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Evolution of the life cycle of residential buildings in Andalusia: Economic and environmental evaluation of their direct and indirect impacts

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ABSTRACT

This article presents a methodology to forecast, the environmental and economic impacts during the building life cycle. Residential buildings in Andalusia are studied during their useful life, from conception to demolition. To this end, the indicators of the footprint family, carbon, water, and ecological footprints, and that of embodied energy have been adapted for the evaluation of each phase of the cycle: transformation of land use (urbanisation), construction, maintenance, and finally, demolition. The maintenance frequency and life expectancy of the construction elements are defined, as are the monetary and environmental updates. The budgets and the construction cost databases of each project taking place during the useful life are used for the resource inventories. The methodology enables the sources of greatest impact in each phase to be located, thereby facilitating the evaluation of the future effects of the design. Of the total impacts, 60% are incurred during the construction/renovation work and 40% during direct use, which indicates that efforts should not only be focused on the energy efficiency during use, but also during the manufacturing and commissioning of construction materials.

1. Introduction

Buildings are responsible for high environmental impacts: it has been estimated that, in 2017, the construction sector emitted 39% (28% due to operations and 11% due to materials) of greenhouse gases (GHG) worldwide (UN Environment Programme, 2018). Certain environmental paradigms that are considered to always be true, such as "*recycled and local products are always the best*", present confusion between the beginning/ending of the life cycle (minimising flows to and from nature) and the middle phases of the life cycle (recycling, reusing, minimising transport distance) (Trusty W. & Horst S., 2002). Similar ideas have emerged regarding a building's environmental performance, such as "*wood is better than concrete and steel*", "*renovation is always preferable to demolishing and rebuilding*", and "*impacts during use are more intense than embodied impacts*" (Marcella Ruschi et al., 2020). These raise the question regarding whether, from the design phase, it is possible to predict the environmental impacts associated with the projects through their building life cycle (BLC) in an objective and contrastable way, and whether it is feasible to intervene and reduce such impacts.

In order to measure the interaction of buildings with the environment and to identify the loads in the service stages of a building, life cycle analysis (LCA) is recommended (UNE-EN-ISO 14040:2006, 2006), which takes into account all flows exchanged between the product/system analysed and the environment. Life cycle analysis provides an overview of the environmental performance of the object under study and helps demystify fixed and biased perceptions regarding environmental mechanisms. Life cycle analysis has been widely applied in the construction sector and is increasingly used as an advocate for decision-making at all levels of the built environment, such as for material (Knoeri et al., 2013; Zabalza Bribián et al., 2011), systems (Guggemos & Horvath, 2005; Zabalza Bribián et al., 2011), entire buildings (Blengini & di Carlo, 2010; Kua & Maghimai, 2017; Verbeeck & Cornelis, 2011), and for neighbourhoods (Skaar et al., 2018; Trigaux D. et al., 2017) .

It remains true that the application of LCA methodologies to the construction sector continues to be extremely complicated, and no exact methodology has yet been established, and therefore researchers are left to use their own interpretations (Martínez-Rocamora et al., 2021). By employing the GREET tool for the evaluation of the embodied and operational greenhouse gas emissions of building components, Cai et al. (Cai et al., 2022) identified the need to benchmark the embodied and operational carbon performance of buildings for comparison to alternative building designs and sustainability practices. Since benchmarking presents a challenging task, Saade et al. (Saade et al., 2020)

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have reviewed over 250 case studies of non-residential buildings, and conclude that operational loads are typically greater than embodied loads, although in energy-efficient buildings the proportion of embodied emissions lies within a wide range of 30 to 70% with respect to that of the total life cycle, and embodied energy ranges between 22-35%. In another review performed by Bahramian and Yetilmezsoy (Bahramian & Yetilmezsoy, 2020), where more than 230 publications were studied, they also report that values vary widely in their results, whereby the embodied energy ranges from 0.533 MJ/m^2 to 883.1 GJ/m^2, and the global warming potential varies between 0.07 to 10,010 kg CO_2-eq/m^2 per year. Their review highlights that the variations in building design (structure and materials), lifetime, functional unit, and in scope all hinder comparisons of the findings and results. In a similar way, Schwartz et al. (2018) reviewed 251 case studies that assess the carbon footprint of the BLC, and found that various scopes and limitations of the analyses are presented, which underlines the need for a unified protocol.

The evaluation of BLC of each project is unique in its quantities, types of materials, and its processes, which makes it difficult to extrapolate from one analysis to another. There is a necessity to define standardised methodologies that enable the comparison of results and that can be employed easily in the construction sector. In this respect, the ARDITEC research group has defined a methodology based on the long tradition of cost control of construction projects (Freire-Guerrero et al., 2019a):, since everybody on the construction site needs to be paid, then the whole resource inventory is covered in the project budget. This inventory enables the assessment of important aspects, such as land occupation, water, energy, and emissions.

In order to minimise the environmental impact generated by buildings, an important question regarding this research arises: Is it possible to predict the environmental impacts of BLC by means of tools already in place for the cost control of construction projects? This paper proposes that the use of construction cost data bases and their systematic classification of work units provides a common thread in the evaluation of the BLC. To this end, the original budget of the project is employed in the definition of present and future work in the building and also of end-of-life activities. This generates the inventory of indirect resources at each stage. For the evaluation of the direct impacts, the energy simulation of the building is employed in its original and future state, after the interventions and repairs. In the case of water consumption, statistical data is utilised to determine present and future scenarios. The objective of this paper and its innovation involves the definition of a methodology for the analysis of the BLC, through the case study of a 4-storey multifamily housing construction project in Andalusia, Spain. To this end, it has been necessary to define not only the phases and duration, but also the limits of the BLC model system for its study. The methodology is sensitive to differences in the constructive solutions, materials used, intensity of the use of machinery, and labour in the projects.

In the review by Bahramian and Yetilmezsoy (Bahramian & Yetilmezsoy, 2020), emissions and embodied energy are identified as the most commonly assessed indicators. But other indicators stand out in the evaluation of buildings, such as the ecological footprint (EF), and the water footprint (WF), in addition to those of carbon (CF) and energy (EE).. Their success is mainly due, first, to the fact that the results they produce are understandable by non-scientific members of society, and second, to their ease of application in environmental policies and decision-making (Bare et al., 2000; Solís-Guzmán et al., 2014). The applications of EF, CF, and WF in building assessment are reviewed in the following sections.

1.1. Ecological footprint

The EF concept was introduced by Wackernagel & Rees (Wackernagel & Rees, 1997), who measured the footprint of humanity and compared it to the carrying capacity of the planet. According to their definition, EF is the area of land that would be needed to supply resources (cereals, feed, firewood, fisheries, and urban land) and absorb emissions (CO_2) from the world's human population. The calculation methodology states that all consumption, both in terms of material and energy, and the absorption of waste have their corresponding expression in productive territory since it is required for their production or disposal. The methodology currently applied (Borucke et al., 2013) is set by an international organization called the Global Footprint Network, in which researchers and sustainability experts from around the world collaborate. There are several studies where it is applied, in the evaluation of the construction of wooden houses (Velasco L. et al., 2019), in the renovation of a centennial house (Bin & Parker, 2012), the construction of schools (Rivero C. & Ferreira-Sánchez A., 2021), and the construction of an exhibition centre in Wuhan, China that analysed the life cycle (project, materialisation, use, and demolition) (Teng & Wu, 2014). The ARDITEC research group (Solís-Guzmán et al., 2013) has developed a calculation model that includes the consumption of food by the operators, or water on site. With its inclusion appear footprints associated with crops, pastures, and fishing. González-Vallejo et al. (González-Vallejo, Marrero, et al., 2015) (González-Vallejo et al., 2019) improve the methodology to evaluate the construction stage, (Martínez-Rocamora, Solís-Guzmán, & Marrero, 2016) evaluate the maintenance stage, and (D. Alba-Rodríguez et al., 2013) the final stage, where they propose a methodology that ascertains the environmental viability of the recovery of buildings versus their demolition. (Freire-Guerrero et al., 2019b) base their evaluation on the inventory of resources that starts from the cost bases of the construction, thereby generating an "environmental budget".

1.2. Carbon footprint

Another commonly used indicator is that of the Carbon Footprint (CF), also based on LCA data, which consists of determining the greenhouse gas emissions caused by a given process (Bare et al., 2000; Weidema et al., 2008). It is calculated following the GHG Protocol and PAS 2050 methodologies (Perez Leal, 2012). This footprint is strongly related to the main objectives of the Kyoto Protocol, can be understood by the non-specialised general public (Dossche, Boel, and De Corte, 2017), and has a straightforward application in decision-making and environmental policy (R. Geng et al., 2017), which together constitute the keys to the success of this indicator. There are bibliographic reviews related to the use of the CF indicator in construction (R. Geng et al., 2017); however, the results are not always comparable, due to the absence of a methodology that follows international standards. Therefore, studies have also been carried out in recent years to establish scales that enable reasonable intervals of CO_2 emissions (Dossche et al., 2017; S. Geng et al., 2017) in construction processes (Chastas et al., 2018a) . In the same way as Chastas et al. (Chastas et al., 2018a) with the EF indicator, the ARDITEC group works on the calculation of the CF in building (Freire & Marrero, 2014; Solís-Guzmán et al., 2014), and has developed the evaluation tool, OERCO2 (Solís-Guzmán et al., 2018, 2020). The CF can be accompanied in its analysis by another indicator, the Embodied Energy (EE) of the processes. Marrero, Rivero-Camacho et al. (2020) show a good association of these indicators in the evaluation of construction and demolition waste (CDW) in the BLC; Ruiz et al. (Ruiz-Pérez et al., 2021) in the urbanisation stage, and Pereira et al. (Pereira et al., 2021) in the energy rehabilitation of buildings.

1.3. Water footprint

Another indicator with a simple message is that of the WF. Buildings and their associated industry consume 30% of the world's available fresh water. A large part of the effort in buildings to reduce water consumption and become more efficient focuses solely on the direct consumption of water through more efficient systems, devices, and appliances, and on better treatment and recycling of wastewater. Direct consumption, however, represents only 12% of total demand since another large part of consumption is carried out indirectly through the production processes of materials and equipment, which is usually called indirect water consumption or virtual water (VW) (Allan, 1993). Materials consume water in their extraction and manufacture, waste management, and reuse. Although the critical readings that this concept has received from different points of view cannot be ignored (Beltran & Velazquez, 2015; Velázquez et al., 2011), the concept has undergone major development. (Crawford & Pullen, 2011) study water in residential BLC over a period of 50 years and conclude that VW in building materials is greater than direct household consumption. The WF of buildings can be analysed from a global perspective (Chang et al., 2016) through an input-output analysis of total consumption in the country or models that analyse the components in construction projects. Bardhan (Bardhan, 2011) measured the virtual water of the construction of a multi-storied residential apartment building in Calcutta, India. In Beijing, Han et al. (Han et al., 2016a) determined the total VW of another nine projects. In Tehran, (Heravi & Abdolvand, 2019) measured the WF of six residential buildings. It is also worth mentioning the research of the ARDITEC group, where they incorporate the WF indicator (Ruiz-Pérez et al., 2017, 2019)

2. Methodology

The methodology followed in this work is summarised in Fig. 1. The structure is divided into three phases: development, application, and validation. The sub-levels are established according to the order of execution of each of the tasks necessary for the achievement of the objective:

Phase 1: Model development

- Level 1 (2.1): BLC design. The limits of the system, objectives, and duration are established.
- Level 2 (2.2): Creation of the economic and environmental data. Definition of quantification procedures and application of environmental indicator methodology. The input data is obtained from generic LCA databases, while the cost data originates from construction cost databases.
- Level 3 (2.3): BLC consumption. Construction budgets are employed in each life cycle stage. Budgets are obtained for the calculation of indirect and direct resources, and they are updated over time. The energy efficiency evaluation is carried out with the country's official software. The water consumption is determined from statistical data published in governmental reports, and forecast scenarios are established.

Phase 2: Model Application: Case study

- Level 1 (3): Evaluation of the case study.
- Level 2 (3.1): Indirect impacts are obtained per stage.
- Level 3 (3.2): Direct impacts are obtained per stage.

Phase 3: Model validation

- Level 1 (4): Analysis and validation of total and staged results.

The content of the aforementioned three phases, as well as the levels of each phase, are described below, whereby the following sections are expanded.

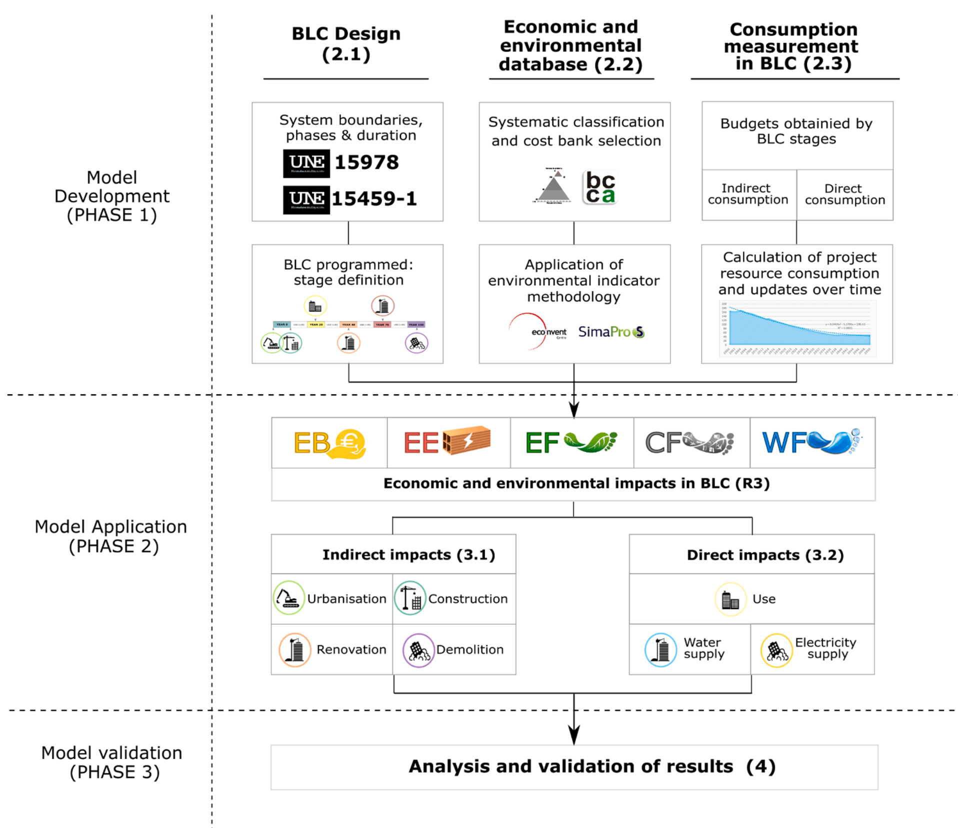


Fig. 1. Methodological map of the environmental assessment model of the building life cycle, BLC. EB stands for economic budget, EF for ecological footprint, CF for carbon footprint, and WF for water footprint.

2.1. BLC design: system limits, stages, and duration of the BLC

The temporal limits of the system are defined by determining the moment at which the BLC begins and ends, longitudinal direction, and the limits between the stages. For example, (Adalberth, 1997) divides the BLC into three stages: construction, which is subdivided in turn into the manufacture of materials, their transport to the site, and the construction itself; occupation with an intermediate period dedicated to renovation; and finally demolition and waste or recycling. This division into stages is widespread, with slight variations from one study to another, whereby the stage of use and maintenance is normally limited to energy consumption and renovation works. Another perspective is raised by (Blengini, 2009), who establishes certain limits of the system similar to those of Adalberth, but does not include maintenance, and is limited to energy, gas, and water consumption according to statistical data in Italy.

These models have demolition in common as the end-of-life of buildings, but what would happen if, instead of being demolished, the building was rehabilitated? In the event that the route of renovation is chosen, the situation arises as to whether the post-rehabilitated building could be considered the same building to which its useful life has been extended or, alternatively, whether it would be a new building whose life cycle begins. This is the case in Spanish legislation, in which, if the rehabilitation budget is greater than 60% of the cost of a new replacement building, then the building life cycle returns to the cradle, Order ECO/805/2003.

In order to establish the time of renovations taking place, the *Energy efficiency of the building* standard is taken as a reference (UNE-EN 15459-1:2018, 2018) and the (UNE-EN 15686-5:2017, 2017). These are completed with the Technical Building Code (España, 2006), which establishes that residential buildings must be designed for a duration of 50 years or expanded to 100 years if they are for public use.

The use stage begins once the building is operational and is occupied by users; this is the longest stage in which two types of consumption take place, the direct consumption of water and electricity, and the indirect consumption of material resources, machinery, and labour required to carry out the renovation actions, and of those necessary to prolong (or halt the reduction of) the life of the building. During this stage, the difficulty arises of updating the environmental and energy data to future values. The predicted values must consider the expected reduction of emissions or water due to commitments, such as the Paris Agreement to cut emissions by at least 55% by 2030 which leads towards the use of cleaner energy and prioritises renewables. Future scenarios reducing consumption of electricity and water are established.

The transversal limits draw a line between our system and other sectors of production, such as the furniture industry, household appliances, manufacture of construction materials, and waste treatment plants. For the definition of the limits, both the standard (UNE-EN-ISO 14044:2006, 2006) on LCA and the standard (UNE-EN 15978, 2012) regarding the *Sustainability of construction work, Evaluation of the environmental performance of buildings, and the Calculation method*, will be considered. Fig. 2 shows the various stages of the BLC developed in the present work. System boundaries are defined for each of the life cycle stages in three sectors: industry, construction, and occupancy, as in previous work (Martínez-Rocamora et al., 2017).

2.2. BLC consumption

2.2.1. Indirect consumption

Indirect consumption refers to the materials, machinery, and labour necessary to execute urbanisation, construction, renovation projects, etc. The inventory of resources is obtained using cost databases. The project budget of each stage of the BLC and its corresponding quantity surveying generate the inventory of resources: this procedure is laid out in Section 2.3. These resources are normally classified in the construction sector into three main groups: labour (working hours), materials (kilograms), and machinery (operating hours). The calculation of their impacts is defined in terms of CF, WF, EF, and EE, and their calculation is described in the following sections.

a) **Labour**

Workers' food generates an EF, since its energy source is considered and is obtained from Equation 1 in Fig. 3. A typical menu for an adult

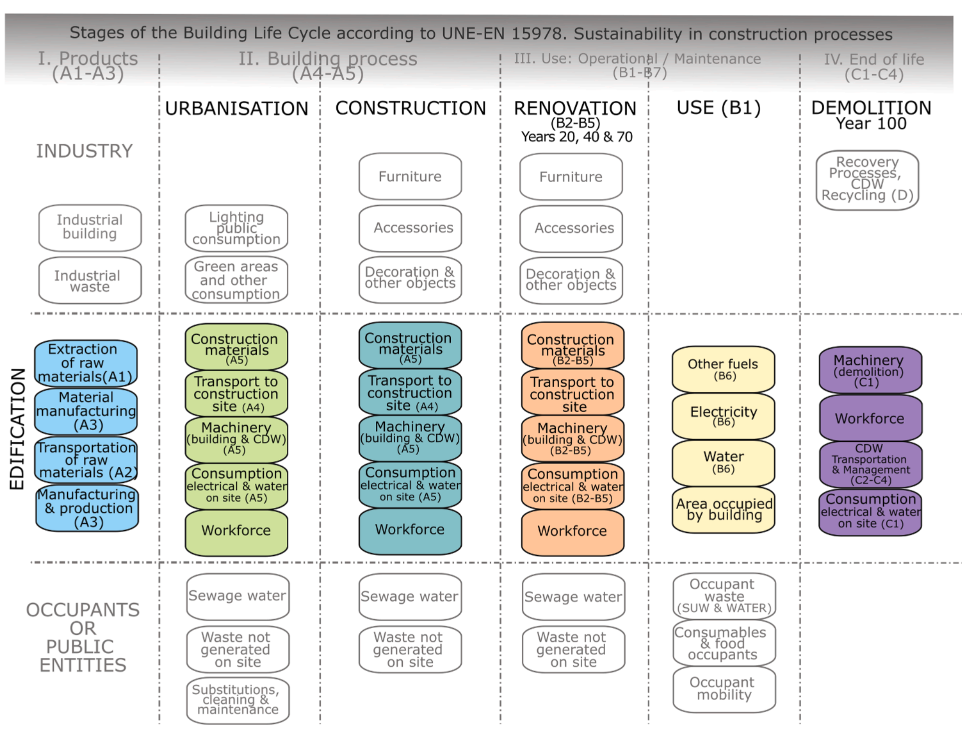
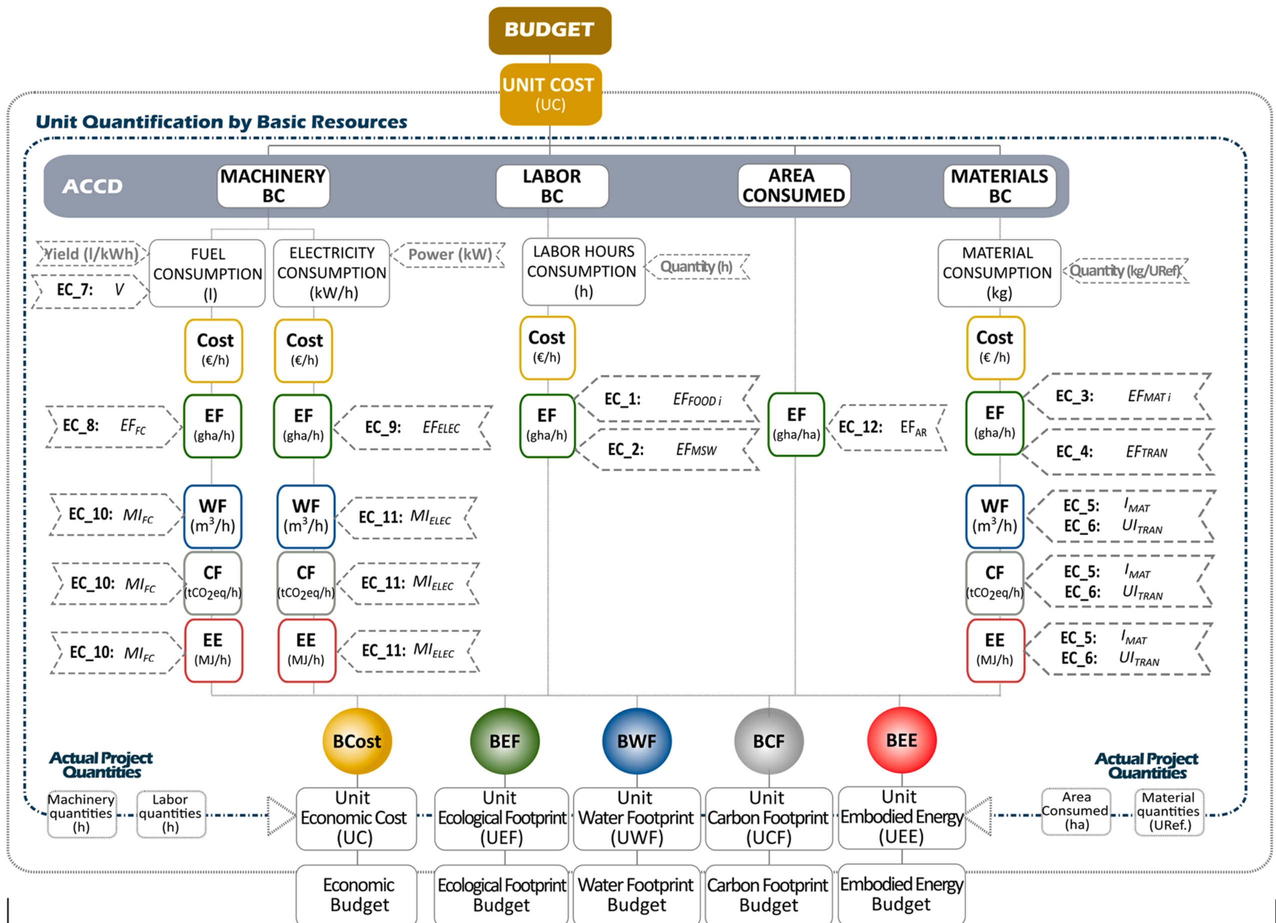


Fig. 2. System limits according to UNE-EN 15978:2012. CDW stands for construction and demolition waste and BLC for building life cycle.



Legend

LABOR BC	EC_1: $EF_{FOOD\,i}=(H_W/H_D)*(PC/100)*(EF_i/365)$;	$EF_{FOOD\,i}$: **Partial Ecological Footprint of food consumption in EF category i (gha/h)**
	H_W: Total number of hours worked (h)	PC: Breakfast and lunch as a percentage of the total daily food intake of a Spanish adult (61%)
	H_D: Number of hours worked per day (8h/day/person)	EF_i: Footprint of food consumption in category i of EF(gha/person) in Spain (González- Vallejo, 2019)
	Crops (10-3 gha) =1.45 **Pastures (10-3 gha)**=0.27	**Sea (10-3gha)** =0.41 **Fossil (10-3 gha)** =0.49
	EC_2: $EF_{MSW}=(H_W*G_w*E_{MSW}*0.72)/A_F)*FE_B$	EF_{MSW}: **Partial Ecological Footprint of MSW management (gha/h)**
	A_F: absorption factor of forests (3.59t CO_2/ha)	E_{MSW}: emission factor per residue (0.244 t CO_2/t MSW) (Almansi and Milios, 2013)
	FE_B: forest equivalence factor (gha/ha)	0.72: CO_2 absorbed by forests. The remaining 28%, ocean absorption (Borucke et al., 2013)
	G_w: Hourly waste generation (0.000077 t/h) (EUROSTAT, 2015)	
MATERIALS BC	EC_3: $EF_{MAT}=\Sigma i(((Cmi * E_{MAT})*0.72)/A_F)*FE_B + EF_{TRAN}$	EF_{MAT}: **Partial Ecological Footprint of consumption of materials (gha/uRef)**
	Cm_i: consumption of material i (kg)	E_{MAT}: Emission factor of material i (tCO_2/kg)
	EC_4: $EF_{TRAN}=\Sigma i(((Cmi/T_{CAP})*D_A)*T_{CON}*E_{FUEL}*0.72)/A_F)*FE_B$	EF_{TRAN}: **Partial Ecological Footprint of the transport of materials (gha/uRef)**
	T_{CAP}: Truck capacity (t)	T_{CON}: Truck consumption (l/100 km)
	D_A: Average distance (km)	E_{FUEL}: Emission factor of fuel (tCO_2/l)
	EC_5: $I_{MAT}(WF_{MAT}; CF_{MAT}; EE_{MAT})=I_{MAT}=\Sigma i(Cmi *UI_{MAT})+UI_{TRAN}$	$I_{MAT}(WF_{MAT}; CF_{MAT}; EE_{MAT})$: **Other impacts (WF, CF, EE) of construction materials (m^3; tCO_{2eq}; MJ)**
	UI_{MAT}: Unit impact per material (m^3; tCO_2eq; MJ/kg material)	
	EC_6: $UI_{TRAN}(UWF_{MAT}; UCF_{MAT}; UEE_{MAT})=\Sigma i(((Cmi/T_{CAP})*D_A)*T_{CON}*UI_{FUEL}$	$UI_{TRAN}(UWF_{MAT}; UCF_{MAT}; UEE_{MAT})$: **Unitary impact of transport of construction mat.(m^3; tCO_{2eq}; MJ)**
	UI_{FUEL}: Impact factor of fuel in WF, CF, EE (m^3; tCO_{2eq}; MJ/l)	
MACHINERY BC	EC_7: V=(Power*UT*Yield)	**V: fuel consumption (litres)**
	Power: motor power of electrical machinery (kW)	Yield: fuel consumed by the engine depending on whether it uses diesel or petrol (l/kWh)
	UT: usage time according to measurements (hours)	
	EC_8: $EF_{FC}=((V*E_{FC}*0.72)/W_F)*FE_B$	EF_{FC}: **EF (fossil) fuel consumption of machinery (gha)**
	E_{FC}: fuel emission factor ($kgCO_2$/l). Spanish data: 2,616 $kgCO_2$/l (IDAE, 2011);	
	EC_9: $EF_{ELEC}=((Power*UT)*E_{ELEC}*0.72)/W_F)*FE_B$	EF_{ELEC}: **EF electricity consumption of the machinery (gha)**
	E_{ELEC}: energy mix emission factor ($kgCO_2$/kWh). Spanish data: 0.248 kg CO_2/ kWh (REE, 2014).	
	EC_10: $MI_{FC}=V*UI_{FC}$	MI_{FC}: **Fuel machinery impact (m^3; tCO_2eq; MJ) (m^3; tCO_{2eq}; MJ)**
	UI_{FC}: Unitary impact of fuel (m^3; tCO_2eq; MJ/l fuel). Data according to LC analysis with Simapro and Ecoinvent database.	
	EC_11: $MI_{ELEC}=(Power*UT)*UI_{ELEC}$	MI_{ELEC}: **Electrical machinery impact (m^3; tCO_2eq; MJ) (m^3; tCO_{2eq}; MJ)**
	UI_{ELEC}: Unit impact of electricity, according to energy mix (m^3; tCO_2eq; MJ/kWh). Data: (REE, 2014) and waterfootprint.org	
AREA CONSUMED	EC_12: $EF_{AR}=S*FEx$	EF_{AR}: EF of area consumed (gha)
	S: Surface of direct occupation by project (ha)	FE_x: equivalence factor of the constructed area (gha/ha).

Fig. 3. Summary of equations and methodology for the calculation of impacts: EF, WF, CF, and EE.

consisting of meat, fish, cereals, and water is used as a base (Grunewald et al., 2015). All types of food also produce an energy footprint, due to the energy consumed in their transformation.

The footprints are generated according to the type of food (meats: EF of pastures; fish: EF of productive sea; EF of cereals: EF of crops), whereupon the corresponding natural productivity and the equivalence factor of each type of productive territory can be applied. The crop equivalence factor is 2.51; for pastures it is 0.46; for forests it is 1.26; sea is 0.37; and for direct occupation area this factor is 2.51 gha/ha (WWF International, 2014). The equivalence factors used, are implicit in the calculation of the EF of each country. In Spain, the footprint of food is 1.45, 0.27, 0.41, 0.49 in 10-3 hag/person and year for crops, pastures, sea, and fossil fuel, respectively. It has been considered that breakfast and lunch (which are carried out on site) represent approximately 61%

of the daily diet of an adult (González-Vallejo et al., 2019).

Workers on site also generate municipal solid waste (MSW), Equation 2 of Fig. 3. In order to obtain the footprint of MSW, an average generation coefficient per worker and the emission factor of MSW treatment are used. The mobility of operators to the workplace is excluded in accordance with the methodology proposed in the UNE-EN 15978, (UNE-EN 15978, 2012) for the Life Cycle Analysis (LCA) of the building.

a) **Materials**

The determination of the, EF, CF, WF and EE indicators (Fig. 5) is carried out following the methodology defined by (Freire-Guerrero & Marrero-Meléndez, 2015). The impact of materials is calculated by converting the traditional unit of measurement of construction products in budgets into kg. To this end, it is necessary to convert the original unit of measurement of each basic element (m^3, m^2, m, t, thousands of brick units, etc.) into m^3, and, with the density defined in the supporting documents Catalogue of Constructive Solutions of the Technical Building Code (IETcc, 2010) and the Basic Document of Structural Safety of the Technical Building Code Actions in the Building DB-SE AE-CTE, 2006 (Gobierno de España (Government of Spain)., 2006), to determine the weight in kilograms of each element.

The impacts per kg are obtained from the LCA database (some examples can be found in Table 1), Ecoinvent LCA (Ecoinvent Centre, 2013), known for being one of the most complete databases at European level (Martínez-Rocamora, Solís-Guzmán, & Marrero-Meléndez, 2016) and for its integration with the Simapro LCA software (PRé Sustainability, 2016). To obtain CO_2, water (VW) and EE emissions in building materials, the Life Cycle Inventory of materials is analysed using the IPCC 100a methodology. This methodology isolates CO_2 emissions and other GHG emissions from the life cycle inventory (LCI), thereby making it easier to take CO_2 emissions into account. Once all the CO_2 emissions of each material have been obtained, then either Equation 3 of Fig. 3 is applied to obtain the EF, or Equation 5 of Fig. 3 to obtain the remaining indicators. The work is similar to that carried out for the calculation of the CF with the SOFIAS tool [68], which uses data from the environmental declarations of products, OpenDAP, or from the BEDEC platform, developed by the Institute of Construction Technology of Catalonia (ITeC) and in previous work by the authors (Marrero et al., 2022).

From the amounts of resources calculated per stage of the BLC, Cmi is obtained per family of materials, measured in weight per constructed area, to which its environmental impact, IU_{MAT}, is applied for each type of material according to either Equation 5 of Fig. 3, or Equation 4 of Fig. 3 to calculate the EF.

The environmental impact of the materials during the cradle-to-gate life cycle is collected. To evaluate the A4 aspect of the UNE-EN 15978 standard, an analysis of the transport of the material is carried out, whereby approximations of the distance travelled by transport is established: the average consumption of diesel, 26 litres/100 km, and its emissions (2.62E-03 tCO_2/litre) is used. The water consumption in its production is 1.26 m^3/litre of diesel and its incorporated energy is 57.7MJ/litre. The capacity of the trucks and travel distance is 2,000 and 24,000 kg, and 20 and 250 km, for the transport of concrete and for the rest of the materials, respectively (Freire-Guerrero et al., 2019).

a) **Machinery**

The impact of construction machinery is calculated according to the engine power and the hours of use on the site, and the energy consumed in kWh is determined, which can then be transformed into CO_2 emissions (Freire-Guerrero & Marrero-Meléndez, 2015). CDW transport machinery is also included in the calculation: the amounts are part of the project budget as established by RD 105/2008 (Marrero & Ramirez-de-Arellano, 2010), which regulates the management of CDW in Spain.

The classified machinery is analysed, whereby a coefficient is applied to the power of each engine (SEOPAN, 2008), depending on whether the machine consumes diesel or petrol (Equation 7 of Fig. 3), and the CO_2 generated by a litre of fuel is applied.(IDAE, 2011) The EE or the VW per litre of fuel are obtained from Ecoinvent, by calculating its CF, WF (Equation 10 of Fig. 3), and EF (Equation 8 of Fig. 3).

For the consumption by electrical machinery, the total kWh consumed is obtained by analysing the engine power and the hours of use (Freire-Guerrero & Marrero-Meléndez, 2015). The CO_2 equivalent emissions, generated in the production of one kWh for the Spanish electricity system (REE, 2014), are obtained from(REE, 2014) GHG emissions, measured through the global-warming potential (GWP) of the various gases emitted. The WF of the electric machines uses the WF associated with the Spanish energy mix (waterfootprint.org). The EF indicator is calculated with Equation 9, and the rest with Equation 11, of Fig. 3.

a) **Area consumed**

Another source of impact that only considers the EF is that of the area of land occupied, which will cease to be productive agriculturally (see Equation 12 of Fig. 3). Two types of land can be considered: crops and forest territory.

Table 1
Environmental impact of electricity and water consumption by periods, depending on environmental indicators.

Electricity	EF (hag/kWh)	WF (m^3/ kWh)	CF ($kgCO_2$ eq/kWh)	EE (MJ/kWh)	Cost (€/kWh)
Years 0-20 (2010/30)	0.00013	0.010	0.549	5.846	0.1198
Period 21-40 (2031/50)	0.00012	0.009	0.283	5.835	0.1365
Period 41-70 (2051/80)	0.00011	0.018	0.057	5.824	0.1557
Period 71-100 (2081/110)	0.00010	0.025	0.028	5.816	0.1775
Water supply	**EF (hag/ m^3)**	**WF (m^3/ m^3)**	**CF ($kgCO_2$ eq/m^3)**	**EE (MJ/ m^3)**	**Cost (€/kWh)**
Period 0-100 (2010/110)	0.00016	2.42	0.607	4.693	2.25

2.3. Creation of economic and environmental database: quantification of resources and environmental impacts

As mentioned in the introduction, the inventory of resources is obtained from the construction cost databases, which are employed by the construction sector for the generation of project budgets, and are regional specific. In Spain, ITEC and CyPe are among those most commonly used (Freire-Guerrero et al., 2019). In the south of Spain, the Andalusian Construction Cost Database, ACCD (ACCD, 2017), is the most frequently employed (Marrero et al., 2020), which is periodically revised and published by the regional government on their institutional web site.

The use of the systematic classification of the ACCD, its pyramidal structure, together with the methodology of environmental indicators in building, has enabled the creation herein of a database that combines economic information with environmental information (Fig. 4). The first step involves obtaining the environmental indicators (EE, EF, CF, and WF) of each element or basic cost (BC), see Fig. 5.

Fig. 4 shows the pyramidal classification of this cost/price structure (Marrero & Ramirez-de-Arellano, 2010). At its apex are the work chapters that classify the tasks that are part of the building projects, such as the foundation, structures, and installations. Subsequently, with the measurement of work units or unit costs (UC), the amount of each specific activity is obtained, and, by aggregation of its resources, the total work budget, or its environmental impact is also attained. The basis from which the pyramidal structure of the cost database created for the evaluation of the indirect consumption of the BLC designed is fed this information. Following the structure presented in Fig. 5, a total of 584-unit costs have been created in this work that incorporate the economic and environmental costs based on the indicators analysed: 104 for urbanisation, 270 for construction, 37 for 20-year renovation, 141 for 40-year renovation, 30 for 70-year renovation, and 2 for demolition.

The direct consumption of water and energy during the execution of the work has been established empirically based on the building floor area (González-Vallejo, Solís-Guzmán, et al., 2015), and the emissions due to the production of a cubic metre of water (Freire-Guerrero & Marrero-Meléndez, 2015).

2.3.1. Direct consumption

a) **Water**

In the year 2000, the average water consumption in Spanish households exceeded 150 litres per person per day; this was reduced to 132 by 2019 (Estadistica, 2019). Based on this data, a polynomial trend line has been determined, which can be extended to cover the entire BLC (Rivero-Camacho & Marrero, 2022) and indicates 50l/inhabitant/day in 2038, which is the consumption recommended by (WHO, 2011). The number of occupants per dwelling is obtained from the Technical Building Code (España, 2006).

In addition, it is necessary to consider the energy expenditure for its transport from the origin to the point of consumption, as well as the losses due to leaks and breakdowns. In Spain, public urban supply networks losses stand at 15.9% (Estadistica, 2019). The energy associated with the collection, supply, and distribution of urban water is 8.345 kW/m^3, see Table 2.

a) ***Electricity***

The change over time of the energy mix and together with the LCA data (Garrido & Hardy, 2010), of kWh consumed, have been updated according to the period of use of the building. According to the data obtained and future projections carried out in the present study, the evolution of energy sources is heading towards the greater use of renewables: by 2070, energy sources will be solar, wind, and/or hydroelectric, see the calculations in Table 1.

For the environmental projection of the WF indicator associated with the energy mix, either the information provided by the energy matrix and the water-energy binomial are used, or the WF of a kWh produced. This is calculated according to the different sources of energy generation (Garrido & Hardy, 2010)(Garrido & Hardy, 2010)(Garrido & Hardy, 2010)(Garrido & Hardy, 2010), whereby it is estimated for each period in the use stage.

Regarding the evolution of the EF indicator, (Moore et al., 2012) develop a projection until 2050 by employing several scenarios. The conservative BLUE map scenario of the International Energy Agency is employed, and it is applied to the different indicators as applied in

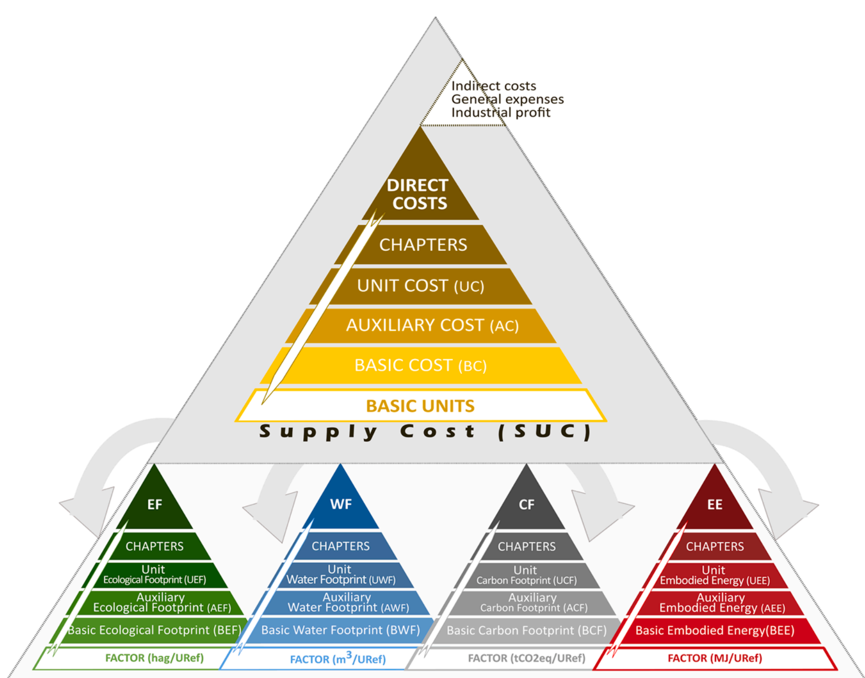


Fig. 4. The basic costs in the pyramid are added in upper levels, in a similar way to that of the environmental impacts.

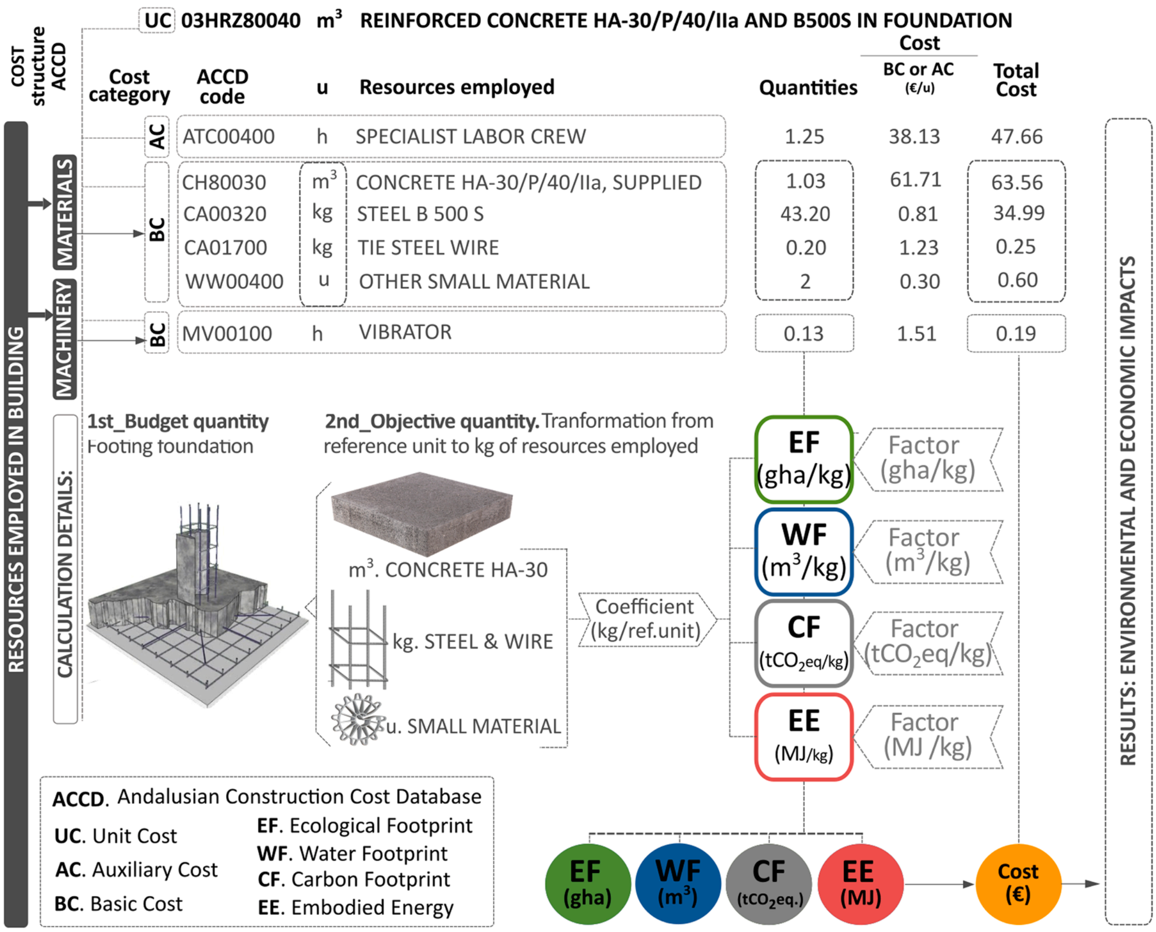


Fig. 5. Example calculation of environmental impacts of foundation at unit cost. (Marrero et al., 2022).

Table 2
Improvement of the energy efficiency in the renovations.

Improvements	U initial Value (W/m^{2}K)	U enhanced value (W/m^{2}K)
Façades	0.81	0.57
Roofs	2.27	0.8
Window frames	4	2.2
Glazing	3.3	1.8

(Moore et al., 2012). In this scenario, reduction rates are extracted for each of the six categories of EF and the current base year is established. In Table 2, the impacts of electricity for the different consumption periods are established. The reference costs are those of 2010, with an increase in the consumer price index (CPI) of 14% per period (Estadistica, 2019).

3. Case study

A residential building project, representative of the most built typology in Spain between 2006 and 2010, is evaluated (González-Vallejo, Marrero, et al., 2015). The construction of houses represents 85% of all new constructions and single-family buildings are 24% of them. The number of occupants living per dwelling is taken to be 3 people for single-family homes, defined with the CTE, as in the previous water consumption calculation (España, 2006).

The BLC analysed is represented in Fig. 6. It is established that the duration of the urbanisation and construction work last one year, work began in 2009. In the use stage, four periods are differentiated, marked by the different energy renovation work, the first two periods last 20 years each, and the last two have a duration of 30 years each. The use and maintenance stage begins in 2010 and ends in 2110.

The quantity surveying of the project is in Fig. 7, which summarises the constructive characteristics, whereby the quantities of materials consumed per floor area are classified into chapters of the classification system. The inventory of resources is obtained in a similar way for each stage of the BLC.

The official Spanish software CE3x_viviendas (CE3X, 2012) has been employed for the evaluation of energy efficiency. The consumption does not consider variations in occupants' habits, but it does consider the renovations that improve energy efficiency, see Table 2. The annual electricity consumption per m^2 is shown in Table 3.

Regarding the water consumption, an average consumer is estimated, with responsible consumption habits. To project these consumption habits, the trend towards its reduction has been considered based on the studies proposed in the theoretical model by (Rivero-Camacho & Marrero, 2022a), together with the number of people living in the dwellings according to the CTE (España, 2006).

4. Results

4.1. Economic evaluation

Fig. 8 shows that the construction stage represents the largest expense, at 31% of the total, and is followed by utility expenses, at 26%. The 70-year renewal is also economically significant, at 18%. The total cost during the life cycle (without monetary actualisations) is 2,011.24 €/m^2. This implies that not only is the construction cost important, but also the future utilities. Special care should be taken in the selection of

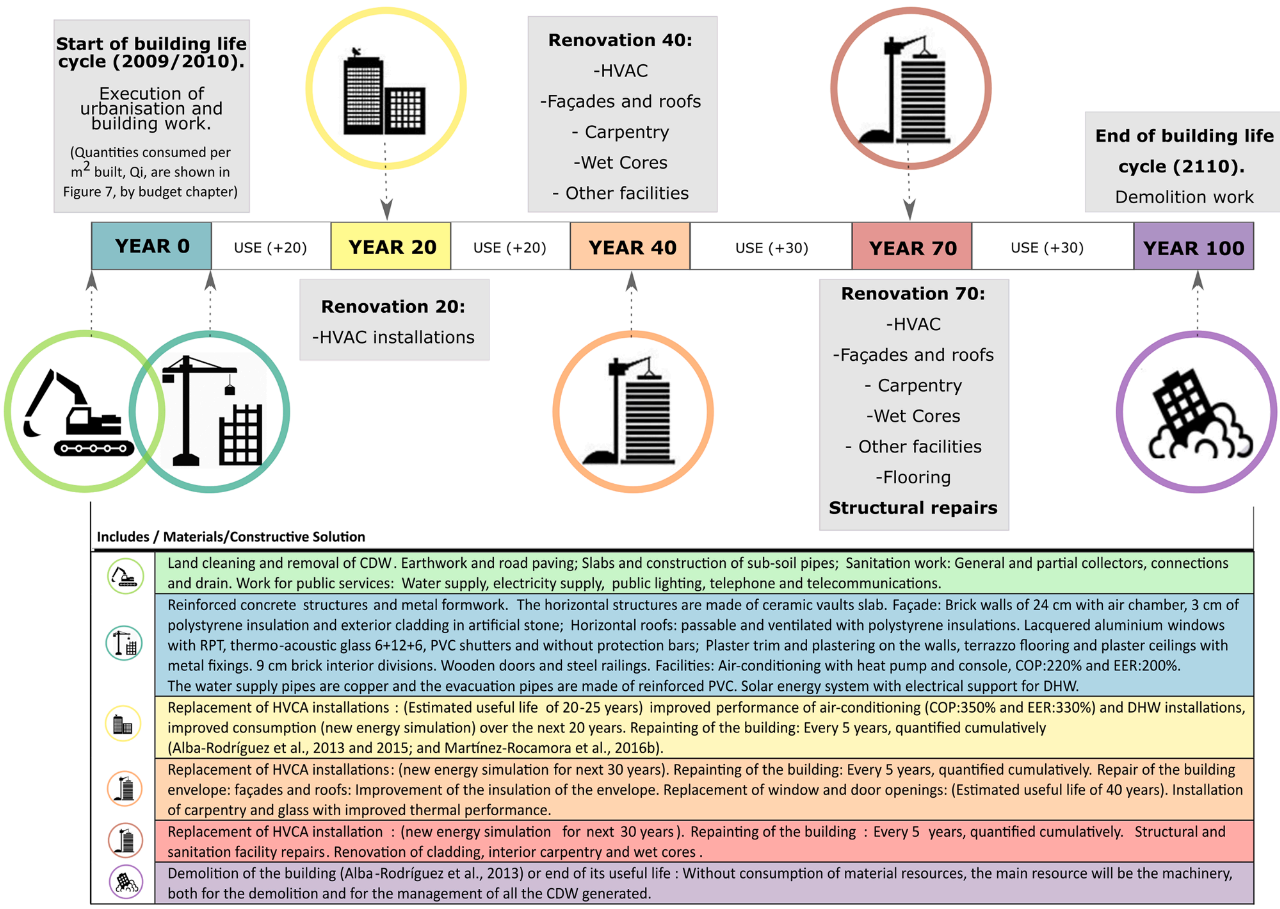


Fig. 6. BLC defined for the study of the environmental assessment model.

materials during the construction since these influence future renovation projects, especially when the building is approaching its end of life.

4.2. Consumption of indirect resources

In the analysis of each stage in the BLC, the construction stage consumes more materials than any others, as expected, see Fig. 9. In the renovations when the building is 40 and 70 years old, some of the work requires previous demolition, thereby needing to invest more in labour and in machinery. In the urbanisation stage, earthworks accentuate machinery consumption. It is observed that many hours of machinery and labour are required in the urbanisation, due to the large volumes of earthworks, and in the 70-year renovation due to minor demolitions. This includes an increase in CDW transport and management, especially during the structural repair work. During the demolition, there is no consumption of materials, but machinery also remains crucial.

4.3. Comparison of resource consumption

In Table 4, direct and indirect consumption have been summarised together with their impacts. Labour can only be evaluated using the EF indicator and it represents only 1.4% of the total footprint, compared to that of 20.2% of machinery and 78. 4% of materials. The most important stages in terms of resource consumption, EF, CF, and WF are, from high to low: construction, 70-year renovation, and 40-year renovation. However, the EE is higher during the 70-year renovation than in the initial construction due to the large quantities of concrete and cement employed in the repair of the structure and foundation. Urbanisation and demolition stages are equally intense in terms of EE due to the equipment employed. When comparing the direct and indirect impacts, the latter represent 60% of the impacts in all the footprints, except for the WF wherein the most significant factor is the direct water consumption by dwellers, at 63% of the total.

The CF of the construction stage lies within the middle range of similar studies, as defined by (Chastas et al., 2018). However, differences derived from the cases analysed by other authors can be observed. For example, (Wolf, 2014) obtains impacts 19% lower, largely because their building structure is made of wood. In contrast, (Solís-Guzmán et al., 2018) obtained a 25% higher footprint due to the inclusion of other technical services (construction of streets, pavements, etc.) within the limits of the system of their study. Differences in methodologies between studies hinder the comparison of their results (Martínez-Rocamora et al., 2021).

Furthermore, the WF of building construction has been determined around the word, resulting in similar results. In Calcutta, India, (Bardhan, 2011) measured the WF of the construction of a multi-storey residential apartment building with a structure of steel and reinforced concrete as 27 m^3_{water}/m^2 of floor area. In a similar way, in E-town, Beijing, China, the analysis was based on the project bill of quantities, for which six landmark buildings had a footprint of 20.83 m_{water}^3/m^2(Meng et al., 2014) Also in Beijing, (Han et al., 2016b) assessed another nine projects with an intensity of 26.5 m^3_{water}/m^2. In Tehran, (Heravi & Abdolvand, 2019) assessed six residential buildings at 18.76 m^3_{water}/m^2. Moreover, the WF of the building life cycle of a detached housing project in Huelva, Spain, has been determined as 27 m^3/m^2 (Rivero-Camacho & Marrero, 2022a).

In the case of the EE indicator, in the 70-year renovation this constitutes 28% of the total: very close to the 26% of the construction stage. Even though the consumption of resources in the construction stage is three times higher than in the renovation stage, energy-intense materials

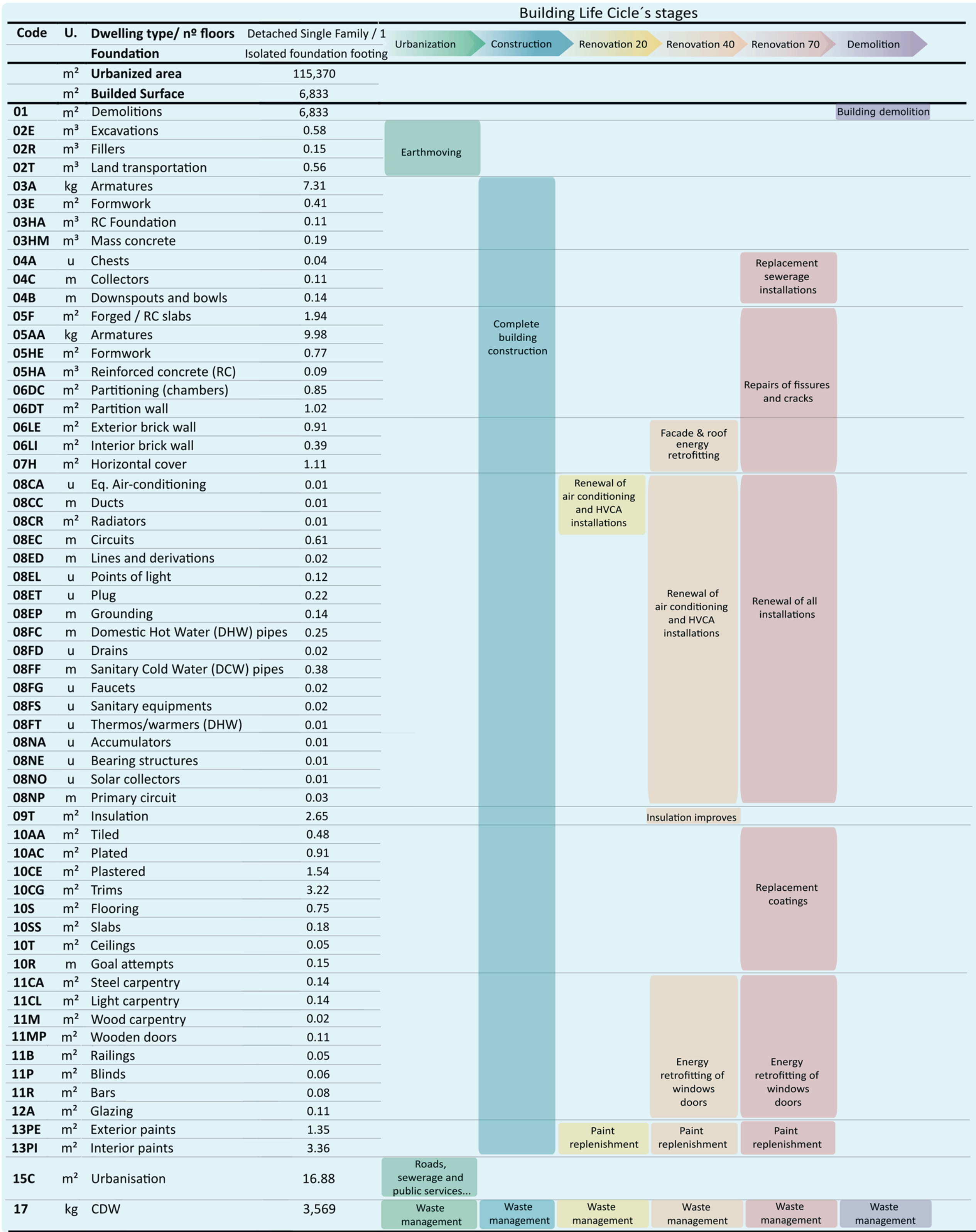


Fig. 7. Definition of the case study and amounts of resources per square metre built.

are needed for the reparation of the structure and for the foundation underpinning. Our results are similar to those found in (M. D. Alba-Rodríguez et al., 2022).

4.4. Results per construction materials

Fig. 10 classifies the environmental impact generated in terms of the main families of materials consumed. The weight of the material consumed is defined per housing floor (kg/m^2). The main material

Table 3
Consumption in the periods of use of the BLC.

Period (year)	Electrical consumption (kWh/ m^2/year)	Carbon emissions ($kgCO_2eq/m^2$)	Water consumption (m^3_{water}/m^2/ year)
0-20	130.7	25.7	36.28
21-40	53.86	10.7	18.35
41-70	39.5	7.96	25.71
71-100	13.64	2.91	25.71

throughout the BLC is concrete, followed by aggregates, stones, and brick. In contrast, the least representative materials in the BLC are glass, wood, and plastic.

The greatest impacts are not due to the most widely consumed materials. For example, plastics and metals are not the most highly consumed, but they do have a high WF and EE. Another of the materials whose impacts are pronounced is metal, also shared by WF and EE. The asphalts and bricks stand out due to their high EE. The top 10 families of materials identified herein as causing the greatest impacts coincide with those of (Rivero-Camacho & Marrero, 2022b) in their analysis of WF in the BLC, and with (González-Vallejo et al., 2020) on evaluating the CF of construction in Spain and Rumania, and with the EE calculated by (Blengini & Di Carlo, 2010) in Italy, and with those obtained by (González-Vallejo et al., 2019), which measure the EF of urbanisation work in Chile. The EF indicator focuses on the fossil fuel footprint of materials; therefore, the CF and EF indicators are more related to each other than to other indicators.

4.5. Evolution of environmental impacts in the BLC

Since they are works that will be executed in different years throughout the life of the building, it is necessary to bear in mind the possible variations that would occur in the environmental impacts caused by the changes in the energy sources used for the manufacture and commissioning. This makes it necessary to establish a methodology for updating the impacts of future scenarios that would consume resources in the BLC. In the doctoral thesis of Rivero Camacho, (Rivero Camacho C., 2020), the evolution of the sources that make up the energy mix is studied and a possible future scenario for Spain is proposed for the years analysed in the case study. Table 5 compares the initial energy mix with the various projected future scenarios for each energy source in the years 20, 40, 70, and 100 of the BLC.

In order to obtain the CF of the energy mix per year, have determined the CF of 1 kWh produced by different energy sources. The CF is obtained for each period by applying the CF for each energy source to the annual energy mixes, see Table 5. Fig. 11 represents the initial impacts obtained from the reference matrix in 2018, and, in an overlapping way, the application of the updated future energy mix.

The trend of the energy mix towards higher percentages in renewable energies means that, while maintaining energy consumption, the impact of emissions decreases. The most noticeable changes are perceived in the first half of the BLC, where the lines clearly curve representing the decrease in emissions associated with consumption. The reductions due to renovation work are also presented. In these, it can be observed how there is a noticeable difference in the emissions produced by each renovation, resulting in reductions close to 50% for the first renovation, up to a reduction of 95% in the emissions in the demolition stage.

5. Conclusion

The methodology developed herein enables the direct and indirect material and energy resources to be quantified and evaluated from the design stage of the building, as consumed in each stage of the building life cycle (BLC). The innovative methodology demonstrates that the budgets of construction projects can be accompanied by environmental

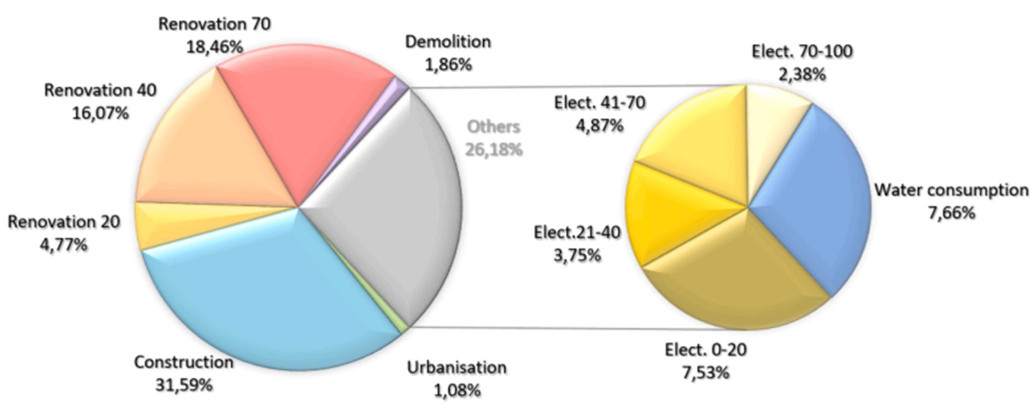


Fig. 8. Evaluation of costs in BLC.

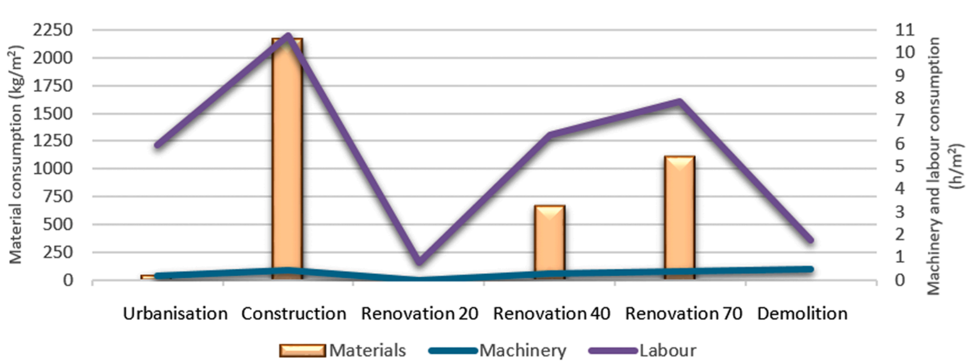


Fig. 9. Comparison of indirect resource consumption.

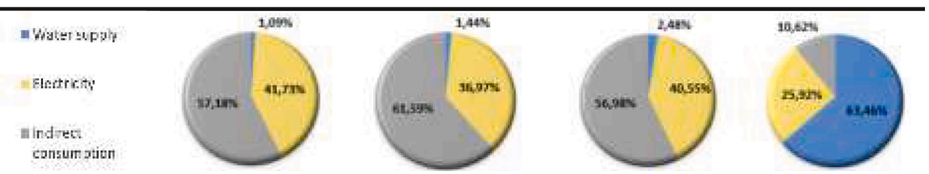
Table 4
Consumption and impacts in the periods of the BLC.

			RESOURCES (u/m^2)	EE (MJ/m^2)	EF (gha/^{m2})	CF (kgCO_2eq/m^2)	WF (m^3/m^2)
Indirect Consumption	Urbanisation	Materials (kg)	41.54	1,131.37	0.03	64.57	1.73
		Machinery (h)	0.16	270.92	0.01	0.02	0.06
		Labour (h)	5.91	0	0.002	0	0
	Construction	Materials (kg)	2,159.249	4,655.494	0.180	371.056	9.062
		Machinery (h)	0.410	422.969	0.013	0.029	0.106
		Labour (h)	10.764	0	0.003	0	0
	Renovation 20	Materials (kg)	7.223	183.990	0.005	10.221	0.470

(continued on next page)

Table 4 (*continued*)

		Machinery (h)	0	0.027	0.00001	0.002	0.001
		Labour (h)	0.777	0	0.0002	0	0
	Renovation 40	Materials (kg)	659.975	2,237.452	0.085	182.006	6.727
		Machinery (h)	0.263	179.620	0.005	10.938	0.040
		Labour (h)	6.401	0	0.002	0	0
	Renovation 70	Materials (kg)	1,102.817	4,997.488	0.134	285.278	8.429
		Machinery (h)	0.405	233.551	0.007	14.271	0.070
		Labour (h)	7.846	0	0.002	0	0
	Demolition	Materials (kg)	0	0	0	0	0
		Machinery (h)	1	1,227.55	0.037	23.309	0.298
		Labour (h)	2	0	0.0006	0	0
Direct Consumption		**Period (years)**	**Consumption**	**EE (MJ/m^2)**	**EF (gha/m^2)**	**CF (kgCO_2eq/m^2)**	**WF (m^3/m^2)**
	Electricity	**0-20**	2,614 kWh/m^2	9,410.40	0.25	514.12	31.24
		20-40	1,077.2 kWh/m^2	3,877.92	0.10	214.21	30.52
		40-70	1,185 kWh/m^2	4,266.10	0.12	238.80	33.81
		70-100	409.2 kWh/m^2	1,473.12	0.04	87.3	9.24
	Water supply	**0-100**	106.04 m^3/m^2	497.67	0.02	64.37	256.63
			TOTAL IC	26,072.5	0.860.86	1481.761,481.76 42.93	42.93
			TOTAL DC	19,525.21	0.530.53	1118.771,118.77 361.44	361.44
			TOTAL	**45,597.71**	**1.39**	**2,600.53**	**404.37**



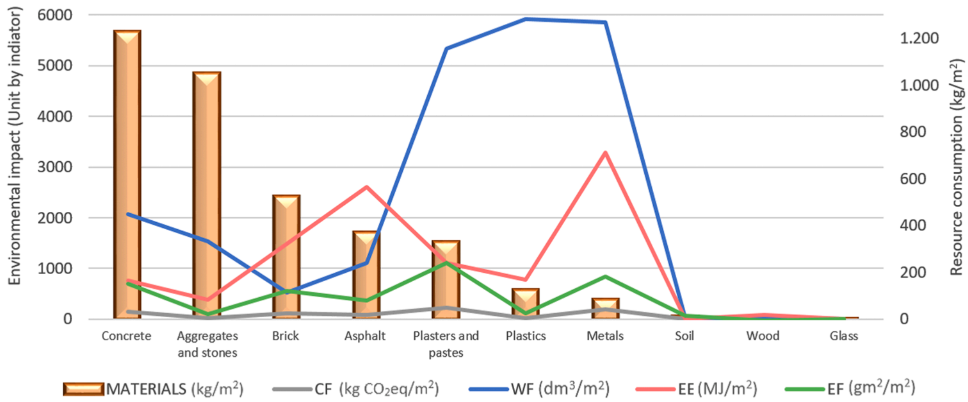


Fig. 10. Results per family of materials during the construction stage.

Table 5
Predicted configuration of the energy matrix in the years with renovations in the BLC. (Rivero Camacho C., 2020).

Power source	Starting year	Year 20	Year 40	Year 70	Year 100
Nuclear	19.7 %	17.1 %	9.1 %	0 %	0 %
Wind	11.7 %	21.6 %	23.6 %	26.6 %	46.6 %
Biomass	1.4 %	0.3 %	0 %	0 %	0 %
Conventional	55.1 %	27.3 %	3.3 %	0 %	0 %
Hydroelectric	10.0 %	26.9 %	51.6 %	59.3 %	33.9 %
Solar	1.9 %	6.8 %	12.2 %	14.3 %	19.9 %
TOTAL	100%	100%	100%	100%	100%
Energy matrix impacts and updates					
Energy matrix CF (kg CO_2eq/ kWh)	0.549	0.283	0.057	0.028	0.023
Reduction percentage	0%	48.5 %	89.7%	94.9 %	95.8%
Updated rate	1	0.515	0.103	0.051	0.042

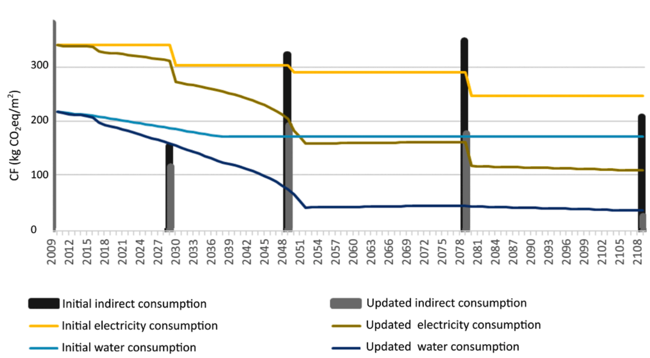


Fig. 11. Comparison of the evolution of CF in the BLC, before and after the environmental updates of the energy mix. Average proportion of the projects analysed.

indicators that allow the economic and environmental impacts to be simultaneously evaluated. As the main findings of the case study, it has been possible to determine the environmental indicators EF (hag), CF (kg CO_2 eq), WF (m^3 $_{water}$), and EE (MJ) throughout its life span. To this end, the limits of the system have been defined, both in terms of longitude, for a 100-year span, and transverse contours of a linear BLC. The systematic classification of a construction cost database has been used for the inventory of the resources, specifically the Andalusian Construction Cost Database, which has been widely contrasted and developed for the last 30 years so that any technician can understand and apply the proposed methodology. Its consolidated structure has made it possible to include the environmental indicators studied. It has been necessary to create and define 584-unit costs, divided into stages of the BLC.

Another important finding is that is possible to include future scenarios in the model and to define environmental temporal actualisations due to the extended duration of the BLC. These consider the increase of renewable sources in the energy matrix that result in progressively decreasing emissions. This causes the CF indicator to lose importance over time and the EE indicator to gain importance, since it represents the energy for the manufacture and commissioning of products, water supply, and waste management.

The total impacts are divided into 60% incurred during the construction/renovation work and 40% during direct use, which indicates that efforts should not only be focused on energy efficiency and savings in the use stage, but also during the manufacture stage, and that the use of the resources required in the work must be optimised at each stage of the building life cycle. The proportion is reversed for the WF, wherein the most significant consumption is due to the direct water consumption by dwellers, at 63% of the total. In the particular case of labour, this can only be evaluated using the EF indicator and represents a mere 1.4% of the total footprint, with similar results found in all stages, as in previous reports.

The construction stage represents the largest cost, at 31% of the total, and is followed by utility expenses at 26%. The total cost during the life cycle (without monetary actualisations) is 2011.24 €/m2. Furthermore, the greatest environmental impacts are incurred in the construction stage, where EE is 5 GJ/m^2, EF is 0.20 gha/m^2, CF is 371 kgCO_2eq/m^2, and WF is 9.2 m^3_{water}/m^2. For the total BLC the footprints are 45.6 GJ/m^2, 1.39 gha/m^2, 2,600 kgCO_2eq/m^2, and 404 m^3_{water} /m^2, respectively. This is due to the high consumption of resources required for their execution. The results also reveal that it is of interest to perform the environmental assessment through several indicators and to assume a broader perspective: for example, the water supply analysis is more significant with the WF indicator. With various indicators, the environmental improvements of the projects can be specifically focused on those elements which control each impact. The set of indicators selected considers a wide variety of aspects of the project (type of materials, characteristics of urbanising plot, transport distance of materials, waste management on site, etc.).

The main limitations of the work are due to the costdatabases used, since they are regionally specific. This aspect can be improved by modelling construction in other countries, by using their cost database, and by employing their environmental and energy data.

The proposed methodology, in future developments, will address the implementation of the environmental assessment in Building Information Modelling. Furthermore, the social factor can be included in the analysis, for example, minimising energy poverty while simultaneously assessing other environmental impacts and considering future climate change scenarios.

Declaration of Competing Interest

we declare that we have no known competing financial interest or personal relationship.

Data availability

No data was used for the research described in the article.

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