of raw materials to demolition. The tools that analyze these impacts generally follow the methodology of life cycle assessment (LCA) (Zabalza Bribián et al. 2011; Malmqvist and Glaumann 2009).

Although several methodologies of environmental assessment can be applied to the construction sector, such as emergy analysis (Meillaud et al. 2005) and material flow analysis (Sinivuori and Saari 2006), there is a current tendency to use simpler methodologies because they can be more easily understood by society. Among these, the ecological footprint and the carbon footprint constitute the most prominent methodologies.

The EF indicator was introduced by Mathis Wackernagel (Chambers et al. 2004), who measured the EF of humanity and compared it with the carrying capacity of the planet. According to its definition, the EF is the amount of land that would be required to provide the resources (grain, feed, firewood, fish, and urban land) and absorb the emissions (CO_2) of humanity (Wackernagel and Rees 1996; WWF 2008). By comparing the EF to the amount of land available, Wackernagel concluded that human consumption of resources currently stands 50 % above the global carrying capacity (WWF 2010). It is now considered one of the most relevant indicators for the assessment of impacts on the environment and can also be used in conjunction with other indicators, such as the carbon footprint and water footprint (Galli et al. 2012).

The carbon footprint is largely used in the business environment for its utility in energy planning and as a marketing tool. Furthermore, its compatibility with the Kyoto Protocol has provided a major incentive for its application. This indicator measures the total amount of greenhouse gas (GHG) emissions caused directly and indirectly by an individual, event, organization, or product, and is expressed in equivalent units of mass of CO_2 (Weidema et al. 2008). The Kyoto Protocol is considered equivalent to the category of Global Warming Potential of LCA methodologies, and is usually calculated according to the GHG Protocol and PAS 2050 methodologies (Pérez Leal 2012).

Although these indicators suffer from known deficiencies because they represent a simplification of reality that certain researchers consider extreme (van den Bergh and Verbruggen 1999), they still enjoy remarkable reception by society and by political bodies. This success is due, first, to their production of results that remain understandable by non-scientific society, and second, to their ease of application in decision-making and environmental policy (Bare et al. 2000).

This chapter aims to bring all previous knowledge related to the carbon footprint indicator into the residential building sector in order to analyze the phase of construction of buildings, to establish a methodology for calculation, and hence to determine the advantages and disadvantages that this indicator yields in the analysis of environmental impact on the building sector.

In the following sections that introduce the methodological analysis for building construction, a construction project is presented and analyzed in terms of building type, m^2 built, location, and time needed to finish the construction works. Afterwards, the whole methodology is explained using flowcharts for each element (i.e., energy, water, mobility, food, construction materials, and waste generation) and defining the auxiliary data necessary for the calculations. Finally, the results from applying the methodology to the case study are shown and expressed in kg CO_2 eq per year.

2 Case Study

For the determination of which building type to analyze, the most representative types of buildings for the residential sector in Andalusia (Spain) (Mercader 2010; Mercader et al. 2010) were first studied. This study concluded that the predominant residential buildings were two-story semi-detached houses and four-story blocks of flats.

The case study chosen is a residential complex formed by two four-story blocks of flats, being the type that theoretically generates a smaller impact on the area per m^2 built (Holden 2004), although it would be necessary to apply the methodology to various dwelling types in order to compare them.

A building and urbanization project of two purpose-built blocks were studied. Each block contained four floors above ground level and two below ground level, amounting to a total of 107 dwellings, with their parking spaces, storerooms, and shops (Fig. 1). This project was initiated in the province of Huelva (Andalusia, Spain) and was completed in 2008, which is the year to be taken as reference. The total constructed area is shown in Table 1.

In the initial assumptions for the case study, it is considered that the only activity that exerts an impact on the area is that which corresponds to the construction of the residential buildings specified above. This impact will be continued for a period of 12 months, which is the time-span considered necessary for the construction. In the event that the implementation period is longer than a year, then the impact of the building process is assumed to be uniform. For example, consider that the construction lasts 18 months; therefore, during the first year, two-third of the total impact of the construction is produced, and during the second year, the remaining one-third is generated. By the time the analysis is being performed, the project is still in the design phase, and hence certain consumption data (e.g., water consumption, power consumption) remains unavailable.

In Sect. 3, the methodology for calculating the carbon footprint due to a real building construction is explained, accompanied by flowcharts, hypotheses, and formulae. Each item of the methodology (i.e., energy, water, mobility, food, construction materials, and waste generation) is analyzed separately. Finally, the results from applying the methodology to the case study are shown and expressed

Fig. 1 Type of residential building under analysis

Table 1 Constructed area of the two blocks

	Floor area (m^2)	
Constructed area	Block 1	Block 2
Ground floor	1,359.06	1,197.86
First floor	1,359.15	1,197.86
Second floor	1,363.35	1,201.53
Third floor	1,363.35	1,201.53
Total	5,444.91	4,798.78
Total area (m^2)	10,243.69	

in kg CO_2 eq per year. The construction materials are identified as the most important element in the project's carbon footprint.

3 Methodology

In order to calculate the carbon footprint of the construction of buildings, it is necessary to establish the functional unit of the study. Unfortunately, no product category rule for entire buildings has been published yet. Currently, this is under development by the International Committee for Normalization CEN TC 350. Despite this temporal inconvenience, we are convinced that the whole project is the functional unit to be used. This functional unit comprises all the processes from cradle-to-gate, which are consequence of the building (or buildings) under construction and the urbanization required for the treated zone.

The reference unit of the study will be kg CO_2 eq/year/project and kg CO_2 eq/year/m^2. However, this will be expressed as kg CO_2 eq/year throughout the chapter, as all the calculations are referred to the project under study; only in the final results do the project and m^2 factors appear. These have been chosen because they are the most descriptive units in a construction project. The year factor is used

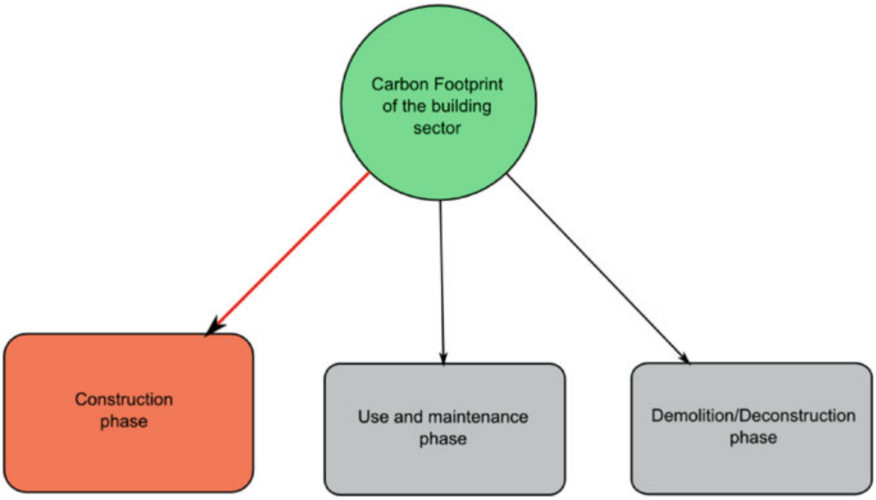

Fig. 2 Boundaries of the study

in order to ease the comparatives between the results and the planet′s CO_2 assimilation capacity.

Although the Total Carbon Footprint is expressed in kg CO_2 eq/year, the work duration factor will not appear in any formula or flowchart because the construction process of our case study lasts one year. If the construction process lasted more (or less) than a year, the total carbon footprint, or the partial carbon footprints instead, should be divided by the number of years.

This carbon footprint assessment focuses on the implementation and construction phase of residential buildings due to the complexity of the calculations; research into the other two phases of the life cycle of buildings, those of use and demolition, is not part of the present analysis (Fig. 2). Thus, the entire project, including two buildings and the corresponding urbanization in this case study, are analyzed following a cradle-to-gate methodology, given that only the construction phase is studied.

These boundaries establish a clear frontier between the three stages of a building′s life cycle. However, some of the impacts included in the methodology might be considered to be part of people′s footprint. Such is the case of food, where it has been decided to include the energy intensity of the various products based on the hypothesis that this is the energy associated with the effort of the workers, and thus it should be taken into account. Also, the mobility of workers to the worksite has been included, because it is considered to be a consequence of the construction process as well. The study follows the methodology described in the flowchart in Fig. 3.

1. Emissions-generating elements. These are the generators of CO_2 (second level of the tree of Fig. 3): direct consumption, indirect consumption, and waste

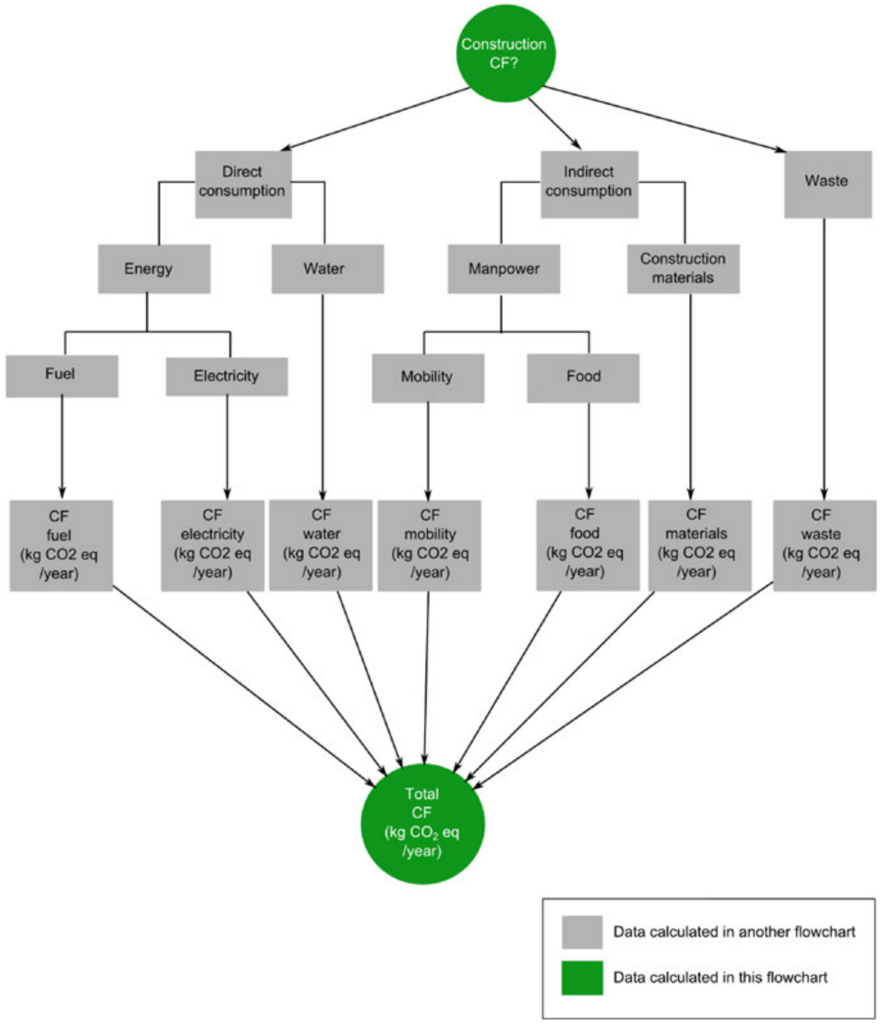

Fig. 3 Methodology flowchart. CF, carbon footprint

generation. Direct consumption is that which causes direct energy expenditure (in the form of fuel or electricity) or water consumption on the construction site. Both are located in the third level of the tree. Indirect consumption is caused by the indirect use of resources, which are in this case:

- Manpower
- Building materials consumption

The manpower in building construction comprises food expenditure by the operators, and the use of fuel for the mobility of the operators (trips to the construction site).

For their part, building materials (listed in Sect. 4.5), through manufacturing processes, transportation, and installation (see Fig. 3), consume fuel (transport of materials to the workplace) and/or energy (necessary for the manufacture of materials and commissioning). For the carbon footprint assessment of material consumption, a quantitative study is performed on the building materials, whose amount is then translated into resources expressible in terms of CO_2 emissions by using the Greenhouse Gas Protocol methodology included in SimaPro 7.3 and GaBi 4 Education. Data for primary energy consumption is also gathered because it will eventually be needed in order to determine the carbon footprint of waste generation and recycling.

LCA databases for building products have their specific limitations, and finding the most suitable data to the project under study is not simple. LCA databases contain data from studies all around the world. The most extended Spanish database (BEDEC) lacks transparency, but at the same time it is better adjusted to the construction model in Spain. Other European databases might not reflect the manufacturing process as it is in Spain. In this study, it has been considered important to use, when possible, transparent data from countries next to the project′s location.

The third factor is the impact of waste generated in the construction phase, which mostly corresponds to the so-called construction and demolition waste (CDW). Therefore, each of the emissions-generating elements uses resources (energy, water, manpower, materials) or generates waste.

2. Intermediate elements (see the key to Fig. 3). Through these elements, consumption is transformed into elements that allow us to define the various footprints that make up the total footprint of the system under study. The intermediate elements are fuel, electricity, mobility, food consumption, and extraction, transport and manufacturing of construction materials. These gray boxes comprise internal calculations developed in several flowcharts corresponding to each intermediate element (Figs. 6, 7, 8, 9, 10 and 11).

3. Partial footprints and the total carbon footprint. By means of the intermediate elements and their implied calculations, the partial footprints that are generated in the construction phase of the buildings projected are obtained. These are located at the bottom level of Fig. 2, represented by gray squares. The result of the addition of all the partial footprints is the total carbon footprint, being all of them expressed in kg CO_2 eq/year.

To apply the above methodology, a budget must be used in accordance with a building cost system. For this analysis, the Andalusian Construction Cost Database (ACCD 2008) is used. This database has been developed over the past 25 years in Andalusia and is the most widespread in this region. Its use is mandatory in public developments in Andalusia. Not only is ACCD valid as an estimation of cost, but it also provides a common method to manage information during the design and construction of buildings (Marrero and Ramirez-de-Arellano 2010). The cost

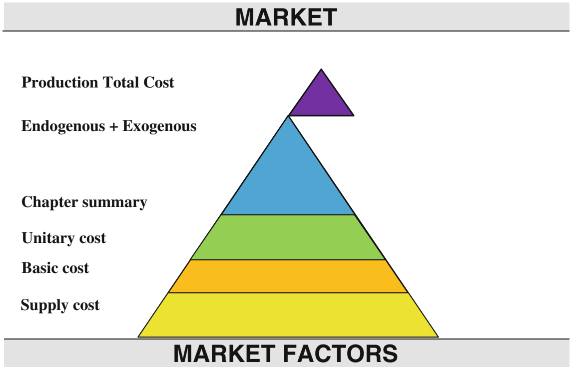

Fig. 4 Pyramidal cost structure (Marrero and Ramirez-de-Arellano 2010)

structure defined distinguishes between direct costs and indirect costs, thereby allowing a clear determination of all costs for each project type. The ACCD structure is arborescent and hierarchical, with clearly defined levels from the apex of the hierarchy down to lower levels, whereby each group is divided into subgroups of similar characteristics (Fig. 4).

For this analysis, the levels used in this structure are (Fig. 5):

1. The production total cost (PTC): covers all production costs incurred by the tasks necessary for the projected work.
2. Basic cost (BC): refers to elements that are a resource: manpower, materials, and machinery.

In our study, all costs are allocated directly, since the indirect costs (IC) are previously analyzed and integrated into the budget in a direct way. Hence, all the costs of the construction process are clearly defined. Therefore, in order to determine the PTC, it is necessary to calculate not only the direct costs of production (PDC) but also the indirect costs of production (PIC) and health and safety costs (HSC), which are usually accounted for separately. Furthermore, in order to make a detailed calculation of the materials, a budget is assumed in accordance with the ACCD for the year 2008, the year taken for this study. Therefore, the procedure for the determination of the total budget is:

1. Obtain the PTC for the construction of the blocks and the urbanization.
2. Recalculate the costs to adjust them to the ACCD (2008).
3. Integrate IC into the PTC.
4. Integrate HSC into the PTC.
5. Calculate the PTC (adjusted to ACCD 2008).

$$\mathrm{PTC} = \mathrm{PDC_B} + \mathrm{PDC_U} + \mathrm{PIC} + \mathrm{HSC_B} + \mathrm{HSC_U} \tag{1}$$

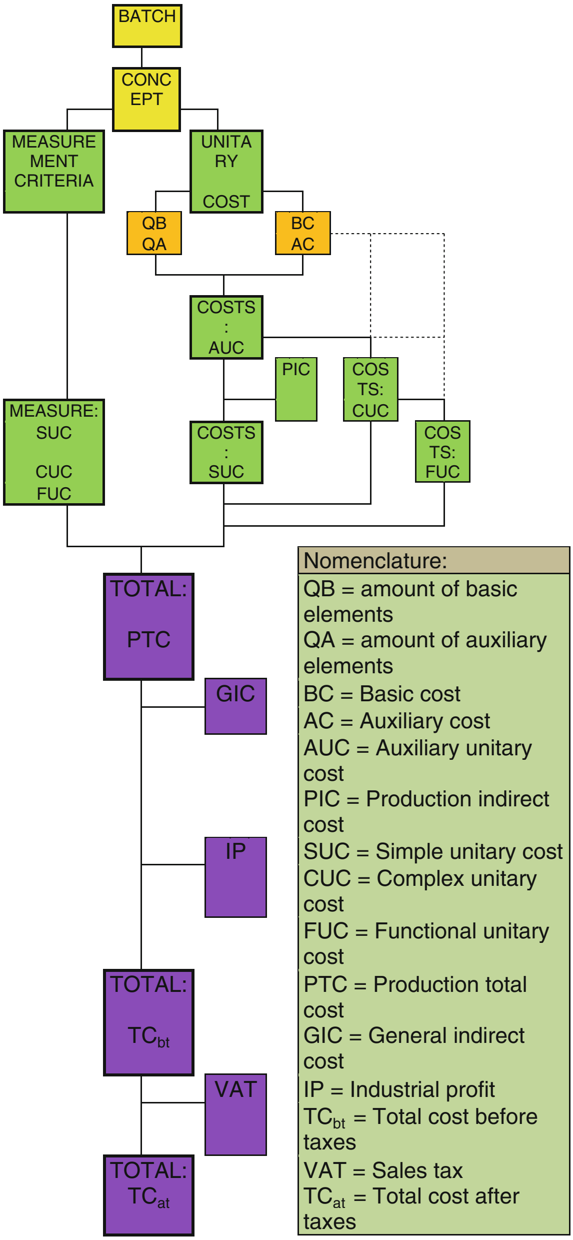

Fig. 5 Budget model (Marrero and Ramirez-de-Arellano 2010)

where

PTC	Production Total Cost
PDC_B	Building Production Direct Costs
PDC_U	Urbanization Production Direct Costs

Table 2 Summary of the overall costs

	Cost (€)
PDC_B	5,067,139.67
PDC_U	187,613.37
PIC	380,726.02
HSC_B	51,867.43
HSC_U	938.07
PTC	5,688,284.55

PIC Production Indirect Costs
HSC_B Building Health and Safety Costs
HSC_U Urbanization Health and Safety Costs.

The overall costs are shown in Table 2.

3.1 Determination of the Emission Factors

Given that a considerable amount of the total carbon footprint will be due to energy consumption in the form of electricity or fuel combustion, an emission factor for each type of consumption is needed.

The emission factor applied for the mobility of workers (E_g) comes expressed in kg CO_2/l, and is as specified in Table 3.

For machinery, due to the higher emissions generated by their engines, the emission factor to be used will be 199.44 kg CO_2/GJ, as it is specified by the International Energy Agency for oil combustion in 2008.

The emission factor for the national energy mix (E_e) is expressed in kilograms of CO_2 per gigajoule (Table 4). The estimates of CO_2 emissions are based on the 1996 IPCC Guidelines and represent the total emissions from fuel combustion. Emissions have been calculated using the IPCC Reference Approach and the IPCC Sectoral Approach. The denominator, total primary energy supply (TPES), is made up of production + imports − exports − international marine bunkers − international aviation bunkers ± stock changes (including biofuels and other nonfossil forms of energy). For our case study, this value is 54.5 kg CO_2/GJ.

Table 3 Fuel consumption and emission coefficients of cars in Spain (IDAE 2011)

Fuel	Consumption (l/100 km)	CO_2 emissions (kg CO_2/l)
Gasoline	7.40	2.35
Gasoil	6.04	2.60

Table 4 CO_2 emissions per total primary energy supply in Spain (2000–2010)

Years	2000	2005	2008	2009	2010
kg CO_2/GJ	55.6	57.1	54.5	52.9	50.2

Source IEA 2012

Table 5 Emission factors used in the present study

Emission factor	Value	Source
Ef (fuel combustion for the mobility of operators)	2.35 kg CO_2/l (gasoline) 2.60 kg CO_2/l (gasoil)	IDAE (2011)
Eo (oil combustion for machinery)	199.44 kg CO_2/GJ	IEA (2012)
Ee (national energy mix)	54.5 kg CO_2/GJ	IEA (2012)

To sum up, the emission factors used in this methodology, except those of construction materials, which are listed in Sect. 4.5, are listed in Table 5.

3.2 Determination of the Carbon Footprint of Energy Consumption

To predict the amount of energy consumed in construction work, data provided by polynomial formulae is used (Spain MP 1970, 1981), which estimates the resources used in the work as a percentage of the total costs for 48 types of construction work (roads, canals, railways, buildings, etc.), both for public and private initiatives (Table 6).

For this case study, type 18 of these formulae is employed: “Those buildings with reinforced concrete structure and facilities that cost less than 20 % of total costs”. Furthermore, as the case study is a public development, it is considered a public initiative.

The coefficients in Table 6 represent the percentage of the PTC, which does not include VAT, industrial profit, general costs, and an additional 15 % of IC. In our case, IC are allocated directly; hence, the percentages in Table 6 are increased to obtain 100 % of the costs (PTC), thereby obtaining the corrected coefficients, multiplying by 1.15, which are those used for the calculations.

Each of the initials of Table 6 refers to the following: m: manpower cost; e: energy; c: cement; s: steel; w: wood, and cr: ceramics.

Therefore, in this example, the energy consumption of the work could be estimated as 9 % of PTC.

As a hypothesis, the total energy consumption of the execution of the work is considered to be shared out between electricity and fuel consumption (Fig. 6), because this is a footprint analysis at the project design stage and therefore the consumption cannot be determined. Therefore, once the total energy consumption

Table 6 Polynomial formulae of type 18 (public initiative)

Type	m	e	c	s	w	cr	Total
18	36	8	12	12	7	10	85
18 (corrected)	42	9	14	14	8	12	100

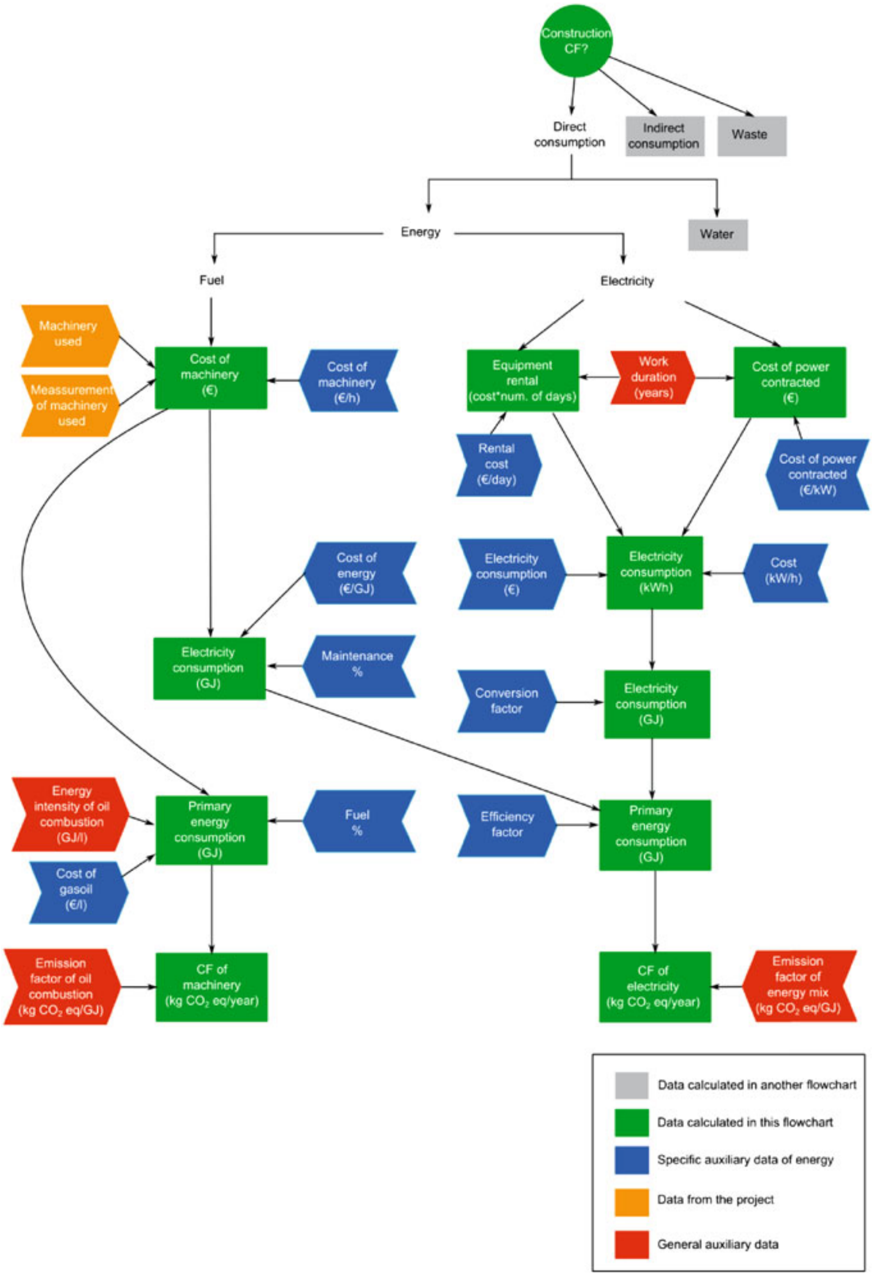

Fig. 6 Flowchart to determine the carbon footprint of energy. CF, carbon footprint

Table 7 Example of calculation of machinery consumption associated with PDC_B

	Hours	Cost (€/h)	Cost (€)	Maintenance (€) (15 %)	Fuel (€) (5 %)
Loader	272.29	23.87	6,499.56	974.93	324.98
Dump truck	1,298.44	25.60	33,240.06	4,986.01	1,662.00
Backhoe	40.93	34.98	1,431.73	214.76	71.59
Bulldozer	0.74	30.30	22.42	3.36	1.12
Vibratory roller	178.00	23.28	4,143.84	621.58	207.19
Manual mechanical tamper	311.09	3.01	936.38	140.46	46.82

and fuel consumption are determined, then the difference between these quantities can be considered to be the electricity consumption.

Once the energy cost of work construction (in Euros) is defined, the next step is to determine the fuel consumption in the work, which is due to the use of machinery. First, the calculation is carried out through measurements of the project, of the hours of machinery used, and then the economic cost of the machinery used can be calculated (Table 7). As concluded in previous studies (Sánchez-de-Mora 2012), approximately 15 % of the total cost of machinery is spent on maintenance (which is supposed to be the only activity comprised in the cost that uses primary energy generated according to the national energy mix), and another 5 % corresponds to fuel consumption. Therefore, the cost of maintenance is assimilated into energy consumption through the cost of electricity, and the cost of fuel consumption is transformed into volume of fuel by means of the average cost of gasoline, which in 2008 (the year of the project) were 1.1233 €/l for gasoline and 1.1414 €/l for gasoil, and 0.092834 €/kWh or 25.787 €/GJ for electricity.

The carbon footprint of fuel consumption can be therefore expressed as:

$$CF_f = (TC_F/C_F) * EI_0 * E_f \qquad (2)$$

where

CF_f Carbon footprint of fuel consumption (kg CO_2 eq)
TC_F Total cost of fuel consumption (€)
C_F Cost of fuel (€/l)
EI_o Energy intensity of oil combustion (GJ/l)
E_f Emission factor of fuel (kg CO_2 eq/GJ)

According to ASTM D-3588-98 (2011), the density of oil at 15 °C is 0.560 kg/l, and the energy intensity of its combustion is 11.250 kcal/kg as a mean value. This results in an EI_o of 0.0252 GJ/l after converting units.

Once the fuel consumption has been determined, the electricity consumption in the construction work can be calculated. To express this data in energy consumption units, the billing model of electricity in Andalusia is used. After obtaining this information, it becomes necessary to determine the electric mix in the project location.

The emission factors obtained in Sect. 3.1 and the efficiency factor for electricity production, which is assumed to be 0.3 (IDAE 2011), are then considered.

The formula used is:

$$CF_e = (TC_E/C_E) * E_{ef} * E_e \tag{3}$$

where

CF_e Carbon footprint of energy consumption (kg CO_2 eq)
TC_E Total cost of energy consumption (€)
C_E Cost of energy (€/GJ)
E_{ef} Efficiency factor for electricity production (1 GJ/0.3 GJ)
E_e Emission factor of energy mix (kg CO_2 eq/GJ).

3.3 Determination of the Carbon Footprint of Water Consumption

The carbon footprint of water consumption is determined assuming water needs a certain quantity of energy to be carried to dwellings. Therefore, the emissions associated to this energy consumption are calculated.

In order to determine the consumption of water for the construction process, the water footprint methodology might be a good option (Hoekstra and Hung 2002). This model is based on the virtual water concept (Allan 1998) and is defined as the total volume of water employed to produce the goods and services consumed by society. In this methodology, water accounts include the withdrawal of water from rivers, lakes, and aquifers (blue water) as well as water from rainfall (green water) that is used in growing crops (Giljum et al. 2011).

However, this methodology is hard to apply for the determination of the consumption of water in our case; hence, it is estimated by comparing to similar examples and then interpolating.

The procedure, shown in Fig. 7, is:

1. Determine the ranges of water consumption and the ranges of costs in work of similar dimensions to that analyzed so that the ratio of the cost of the work to water consumption can be established.
2. Define the average water consumption of the work analyzed, by interpolating with the data obtained in the previous section. Interpolation is based on the TPC.
3. Determine the carbon footprint. This is defined by the calculation procedure that considers the energy needed to bring water to the dwellings, which according to EMASESA (2005) is 0.44 kWh/m^3 or 0.001584 GJ/m^3, employed to conduct water to the dwellings, for drinking water, and treatment of waste water.

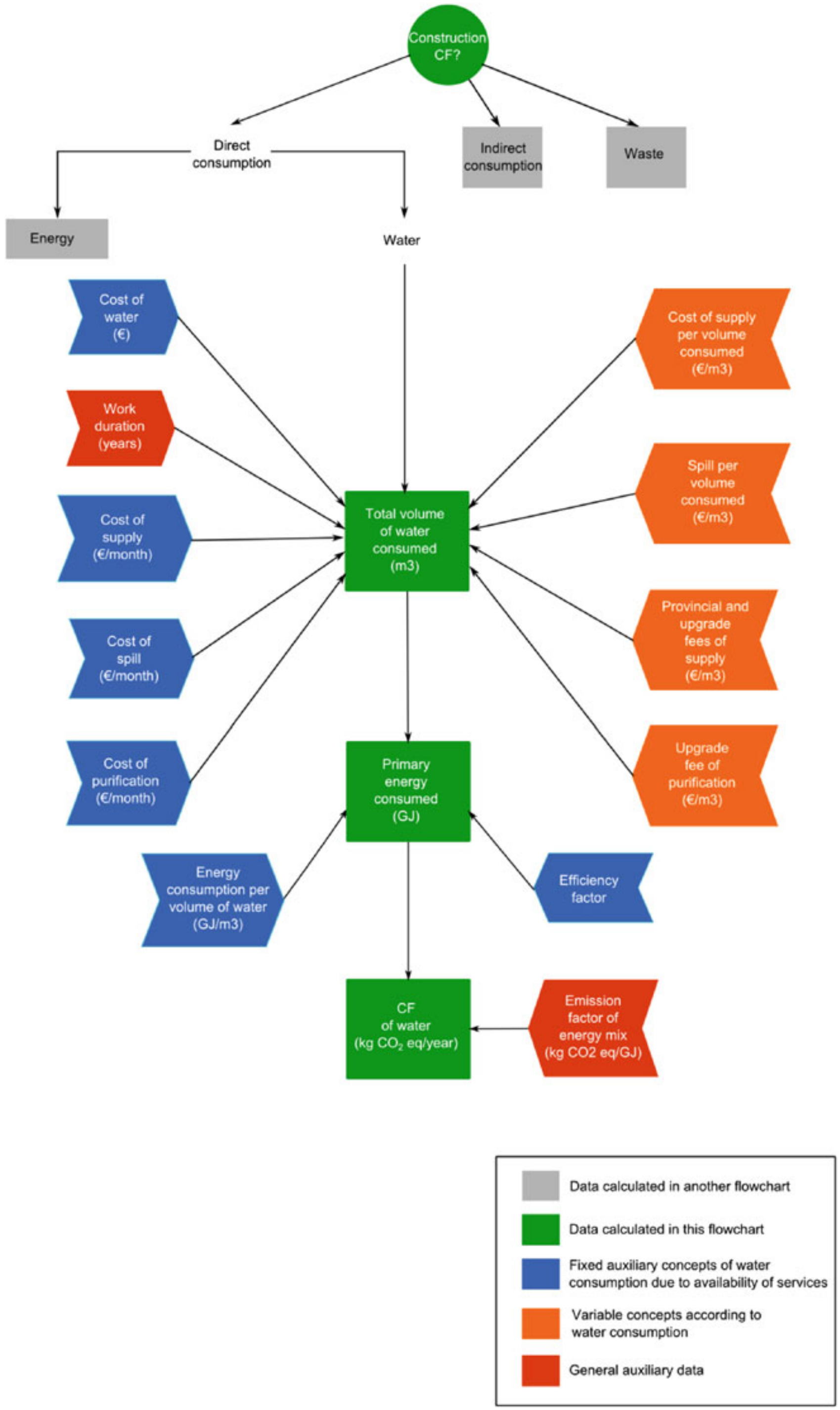

Fig. 7 Flowchart to determine the carbon footprint of water consumption. CF, carbon footprint

Therefore, the formula employed for the calculation of the carbon footprint of water consumption is:

$$CF_w = W * E_w * E_{ef} * E_e \quad (4)$$

where

CF_w	Carbon footprint of water consumption (kg CO_2 eq)
W	Water consumption (m^3)
E_w	Energy consumption per volume of water consumed (GJ/m^3)
E_{ef}	Efficiency factor for electricity production (1 GJ/0.3 GJ)
E_e	Emission factor of energy mix (kg CO_2 eq/GJ)

3.4 Determination of the Carbon Footprint of Food Consumption

The initial hypothesis of this section is that workers′ food is attributed to the carbon footprint of the building construction because this activity takes place on the worksite, in the same way as in the methodology developed by Solís-Guzmán et al. (2013) where business meals are allocated to the ecological footprint of building construction.

To this end, the total number of manpower hours for the entire work must first be calculated, which is obtained by measuring the project. Such manpower is broken down with ACCD Systematic Classification (ACCD 2008). This classification also gives the economic cost of the manpower (€/h).

The footprint is calculated using the expression:

$$CF_{fd} = CF_{me} * (N_h / h_{me}) \quad (5)$$

where

CF_{fd}	Carbon footprint of food consumption (kg CO_2 eq)
CF_{me}	Carbon footprint per meal (kg CO_2 eq/meal)
h_{me}	8 h/meal (one meal per working day is assumed)
N_h	Total number of hours worked

Therefore, it is necessary to obtain the carbon footprint of the various types of food that make up the daily meal of every worker. This carbon footprint is generated due to their required processing, or, as in the case of fish, this factor represents the fuel consumed for the capture of the fish. This translates into CO_2 emissions with the formula:

$$CF_{me} = C * EI * E_e \quad (6)$$

Table 8 Parameters for the calculation of the food footprint (Domenech Quesada 2007)

Foods	F_i %	C_i (t/1,000 €)	EI_i(GJ/t)
Meat	25	0.65	80
Fish	25	0.50	100
Cereals	12	4.69	15
Beverages	10	0.34	7
Vegetables	8	1.45	10
Sweets	6	0.70	15
Oil	5	0.71	40
Dairy	5	0.93	37
Coffee	4	0.54	75

where

CF_{me} Carbon footprint per meal (kg CO_2 eq/meal)
C Food consumption (t/meal)
EI Energy intensity (GJ/t)
E_e Emission factor of energy mix (kg CO_2 eq/GJ)

If we develop this expression:

$$C * EI = C_{me}/1000 * \sum (F_i\%/100) * C_i * EI_i \quad (7)$$

where each of the factors considered would be:
C_{me} cost per meal (assumed at a cost of 10 € per meal)
F_i % Percentage of the meal cost that each type of food represents (Table 8)
C_i Consumption in tons per 1,000 € (Table 8)
EI_i Energy intensities (Table 8)

The whole process to determine the carbon footprint of food consumption is shown in Fig. 8.

3.5 Determination of the Carbon Footprint of Mobility

In order to determine the carbon footprint related to the mobility of workers (Fig. 9), the following assumptions are made:

1. Private vehicles are established as the only means of transport, because it is assumed that the construction work is placed in a remote area away from the city center.
2. The average distance traveled by the vehicles is established. It assumes an average distance of 15–30 km.
3. The average vehicle occupancy is 1.2 people per vehicle (IDAE 2011). In order to determine the number of workers, the total number of hours worked must be

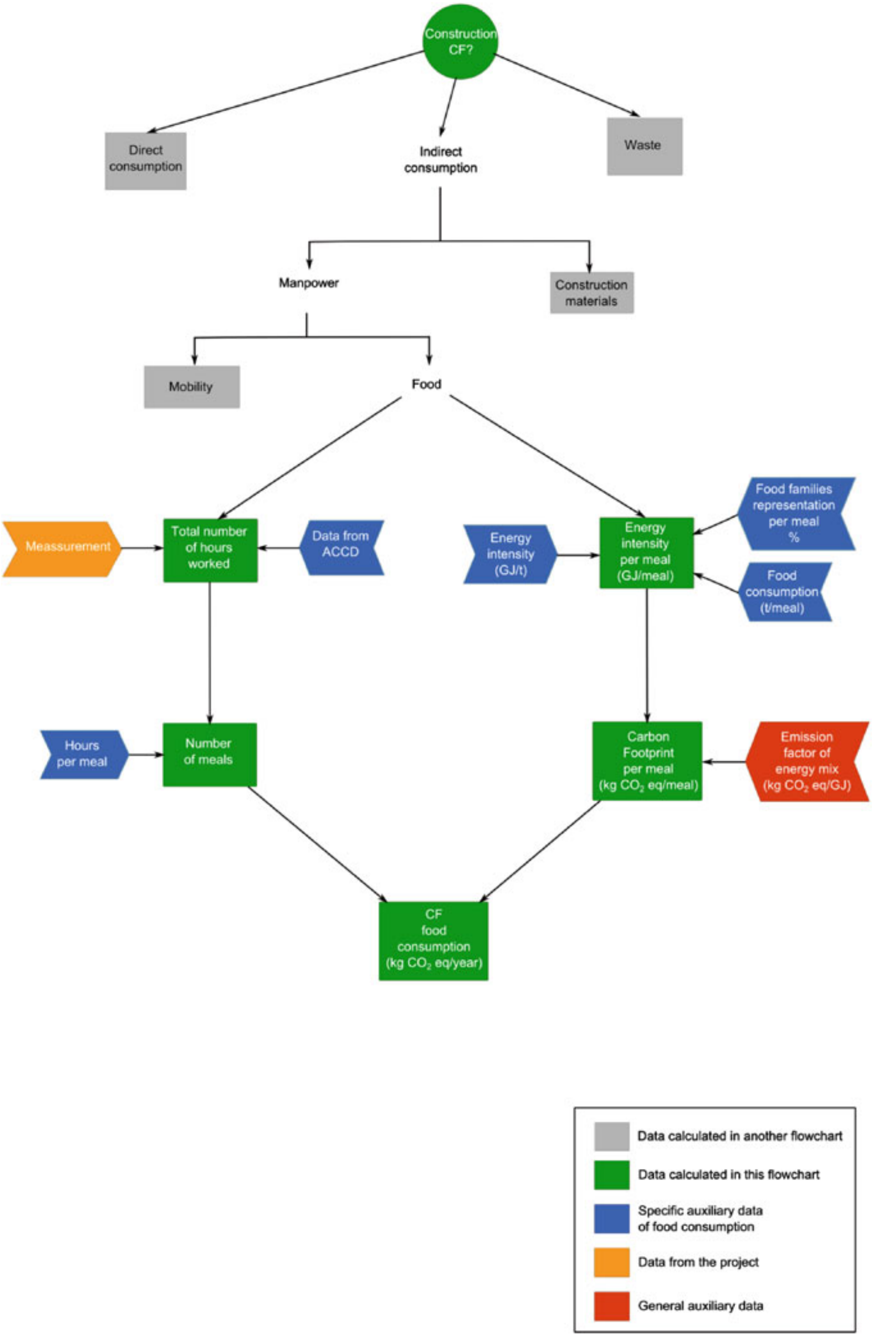

Fig. 8 Methodology for determining the carbon footprint of food consumption. CF, carbon footprint

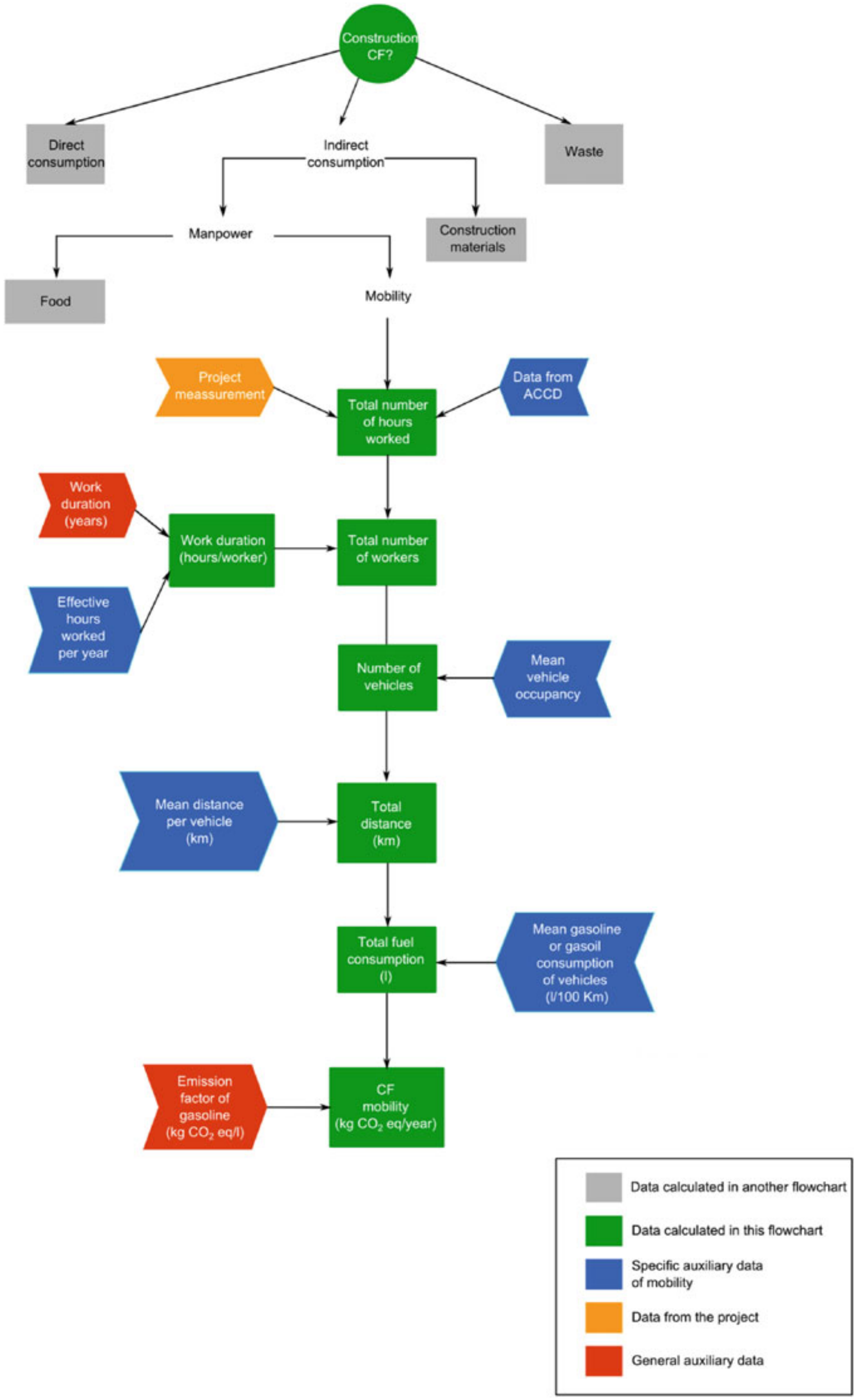

Fig. 9 Carbon footprint of mobility. CF, carbon footprint

known (calculated in the previous section on food), as well as the effective duration of the work (in hours). Both items can be obtained from the ACCD (ACCD 2008).

4. For the calculation of the fuel consumption, consumption coefficients of cars in Spain (IDAE 2011), shown in Table 3, are applied.
5. The mobility footprint is determined by following the procedure in the energy section.

3.6 Determination of the Carbon Footprint of Construction Materials

The footprint of construction materials (Fig. 10) is determined using the following expression:

$$CF_m = \sum Cm_i * Em_i \tag{8}$$

where

CF_m Carbon footprint of construction materials (kg CO_2 eq)
Cm_i Material consumption (kg)
Em_i Emission factor of material i (kg CO_2 eq/kg).

The emission factor values were obtained from various databases, (ITeC 2013; ELCD 2013a; PlasticsEurope 2013; Ecoinvent Centre 2013), by taking the most suitable values according to the origin of the data, its transparency, and comprehensiveness (Martínez-Rocamora 2012). The data for CO_2 emissions is calculated by applying the GHG Protocol methodology. These emission factors are retrieved for a batch of 32 construction materials, which represent 91.81 % of the total embodied energy of materials in this case study. The remaining materials are converted into carbon footprint through their embodied energy and the emission factor calculated in Sect. 3.1 for the national energy mix.

Based on these values, the consumption of materials (by weight) is determined through measurements of the project studied. Basic costs (BC) of the ACCD (2008) are used (see Fig. 10). In order to convert units of measurement of BC (m, m^2, m^3, etc.) into weight, the coefficients calculated by Mercader (2010) are used (Table 9).

The example shown in Table 9 corresponds to the study of the construction of our building project and features a number of the most representative materials of the work from a quantitative point of view. The grouping of BC is based on representative materials or those whose information of CO_2 emissions is available. The second column of Table 9 shows the unit in which the BC is measured. The remaining columns represent:

M_{mi} Measurement of the basic cost of the material i of the project concerned
BC_{mi} Basic cost of the material i (according to ACCD 2008)
TC_{mi} Total cost of the construction material i (€)

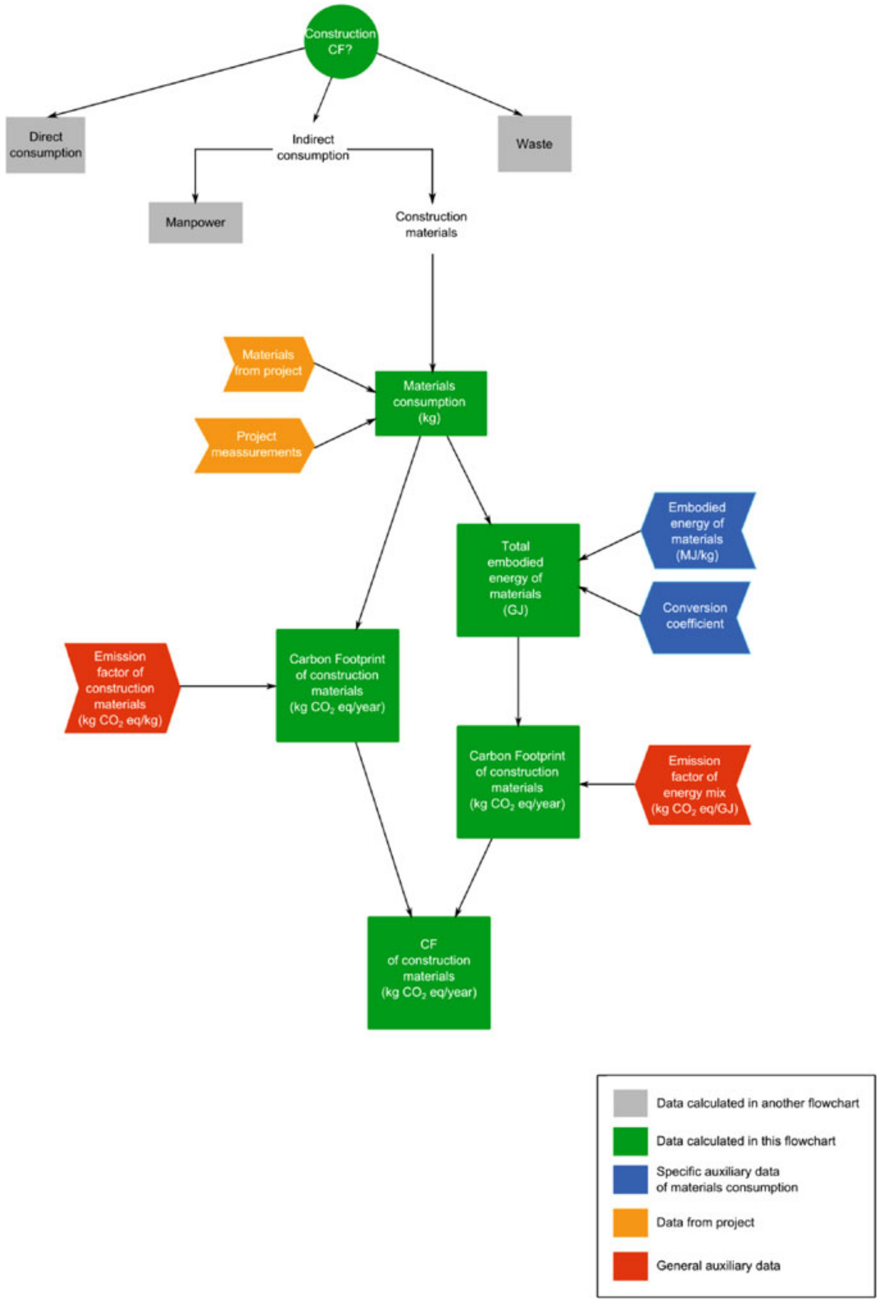

Fig. 10 Methodology for determining the carbon footprint of construction materials. CF, carbon footprint

Table 9 Examples of the calculation of carbon footprint of the most representative materials in the case study

	u	M_{mi} (u)	M_{mbi}(u)	BC_{mi} (€/u)	TC_{mi} (€)	C_{ci} (kg/u)	Cm_i (kg)	Em_i (kg CO_2 eq/kg)	CFm_i (kg CO_2 eq/year)
Steel B 500S	kg	234,915.31	223,728.87	0.77	180,884.79	1.00	223,728.87	1.26	281,898.38
Concrete HA25/B/40	m^3	1,271.37	1,234.34	69.32	88,131.37	2,500.00	3,085,849.51	0.1013	312,596.55
Brick 24/11.5/9 cm	mu	239.61	226.05	98.28	23,548.87	1,550.00	350,373.11	0.219	76,731.71
Gypsum board 13 mm thickness	m^2	21,253.45	20,241.38	4.55	96,703.20	10.00	202,413.81	0.36	72,868.97
Cement II/AL 32.5 N	t	173.07	164.83	92.54	16,015.81	1,000.00	164,827.65	0.899	148,180.06
Coated aluminum sliding door	m^2	327.60	327.60	69.60	22,800.96	20.00	6,552.00	2.39	15,659.28

$$TC_{mi} = M_{mi} * BC_{mi} \tag{9}$$

M_{mbi} Measurement of the material i, which is integrated into the building. It relates to M_{mi} through a loss coefficient, which takes into account those materials that are not integrated into the building.

C_{ci} Conversion coefficient of the unit measure of the basic cost into weight (kg). For this purpose, those coefficients calculated by Mercader (2010) are used.

Cm_i Consumption of the material i (kg)

$$Cm_i = M_{mbi} * C_{ci} \tag{10}$$

Em_i Emission factor of the material i. Em_i values come from the sources referenced above.

EEm_i Embodied energy of the material i (GJ).

E_e Emission factor of energy mix (kg CO_2 eq/GJ).

CFm_i Carbon Footprint of the material i (kg CO_2 eq)

$$CFm_i = Cm_i * Em_i \tag{11}$$

or

$$CFm_i = Cm_i * EEm_i * E_e \tag{12}$$

By performing a similar analysis with all the materials measured in the design project, the consumption and the carbon footprint of the materials are obtained.

3.7 Determination of the Carbon Footprint of Waste

The types of waste generated throughout the life cycle of a building are varied in content and origin. By focusing on the construction phase of the building, one must consider, on one hand, the municipal solid waste (MSW) generated in the workplace, and second, the construction and demolition waste (CDW) generated during this phase. Municipal solid waste can be broken down into four types: organic matter, paper/cardboard, plastics, and glass. In the case of the construction and demolition waste, two types of waste are considered in accordance with the management models that exist in the CDW treatment plants in Andalusia: excavated earth and mixed CDW. Mixed CDW groups the remains of materials generated during the execution of the work unit and the packaging used in the transport of the materials. In new construction work, excavated earth may represent over 80 % of CDW, while the mixed CDW is distributed among the remains of materials and packaging (Solís-Guzmán et al. 2009).

The procedure is based on the energy intensity (EI) of the production of the material from which the waste is made (embodied energy data collected in Sect. 3.6), with a deduction of the percentage of energy that can be recovered by recycling. Some of the waste is organic, excavated earth, or mixed CDW. The carbon footprint of waste is calculated by using the formula,

$$CF_x = \sum G_i * E_e, \tag{13}$$

where each of these terms is:

CF_x Carbon footprint of waste

G_i Waste generation (t)

EI_{xi} Energy intensity of the production of the material from which the waste is made (GJ/t). For these values, the energy intensities of the materials to be recycled must be known. The data is summarized in Table 10. Although it is known that there is no direct correspondence between embodied energy and GHG emissions, and given that we have no data source for emission savings when recycling the various waste, we are forced to use the energy intensity data and convert it into emissions using the emission factor of energy mix obtained in Sect. 3.1.

$\%R_{xi}$ Recycling rate of waste i. In the case of organic waste, nationwide information (OSE 2008) is used, by determining the percentage given in Table 10 (13 %) for composted organic waste. For the other flows, (paper, plastic, and glass), data from the Regional Government (Andalusia ME 2009) on recycling rates in Andalusia is used. For excavated earth, 50 % reuse on site and 80 % recycling on treatment plant is estimated, although all material can be recycled. For mixed CDW, a recycling rate of 15 % (GERD 2009) is considered, which is well below the national and European objectives.

$\%SE_{xi}$ Percentage of energy saved by recycling

E_e Emission factor of energy consumption (kg CO_2 eq/GJ).

In short, the procedure shown in Fig. 11 is as follows:

1. Determination of the generation of MSW and CDW. These calculations are either based on statistical data (Spain ME 2001; Andalusia ME 2009) or on a software tool (Ramirez-de-Arellano Agudo et al. 2008; Solís-Guzmán et al. 2009).
2. Calculation of the carbon footprint of the waste.

In Sect. 4, this methodology is applied to the case study described in Sect. 2. Each individual carbon footprint (i.e., energy, water, food, mobility, construction

Table 10 Parameters for the calculation of conversion rates

	Organic	Paper	Plastic	Glass	Earth	Mixed CDW
EI_x (GJ/t)	20	30	43.75	20	0.10	5
$\%R_x$	13	50	40	40	80	15
$\%SE_x$	100	50	70	40	90	90

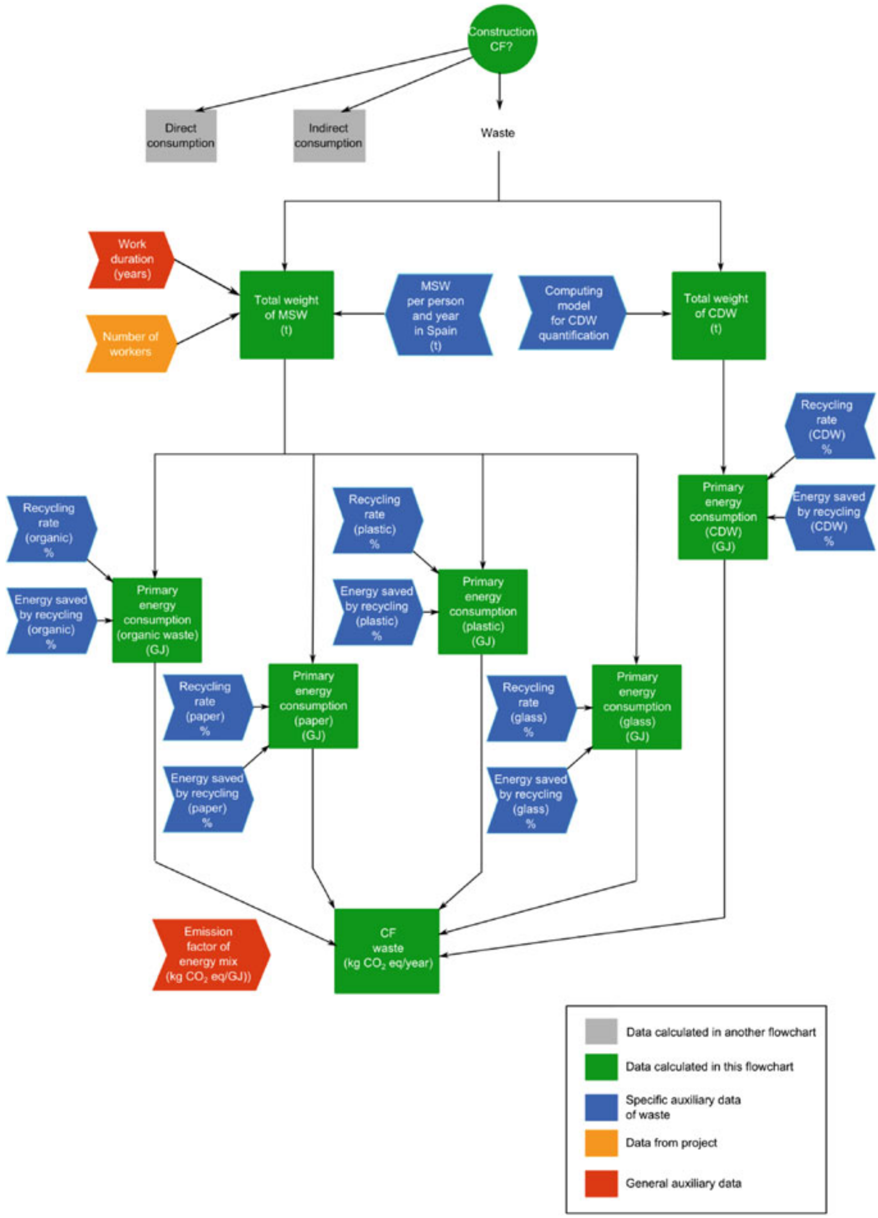

Fig. 11 Flowchart to calculate the carbon footprint of waste. CF, carbon footprint

materials, and waste) is calculated, and finally they are all summed up in a total carbon footprint of the whole construction process of the buildings included in the project under study.

4 Results

4.1 Carbon Footprint of Energy Consumption

The cost of machinery fuel and maintenance and its corresponding energy consumption is determined by the project quantities and costs. The results appear in Table 11.

By means of polynomial formulae (Table 6), the percentage of overall costs that correspond to the energy consumption is computed. Because the energy consumption of machinery is already calculated, the difference between energy consumption and fuel consumption is therefore the electricity consumption.

The electricity consumption in GJ is obtained from the billing model used by the electricity supplier. In order to obtain the electricity footprint, it is necessary to determine the source of electricity in Spain (IEA 2012). The results appear in Table 12.

4.2 Carbon Footprint of Water Consumption

The results of consumption are 2,599.48 m^3 of water, thereby resulting in a carbon footprint of water consumption of 748.03 kg CO_2 eq (Table 13).

Table 11 Overall costs and carbon footprint of machinery

Machinery	Cost (€)	Primary energy onsumption (GJ)	Carbon Footprint (kg CO_2 eq/year)
Building	167,708.63		
Urbanization	16,588.42		
Indirect costs	71,152.76		
Total cost	255,449.81		
15 % (maintenance)	38,317.47	4,953.07 (energy mix)	269,942.13
5 % (fuel)	12,772.49	281.99 (fuel)	56,240.67

Table 12 Carbon footprint of electricity

Energy total cost (€)	511,945.61
Electricity total cost (excluding machinery maintenance and fuel) (€)	460,855,65
Price of electricity (€/GJ)	25.787
Electricity consumption (GJ)	17,871.63
Efficiency factor	0.30
Primary energy consumption (GJ)	59,572.09
Emission factor for energy mix (kg CO_2 eq/GJ)	54.5
Carbon footprint of electricity consumption (kg CO_2 eq/year)	3,246,678.94

Table 13 Carbon footprint of water consumption

Water total consumption (m^3)	2,599.48
Energy consumption per volume of water consumed (GJ/m^3)	0.001584
Energy consumption (GJ)	4.1176
Efficiency factor	0.30
Primary energy consumption (GJ)	13.725
Emission factor for energy mix (kg CO_2 eq/GJ)	54.5
Carbon footprint of water consumption (kg CO_2 eq/year)	748.03

Table 14 Total cost of manpower

Task	Manpower hours	Cost (€)
Building	98,686.05	1,470,946.35
Urbanization	4,280.57	62,590.07
Building health and safety	604.46	8,752.26
Urbanization health and safety	10.93	158.29
Indirect costs	15,836.82	264,474.95
Total	119,418.84	1,806,921.92

4.3 *Carbon Footprint of Food Consumption*

First, the total number of manpower hours worked for the entire project is calculated, obtained by measuring the project. Such manpower is broken down according to the ACCD Systematic Classification (ACCD 2008). The manpower costs (€/h) are also obtained in this classification. The results appear in Table 14.

The primary energy from the different foods that make up the daily meals of the workers is then obtained by using the data in Table 8. The results are shown in Table 15.

4.4 *Carbon Footprint of Mobility*

Following the guidelines outlined in Sect. 3.5, the carbon footprint of mobility is obtained as expressed in Table 16.

Table 15 Carbon footprint of food consumption

Total number of hours worked (h)	119,418.84
Hours per meal	8
Number of meals	14,927.355
Energy intensity per meal (GJ/meal)	0.407305
Emission factor for energy mix (kg CO_2 eq/GJ)	54.5
Carbon footprint per meal (kg CO_2 eq/meal)	22.198
Total carbon footprint of food consumption (kg CO_2 eq/year)	331,359.25

Table 16 Carbon footprint of mobility

Total number of hours worked (h)	119,418.84
Hours per worker in a year (h/worker)	1,533
Number of workers	77.90
Mean vehicle occupancy (workers/vehicle)	1.2
Number of vehicles	65
Distance per vehicle (km)	30
Total distance (km)	1,950
Gasoline consumption (l/100 km)	7.4
Emission factor (kg CO_2/l)	2.35
Total carbon footprint of mobility (kg CO_2 eq/year)	339.105

4.5 Carbon Footprint of Construction Materials

In a previous study, considerable differences in the data for embodied energy and GHG emissions of construction materials from the various LCA databases were detected (over 60 % in some cases), as can be observed in Fig. 12. These discrepancies were mostly due to the use of different flowcharts and methodologies and distinct recycling rates; however, the sensitivity of the model to changes of LCA databases is proved (Martínez-Rocamora 2012).

As mentioned in Sect. 3.6, the emission factors are retrieved for a batch of 32 construction materials which represent 91.81 % of the total embodied energy of materials in this case study. The remaining construction materials are converted into carbon footprint through their embodied energy and the emission factor calculated in Sect. 3.1 for the national energy mix. The results are shown in Table 17.

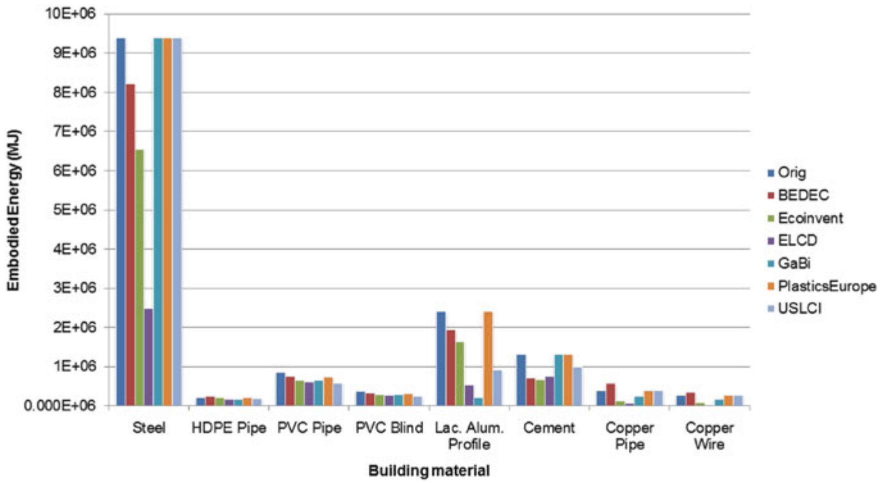

Fig. 12 Comparative analysis of the embodied energy of 8 construction materials from various LCA databases

Table 17 Carbon footprint of construction materials

Carbon footprint (91.81 %) (kg CO_2 eq/year)	6,463,263.60
Embodied energy (8.19 %) (GJ)	6,816.52
Emission factor of energy mix (kg CO_2 eq/GJ)	54.5
Carbon footprint (8.19 %) (kg CO_2 eq/year)	371,500.34
Total carbon footprint of construction materials (kg CO_2 eq/year)	6,834,763.94

The individual contribution of each construction material to the carbon footprint, sorted by quantity, is shown in Table 18.

4.6 Carbon Footprint of Waste

The generation of MSW and CDW are determined through statistical databases and tools. Conversion rates are calculated using the methodology proposed. In the case of CDW, a software tool enabled the result of 22,400 m^3 of excavated earth (of which 50 % is reused) and 1,920 m^3 of mixed CDW to be obtained. The results are shown in Table 19.

4.7 Total Carbon Footprint

The total CF of the whole construction process of the two buildings projected and the urbanization of the area is 11,250,501.85 kg CO_2 eq. Tables 19 and 20 show the overall results, expressed in kg CO_2 eq/year/project and kg CO_2 eq/year/m^2, respectively. In Table 21, the constructed area considered is that of blocks, not the built land. Therefore, the data used is 10,243.69 m^2 (Table 1).

Moreover, a sensitivity analysis should be performed to observe the behavior of the variables. For example, two models of CDW management are compared. In the first scenario, the excavated soil is not reused and the waste is neither separated nor recycled, and therefore the carbon footprint is 596,448 kg CO_2 eq. In a second scenario, 50 % of the excavated soil is reused and the remaining 50 % goes to a treatment plant, which recycles 80 % out of it. Other types of CDW are 15 % recycled, as in Sect. 4.6. The resulting carbon footprint is 473,077.44 kg CO_2 eq in this second scenario. We therefore conclude that the indicator is sensitive to changes in its variables.

Due to the complexity of the building process, with numerous elements involved (water and energy supply, machines, workers from different professional sectors, waste generation and recycling, and building materials among others), it is not easy to establish solid boundaries and not to trespass them and include impacts belonging to people′s or other sectors′ carbon footprints. In fact, other similar

Table 18 Contribution of each construction material to the total carbon footprint of construction materials

Construction material	Emission factor (kg CO_2 eq/kg)	Carbon footprint (kg CO_2 eq/year)	Source database	Source study
Mortar binder	13.73	2,060,886.18	BEDEC	–
Concrete	0.098	1,408,600.96	Base Carbone	SNBPE (2012)
Adhesive paste	13.73	1,032,737.51	BEDEC	–
Bricks	0.219	296,333.89	Ecoinvent	Kellenberger et al. (2007)
Steel	1.03	241,962.78	ELCD	WSA (2011)
Asphalt	0.25	199,027.91	BEDEC	–
Terrazzo	0.22	170,725.85	BEDEC	–
Cement	0.899	169,682.31	ELCD	ELCD (2013b)
Plasterboard	0.36	158,428.34	BEDEC	–
Painting	2.95	150,179.99	BEDEC	–
Tar-epoxy	7.09	108,819.31	BEDEC	–
Modified bitumen	6.67	95,132.88	BEDEC	–
Cement tiles	0.18	86,301.07	BEDEC	–
Tiles	0.57	57,397.60	BEDEC	–
Brass	4.66	52,394.99	GaBi	PE International (2013a)
PVC	3.24	47,384.25	PlasticsEurope Eco-profiles	Ostermayer and Giegrich (2006)
Aluminum	2.39	28,656.51	ELCD	EAA (2013)
Gravel	0.00335	26,282.99	ELCD	ELCD (2013c)
Gypsum	0.108	20,259.36	ELCD	ELCD (2013d)
Copper	2.933	18,932.72	Base Carbone	NIES (I2013)
Crushed stone	0.008	15,691.48	BEDEC	–
HDPE	2.50	6,576.28	PlasticsEurope Eco-profiles	Boustead (2005)
Sand	0.00242	5,119.77	ELCD	ELCD (2013e)
Polyester resin	4.46	3,870.03	GaBi	PE International (2013b)
Bentonite	0.01	886.26	BEDEC	–
Methacrylate	15.00	873.15	BEDEC	–
EPS	3.39	118.75	PlasticsEurope Eco-profiles	Boustead (2006)
Rubber pavement	0.000215	0.47	BEDEC	–
Rest of materials		371,500.34	–	–
TOTAL		6,834,763.94		

Table 19 Carbon footprint of waste

	Organic	Paper	Plastic	Glass	Earth	Mixed CDW	
G (t)	17.71	8.45	4.43	2.83	13,440	1,920	
EI_x (GJ/t)	20	30	43.75	20	0.10	5	
$\%R_x$	13	50	40	40	80	15	
$\%SE_x$	100	50	70	40	90	90	
Carbon footprint (kg CO_2 eq/year)	16,794.18	10,361.81	7,605.20	2,591.15	20,509.44	452,568	
Total carbon footprint of waste (kg CO_2 eq/year)							510,429.78

Table 20 Carbon footprint per year

	Carbon footprint (kg CO_2 eq/year/project)
Energy	3,572,861.74
Water	748.03
Food	331,359.25
Mobility	339.11
Materials	6,834,763.94
Waste	510,429.78
TOTAL	11,250,501.85

Table 21 Carbon footprint per year per m^2

	Carbon Footprint (kg CO_2 eq/year/m^2)
Energy	348.79
Water	0.07
Food	32.35
Mobility	0.03
Materials	667.22
Waste	49.83
TOTAL	1,098.29

approaches considered less elements of the construction process in order to avoid double accounting (see Bastianoni et al. 2007).

Also as explained in Sect. 3, LCA databases for building products have their own limitations, and finding the most suitable data to the project under study is not simple. LCA databases contain data from studies all around the world, and here it has been considered important to use data from countries next to the project′s location. Also, the most extended Spanish database (i.e., BEDEC) lacks transparency, and other European databases might not reflect the manufacturing process as it is in Spain, which limits the calculation′s precision.

5 Conclusions

1. Footprint studies are primarily focused on an urban scale, thereby making it difficult to extrapolate information to the scale of individual buildings. Furthermore, the definition of the measurement units of the indicator for buildings is complicated due to the peculiarities of construction activity. Moreover, the dependence of analysis on charts and graphs necessitates a periodic review thereof.
2. An in-depth study into the innovative aspects of research is necessary, such as research into the impacts caused by water consumption, the study of the embodied energy and GHG emissions of building materials, and that of waste generation.
3. The difficulty of establishing the overall costs of a project as adjusted to a standard cost base, in this case ACCD, is evident because most construction companies often have their own cost databases. Furthermore, for the calculation of the overall costs, it has become necessary to determine the direct costs and indirect costs in full, with the subsequent difficulty of integrating these costs into the methodology of calculation of the indicator.
4. The inclusion of the time factor has been shown to be critical because it determines hypothesis testing throughout the entire methodology. Furthermore, the assumption of carbon footprint per year as the calculation unit allows for a greater generalization of results.
5. The effect of consumption of construction materials is highly significant. For this type of activity, mobility carries no decisive impact. Other sources leading to the carbon footprint are machinery, electricity, and food. Finally, the footprint of water usage has little appreciable effect in this study. All these results require further review toward the improvement of the current model (Ostermayer and Giegrich 2006).

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