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What are we discarding during the life cycle of a building? Case studies of social housing in Andalusia, Spain.

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1. Introduction

In order to measure overall environmental impacts of buildings, all life cycle stages need to be assessed, including their environmental impact concerning construction materials, construction activities, dismantling operations and materials at end of life (Blengini, 2009). Life Cycle Analysis (LCA) has been widely applied to assess the environmental performance of buildings, the embodied energy and carbon emissions or their products, materials and waste (Bovea and Powell, 2016). The construction and demolition waste (CDW) life cycle has also been studied; Butera et al., (2015) study 1 Mg of mineral of classified waste, which is either utilised in road construction as a substitute for natural aggregates or landfilling soil. The scenarios comprised all stages of the end-of-life management of CDW, until final disposal of all residues.

Laurent et al. (2014) reviewed studies that focused on the application of LCA to waste management in general, concluding that few LCA studies address CDW. Specifically, the CDW life cycle has been assessed in different environmental impact categories such as: global warming, ozone depletion, acidification, eutrophication suspended particulate matter, solid waste and land consumption (Wang et al., 2018).

In Spain the concern on the assessment of CDW started over a decade ago. First, the European Directive 2006/12/EC has been implemented successfully. During the first decade of the present century, the construction sector was very active and a large amount of CDW ended up in uncontrolled landfills. See Table 1. But after 2008, Spain implemented Royal Decree 105/2008 in order to promote prevention, re-use, recycling and other forms of recovery, ensuring that disposal operations receive adequate treatment, and contribute to sustainable construction activity (Integrated Waste Plan, 2007). Table 1 summarizes the impact of this legislation up to 2012.

Table 1. *CDW management in Spain during 2005 (Integrated Waste Plan, 2007) and 2012 (Statistics National Institute, 2012); ND stands for no data available.*

DESTINATION	CDW (Mt)	2005	CDW (Mt)	2012
Recycling plant	3.2	7.8%	19.0	68.8%
Controlled landfill	15.8	38.5%	4.3	15.6%
Uncontrolled deposit	22.0	53.7%	ND	ND
Refill soil	ND	ND	4.3	15.6%
Total	**41.0**	**100%**	**27.6**	**100%**

For the decree to be effective, the amount of waste expected during construction need to be determined. The forecasted quantities establishes the container sizes and collection frequency, and defines the nature of material recycling and/or re-use (Marrero et al., 2017). An adjusted forecasting prevents contamination and deterioration (Río Merino et al., 2017). A more recent political strategy is the inclusion of environmental impact assessment in awarding public contracts (Ley 9/2017). In this regard, it is important to incorporate simple methodologies that can be easily understood by society whose application is faster more simple and direct (Freire-Guerrero et al., 2019).

For the waste quantification, many models and software development can be found in the work by Cheng and Ma, (2013). Wu et al. (2014) review 57 international proposals for the classification and quantification of CDW, structuring them into: site visits, calculation of average generation (Yost and Halstead, 1996), material flow analysis (Cochran and Townsend, 2010), systems by variables (Aguirre et al. (2005) and Mokhtar et al. (2011), Wimalasena et al. (2010)) and cumulative systems.

The cumulative systems are the most used in the literature (Coelho and de Brito, 2011; Llatas, 2011; Mercader-Moyano and Ramírez-de-Arellano-Agudo, 2013; Solís-Guzmán et al., 2009). In these methods a systematic classification of construction works is necessary; these represent the basis of the calculation and estimates for each construction material. These systems offer an effective way of determining waste, defining specific strategies for each stream and combining computer programs or calculation tables.

The above enables the incorporation of environmental indicators, for example Ecological (Bastianoni et al., 2007; González-Vallejo et al., 2015), Carbon (Solís-Guzmán et al., 2014; Weidema et al., 2008) or Water Footprint (Rivero-Camacho et al., 2017) and Energy Analysis (Pulselli et al., 2014; Marchi et al., 2015).

The present authors, have established a quantification model to evaluation the amount of waste produced by a series of construction projects, such as new constructions, demolition work, rehabilitations, and others (Solís-Guzmán et al., 2009). The model of quantification has been verified at the Province of Seville, Spain treatment plants (Pérez-Carmona et al., 2013). The cataloguing code used is employ by Spanish quantity surveyors to obtain the budget of quantities, what simplifies that the model is easy to implement and to understand (Marrero and Ramirez-De-Arellano, 2010). Subsequently the work units are fragmented down into three types of elements: machinery, manpower and materials. Embodied energy, virtual water or emission factors are then assessed for those elements.

Three representative housing projects are analysed: single family, 4 and 10 floor multifamily buildings. The current work establishes a method in order to estimate the amounts of waste and the energy and embodied water that is incorporated at the different life stages of the building.

The model evaluates for the first time the embodied impact in CDW during the buildings life cycle by means of the bill of quantities of construction projects. The main objective is to be able to predict the future CDW to be generated by a project in the design stage, by means the bill of quantities of the urbanization, construction, renovation, rehabilitation and demolition projects. The tools already in place for cost control of projects can be used as instrument for the introduction of sustainability considerations.

2. System boundaries

The sustainability of construction works, like so the environmental performance and the calculation method, define the building life cycle according UNE-EN 15978 (2012). Figure 1 shows the different stages of the life cycle of the building accordingly and the construction phases identified in the CDW quantification model, developed in the present work. The limits of the system are the waste produced by the construction materials, demolition waste, and their transport.

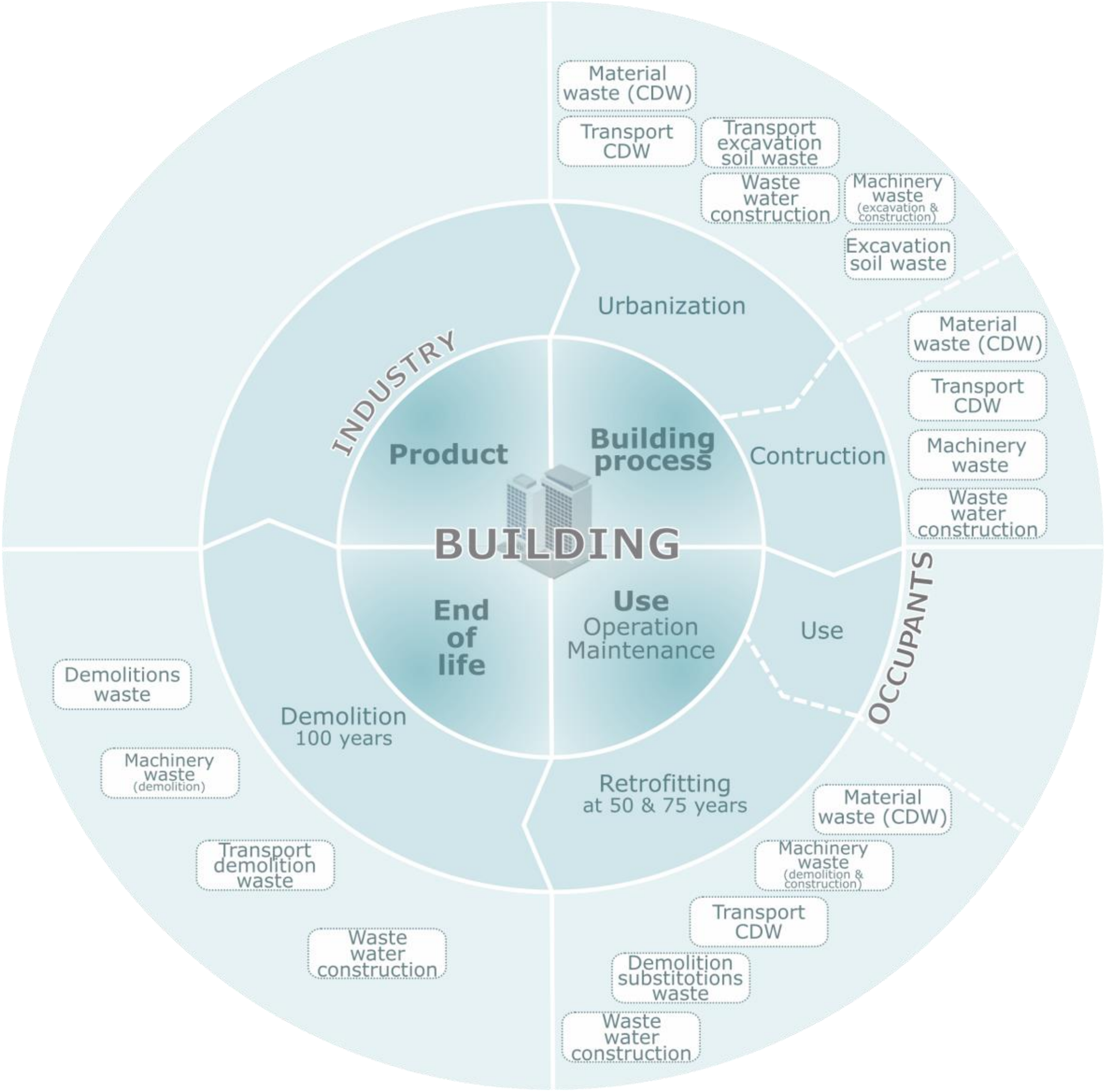


Figure 1. System boundaries

Urbanization: The work necessary to transform rural land into an urban plot that has all the necessary services such as running water, sewerage, electricity, roads, pavements, signage, etc. The CDW includes any construction materials that cannot be included in the transformation, such as material packaging and losses, broken parts or soil from earth works (Marrero et al., 2017).

Construction: The construction of a building starts on a developed plot (Law 22/2011, 2011). The waste generated is from construction materials that are not part of the new building, such as in the case of urbanization (Solís-Guzmán et al., 2009).

Retrofitting/renovation: Retrofitting (including maintenance) is the work needed in the building due to obsolescence or deterioration of some of its elements and is programmed to happen after it reaches 50 and 75 years (Ruiz-Pérez et al., 2019). The waste generated is from construction materials that cannot be included in the retrofit works and the corresponding packaging.

Rehabilitation or Demolition: in the UNE-EN 15978 sustainability of construction works standards are established. The rehabilitation occurs when the building ceases to be habitable and a major rehabilitation takes place, then significant changes also occur in its use profile, installations, materials and energy demand, and the building can no longer be considered the same as it was before the intervention (ECO/805, 2003). In this way, the rehabilitated building starts a new service life. Contrarily, if the end of life is reached, the building is demolished, and all building materials become waste (Alba-Rodríguez et al., 2017, 2013).

In summary, it is considered that the only activity which takes place during the first year is urbanization, during the second, construction, and occupancy in the subsequent 100 years (CTE, 2006), and, at the end of service life, rehabilitation or demolition can take place, that is the only activity during the last year of life; the time for renovations to be completed is also assumed to be the only construction-related activity in the 50th and 75th years of service life.

The maintenance of urbanization is not analysed or quantified in this study. The reason is that this work is done by municipalities and therefore, these impacts are not applicable to management of the building and are deemed outside the scope of the BLC. Other minor activities such as cleaning, polishing and minor repairs, painting, etc. that take place several times during the life of the building are not included either.

3. Methodology

The methodology proposed starts with a good description of the construction project. A precise and robust definition of all the elements in the project is necessary in order to determine correctly the amount of waste expected. For this, because construction cost are well controlled in projects as part of a long tradition, which includes a detailed description of its work units. For the work unit definition, construction work breakdown systems (WBS) are a generally used in the construction industry. The most frequently used are: MasterFormat (CSI/CSC, 2016), Uniformat (UniFormatTM, 1998), Standard Method of Measurement of Civil Engineering (Telford, 1991), Uniclass (Omniclass., 2012) and ISO 12006-2, (2015).

A WBS is employed for the calculation and prediction at different life stages of the CDW quantification; they transform the construction project into small parts that can then be easily added to form the whole.

Once all the elements necessary in the construction project are codified, information about the nature of each element is allocated which allows the calculation and classification of waste. This is done by the definition of transformation coefficients; the method is develop by the authors among others in previous work (Solis et al. 2009) is implemented.

Finally, the material quantities are expressed in kilograms and the machine and trucks consumption in working hours, both are transformed into environmental indicators such as embodied water, energy and CO2 emissions, by means of LCA databases. Each step is explained in detail in the following sections.

3.1. <u>Work breakdown system</u>

The Andalusia Construction Information Organisation Structure (ACCD, 2016) is the WBS employed in the present work. ACCD has a bottom-top organization, the completed building being the highest level. The project is then divided into chapters, which are construction procedure: Waste Management, Safety, Urbanization, Decoration, Coating, Carpentry, Finish, Insulation, Installation, Roof, Partition, Structure, Water disposal, Foundation, Earthworks and Demolition (Marrero and Ramirez-De-Arellano, 2010). The other levels and examples are illustrated in Figure 2.

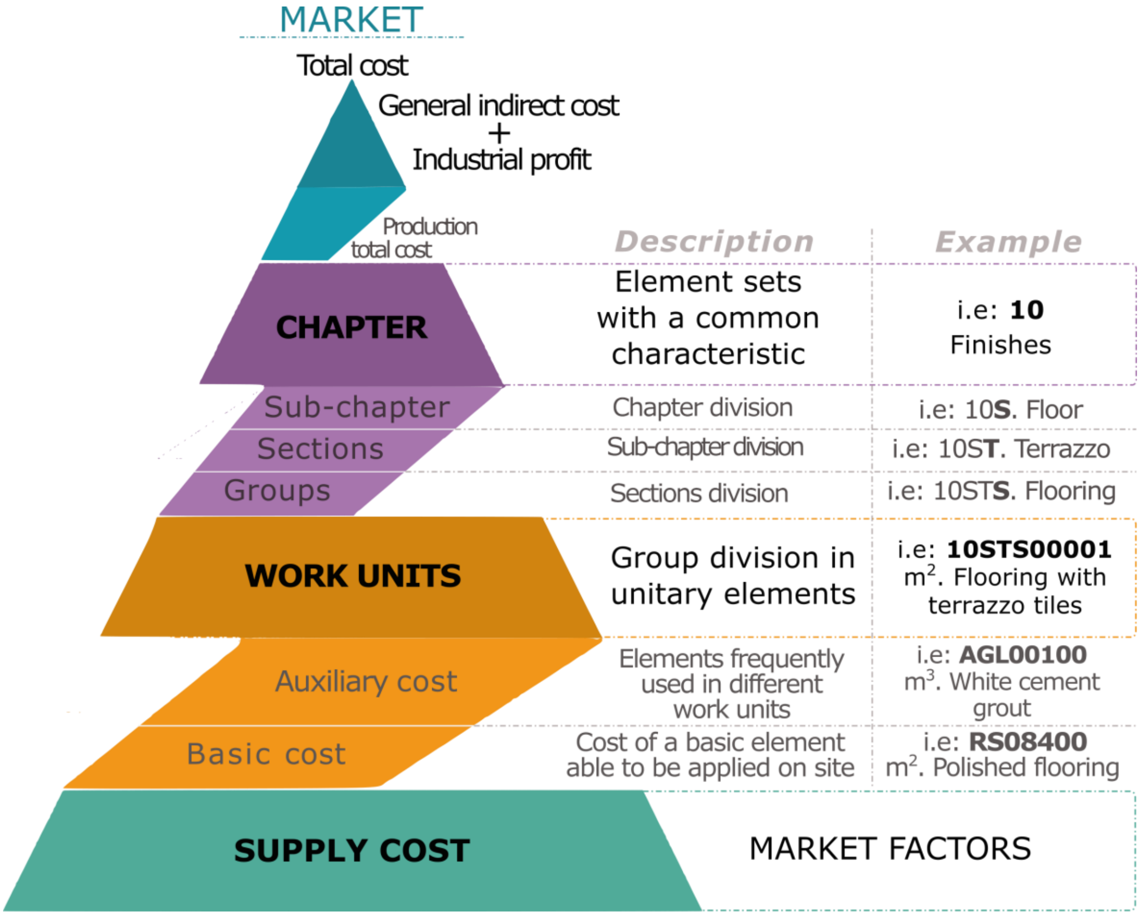


Figure 2. Pyramidal cost structure with internal cost classification.

Each work unit has an associated unit cost where all its components (materials, machinery and manpower) are described and quantified. The description of these components by an alphanumeric code facilitates the calculation of not only their cost but also their quantities, see Table 2.

In Figure 2, the pyramidal structure is represented using the unit cost of the work unit "Flooring with terrazzo tiles". Q is the quantity in the unitary cost of basic and auxiliary costs; in the example all elements in this unit cost are basic costs except ACM00039, which is an auxiliary cost. The latter corresponds to a combination of activities or materials frequently used in different work units but that are not sufficient to be deemed a work unit per se.

Table 2. Example: unit cost.

10STS00001	m^2	Flooring with terrazzo tiles of 40 cm X40 cm, medium grain.

Flooring with 40 x 40 cm terrazzo tiles with medium-grain marblewith M-4 (1: 6) mortar, levelling with 2 cm thick sand layer, including grouting, polishing and pavement cleaning; in compliance of norm NTE/RSR-6.

CODE	CONCEPT	Q	COST	AMOUNT
TO01100	h Official 1st tiler	0.245	13.06	3.20
TP00100	h Special peon	0.125	12.26	1.53
AA00200	m^3 Fine sand	0.020	8.85	0.18
TO01100	h Official 1st tiler	0.245	13.06	3.20
AGL00100	m^3 White cement grout	0.001	85.75	0.09
RS08400	m^2 Polished flooring	1.00	2.73	2.73
AMC00039	m^3 Mortar cement and river sand M-4 (1: 6)	0.021	43.63	0.92
			Direct cost	14.35
			13% Indirect cost	1.87
			TOTAL	16.22

3.2. Waste quantification. Coefficient determination.

Once the elements in the project are identified the following step is the quantification of the waste expected from those. The waste-generating elements are identified by a standardized classification, by using coefficients the waste is determined (Solís-Guzmán et al., 2009),

$$QR_i = Q_i \cdot CR_i \cdot CC_i \cdot CT_i \qquad (1)$$

where: QR_i is the waste amount "i" generated by the material "i" per floor area, Q_i; CR_i determines the amount of material which is wasted; CC_i changes the constructive component units into waste units; CT_i is for the change in volume of the material when it is distorted into waste. The unit system is the one employed in the construction sector for each family of construction materials, kg, m^3, m^2, m or unit (u). The coefficients are calculated from the ACCD (ACCD, 2016) (See Annex A).

3.3. Environmental assessment

The environmental impact is calculated for the trucks and machines for the in-situ waste management and transport to the treatment plant. Also each construction material and its package that becomes waste is calculated its embodied impact in terms of water, energy and CO_2 emissions. The boundaries defined in the calculation of the cost in the ACCD are also used for the environmental assessment (Figure 3).

Machinery impact.

Machinery fuel consumption is considered its main environmental impact which is linked to its engine power (fuel and electricity) and working hours (Marrero et al., 2017). The data of dissimilar models and kinds of machines, diesel consumption is 0.15 to 0.20 and petrol is 0.30 to 0.40 l / hr/kW (SEOPAN, 2008):

The fuel consumed are:

$$V = P \cdot Wh \cdot R \qquad (2)$$

Where: V: fuel consumption (l/yr); Wh: Working hours (h/yr); P: Engine power (kW); R: Engine performance (l/kWh).

Electrical machines consume:

$$C = P \cdot Wh \cdot C_f \qquad (3)$$

Where: C: Consumption (GJ/yr); Wh: Working hours (h/yr); P: Power (kW); Cf: Conversion factor (GJ/kWh).

Two basic costs of the ACCD are assessed, corresponding to the machines employed in the in-situ waste transport and handling, corresponding to loading shovel and truck with the following values, respectively: virtual water 13.595 m^3/h - 28.319 m^3 / h, built-in energy 1090.362 MJ/h - 2271.36 MJ/h and carbon footprint 62.784 t CO_2 eq/h and 130.8 tCO_2 eq/h. The data is obtained from EcoInvent as described in the next section.

Transport impact.

The transport impact is demarcated for average distances travelled to the landfill or recycling site, the maximum distance considered is 15 km.

Environmental indicators assessment of the quantified CDW

Environmental information is from the EcoInvent database through SimaPro, since this database covers the usually employed materials in construction (Martínez-Rocamora et al., 2016). In order to obtain CO_2 emissions, water and energy embodied in construction materials, their Life Cycle Inventory (LCI) is analysed after applying the IPCC 100a methodology. This methodology isolates CO_2 and other GHG emissions from the LCI, being thus easier to account for CO_2 emissions.

From calculation quantities of CDW according to the stages in the building life cycle, we obtain Qi for families of materials in tonnes per floor area, and the impacts can be measured:

$$E_i = Q_i \cdot U_i \qquad (4)$$

Where E_i is virtual water, embodied energy or CO_2 emissions ($kgCO_2e$) of material i and Ui is the unitary impact of material i, see Annex B.

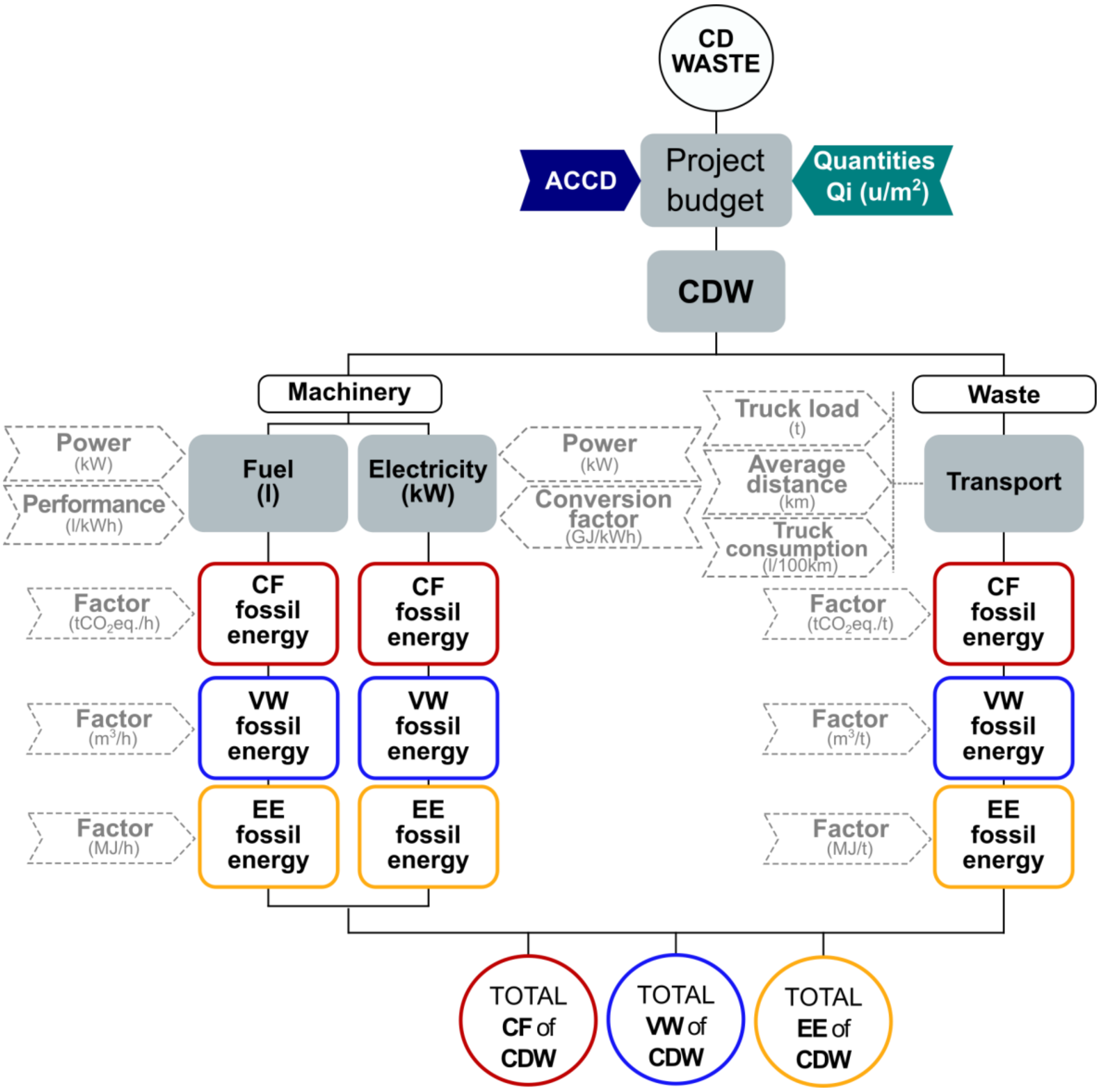


Figure 3. Flowchart; determination of the CF, VW and EE of CDW.

4. Case studies.

The selected projects are representative of the most commonly built dwellings from 2006-2010 in Spain (González-Vallejo et al., 2015). Dwelling construction represents 85 % of all new builds during that period. Single family dwellings are 24%, four-floor multifamily buildings are 32% and ten or more floor buildings represent 18 %.

Three social housing construction projects in Andalusia, Spain are assessed. P1 is single family and P2 and P3 are multifamily buildings, all do dot have basements. The structures are reinforced concrete. The flooring is of terrazzo tiles except for ceramic tiles in kitchen and bathroom floor. All partition walls are made of gypsum board with steel frame. Interior doors are wooden and widows have aluminium frames and double glasses. Additional characteristics are summarized in Table 3.

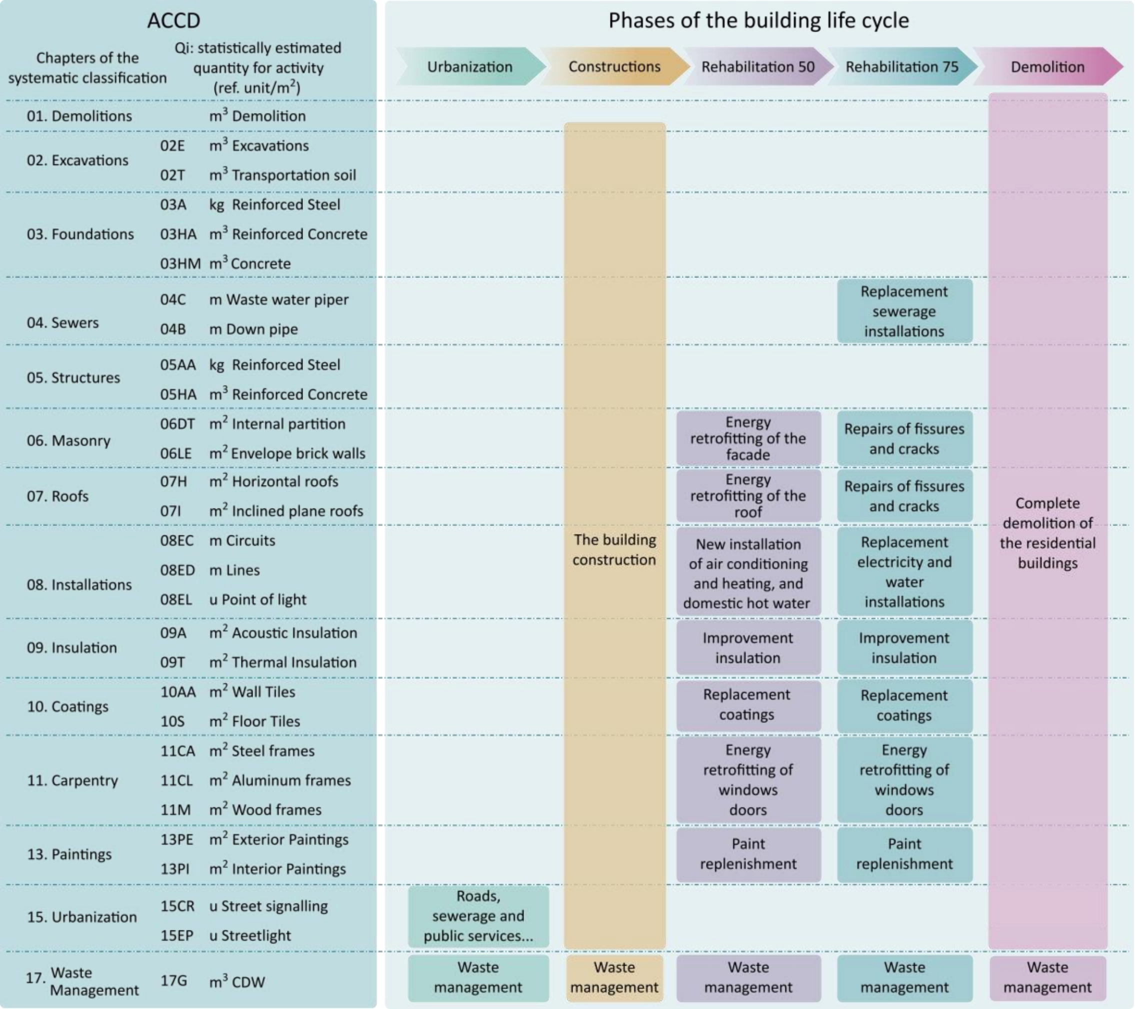
The projects are analysed by the following steps:

1. Quantity plotting is carried out on dwelling construction projects.
2. The elements or basic costs that produce waste are identified which are mainly wood (pallets and trees), metals (steel, copper and aluminium), concrete, plastic, ceramics, and soil.
3. The coefficients (CR, CC and CT) defined in Annex A are employed.
4. The embodied energy, emissions and virtual water are assessed in the projects.

Table 3. Projects description

	Urbanization area (ha)	Construction floor area (m^2)	Roof	Exterior walls	Foundation	Concrete slab
P1	15.688	6,836.17	Horizontal cover, ventilated walkable	1 foot wall with polyurethane insulation chamber and plastering finish	Concrete blocks	Reinforced concrete
P2	0.962	9,524.17	Horizontal cover, ventilated walkable	Ventilated facade with ceramic cladding, polyurethane insulation	Concrete slab	Reinforced concrete
P3	11.537	11,100.97	Horizontal cover, ventilated	Ventilated facade with ceramic cladding,	Concrete slab	Reinforced concrete

		walkable	polyurethane insulation	



ACCD			Phases of the building life cycle				
Chapters of the systematic classification		Qi: statistically estimated quantity for activity (ref. unit/m^2)	Urbanization	Constructions	Rehabilitation 50	Rehabilitation 75	Demolition
01. Demolitions		m^3 Demolition					Complete demolition of the residential buildings
02. Excavations	02E	m^3 Excavations		The building construction			
	02T	m^3 Transportation soil					
03. Foundations	03A	kg Reinforced Steel					
	03HA	m^3 Reinforced Concrete					
	03HM	m^3 Concrete					
04. Sewers	04C	m Waste water piper				Replacement sewerage installations	
	04B	m Down pipe					
05. Structures	05AA	kg Reinforced Steel					
	05HA	m^3 Reinforced Concrete					
06. Masonry	06DT	m^2 Internal partition			Energy retrofitting of the facade	Repairs of fissures and cracks	
	06LE	m^2 Envelope brick walls					
07. Roofs	07H	m^2 Horizontal roofs			Energy retrofitting of the roof	Repairs of fissures and cracks	
	07I	m^2 Inclined plane roofs					
08. Installations	08EC	m Circuits			New installation of air conditioning and heating, and domestic hot water	Replacement electricity and water installations	
	08ED	m Lines					
	08EL	u Point of light					
09. Insulation	09A	m^2 Acoustic Insulation			Improvement insulation	Improvement insulation	
	09T	m^2 Thermal Insulation					
10. Coatings	10AA	m^2 Wall Tiles			Replacement coatings	Replacement coatings	
	10S	m^2 Floor Tiles					
11. Carpentry	11CA	m^2 Steel frames			Energy retrofitting of windows doors	Energy retrofitting of windows doors	
	11CL	m^2 Aluminum frames					
	11M	m^2 Wood frames					
13. Paintings	13PE	m^2 Exterior Paintings			Paint replenishment	Paint replenishment	
	13PI	m^2 Interior Paintings					
15. Urbanization	15CR	u Street signalling	Roads, sewerage and public services...				
	15EP	u Streetlight					
17. Waste Management	17G	m^3 CDW	Waste management	Waste management	Waste management	Waste management	Waste management

Figure 3. *Activities which generate CDW in each phase of the building life cycle.*

The construction works carried out at each stage of the life cycle are shown in Figure 3, where the first column is the budget chapter, the second its title, and the third the sub-chapter code per ACCD. The next column are the measurement units employ in the construction sector for those specific works. The remaining columns are the chapters that intervene in each life stage. Each chapter is define in a pyramidal way, Figure 2, which means that each action to be taken in the building correspond finally to a unitary cost in a project budget. The units are formed by materials, machinery and manpower.

The action taken at each stage are defined by the budget of each project:

- Urbanization: Road works, sewerage and installations, public services, etc.
- Construction: The building construction.
- Retrofitting 50: Energy retrofitting of the facade (including windows) and roof including their insulation. New installation of air conditioning and heating, and domestic hot water production by solar thermal panels.
- Retrofitting/renovation 75: Repairs of fissures and cracks and replacement of all installations: electricity, water and sewerage.
- Demolition: Complete demolition of residential buildings.

5. Results

In Table 4, the main families of materials identified match those identified in construction projects in Spain by (Solís-Guzmán et al., 2018), in Italy (Blengini, 2008), Brazil (Maciel et al., 2016) and Chile (Rivero Camacho et al., 2018). In China, the most important materials are also concrete, 58.9%, ceramics 29.3% and mortars 9.8% (Wang et al., 2018).

Table 4. *Quantities of material, machinery and workforce in CDW in the building life cycle.*

		P1		P2		P3	
	Stage	Construction	CDW	Construction	CDW	Construction	CDW
Urbanization	Material	(Kg/m^2)	(Kg/m	(Kg/m^2)	(Kg/m^2	(Kg/m^2)	(Kg/m^2
	Soil	598.10	417.2	339.69	1209.5	729.40	1456.1
	Wood	0	177.8	0	243.80	0	419.29
	Concrete	51.50	2.58	91.03	4.55	118.01	5.90
	Asphalt	36.38	1.09	80.75	2.42	98.98	2.97
	Brick	6.18	0.37	5.68	0.34	7.83	0.47
	Others	119.11	5.96	353.16	17.66	459.92	22.30
	Total	**811.27**	**605.1**	**870.32**	**1478.2**	**1414.14**	**1907.7**
	Machinery/Tr	**0.03**	**0.19**	**0.05**	**0.47**	**0.16**	**0.61**
	Workforce	**0.21**	**0.50**	**1.74**	**1.21**	**0.59**	**1.56**
Construction	Concrete	2202.95	110.1	1178.29	58.91	1047.13	52.36
	Brick	644.93	38.70	515.53	30.93	516.49	30.99
	Aggregates/st	476.21	23.81	264.65	13.23	233.88	11.69
	Metals	35.61	1.07	40.68	1.22	39.63	1.19
	Plastics	20.18	1.01	11.20	0.56	9.61	0.48
	Others	130.01	5.20	22.19	0.89	66.78	3.11

	Total	**3527.06**	**180.6**	**2040.15**	**106.03**	**1920.25**	**100.04**
	Machinery/Tr	**0.37**	**0.06**	**0.41**	**0.03**	**0.39**	**0.03**
	Workforce	**13.85**	**0.15**	**11.19**	**0.09**	**11.58**	**0.08**
Retrofitting 50	Metals	7.50	7.73	7.18	7.40	7.29	7.51
	Aggregates/st	2.11	2.21	1.95	2.05	2.00	2.11
	Plastics	0.99	1.03	0.99	1.03	0.99	1.03
	Glass	0.23	0.24	0.18	0.19	0.20	0.21
	Cement	0.19	0.20	0.19	0.20	0.19	0.20
	Others	0.44	0.47	0.31	0.33	0.44	0.47
	Total	**11.46**	**11.88**	**10.81**	**11.21**	**11.11**	**11.52**
	Machinery/Tr	**0.001**	**0.004**	**0.001**	**0.004**	**0.001**	**0.004**
	Workforce	**2.15**	**0.01**	**2.06**	**0.01**	**2.10**	**0.01**
Retrofitting 75	Aggregates/st	172.96	181.6	65.87	69.17	43.01	45.17
	Concrete	47.91	50.30	18.83	19.77	13.11	13.76
	Brick	15.19	16.10	3.97	4.21	1.64	1.74
	Plasters and	12.15	12.76	9.68	10.16	10.49	11.02
	Plastics	5.26	5.53	3.06	3.22	3.31	3.47
	Others	2.26	2.38	2.01	2.12	2.11	2.21
	Total	**262.24**	**275.3**	**105.94**	**111.23**	**75.84**	**79.60**
	Machinery/Tr	**0.31**	**0.09**	**0.24**	**0.04**	**0.20**	**0.02**
	Workforce	**7.94**	**0.23**	**4.60**	**0.09**	**4.62**	**0.06**
Demolition	Concrete	0	2,202.	0	1,178.	0	1,047.
	Brick	0	644.9	0	515.5	0	516.5
	Aggregates/st	0	476.2	0	264.7	0	233.9
	Metals	0	35.6	0	40.9	0	39.6
	Plastics	0	20.2	0	11.2	0	9.6
	Others	0	130.0	0	22.2	0	66.8
	Total	**0**	**3,527.**	**0**	**2,040.**	**0**	**1,920.**
	Machinery/Tr	**0**	**1.13**	**0**	**0.65**	**0**	**0.61**
	Workforce	**0**	**2.89**	**0**	**1.67**	**0**	**1.57**
Total BLC	**Total**	**4,612.03**	**4,600.**	**3,027.22**	**3,746.**	**3,421.33**	**4,019.**
	Machinery/Tr	**0.71**	**1.47**	**0.70**	**1.20**	**0.76**	**1.29**
	Workforce	**24.16**	**3.77**	**19.59**	**3.07**	**18.89**	**3.29**

Figure 4 shows the most representative per quantity of CDW generated in the three projects. The results show that soil, concrete, brick, wood and aggregates are between 95 to 98% of the CDW, see Figure 4, thereby emphasising that improvements in its management and treatment can lead to substantial impact decrease in the BLC. Another study in Spain shows similar results (Río Merino et al., 2017). The excesive concrete waste of project 1 has to do with the type of construction, a single family dwelling which has a higher concrete comsuption than multifamily buildings.

Soil is the most important CDW in terms of weight in projects 2 and 3. This is due to the earthworks during urbanization and construction. Soil, if not mixed with other debris, can be easily reused in-situ or on a different construction site. This can be achieved by using it as a filler; this strategy needs to be included during project design and in the management plan (del Río Merino et al., 2010).

The second material in importance is concrete. In Spain, efforts have been made to recycle it, since 2008, the Code of Structural Concrete (EHE, 2008) includes an annex on how to recycle and quality control of recycled concrete, but few structures have been built using recycled aggregates (Statistics National Institute, 2012). The recycling of concrete takes places when replacing concrete subject to lesser restrictions such as in the sub-base of cycling tracks, trench filling and electric shaft foundations (GERD, 2018). In these applications it has been shown that in-situ recycling of concrete can generate significant cost savings (Marrero et al., 2017).

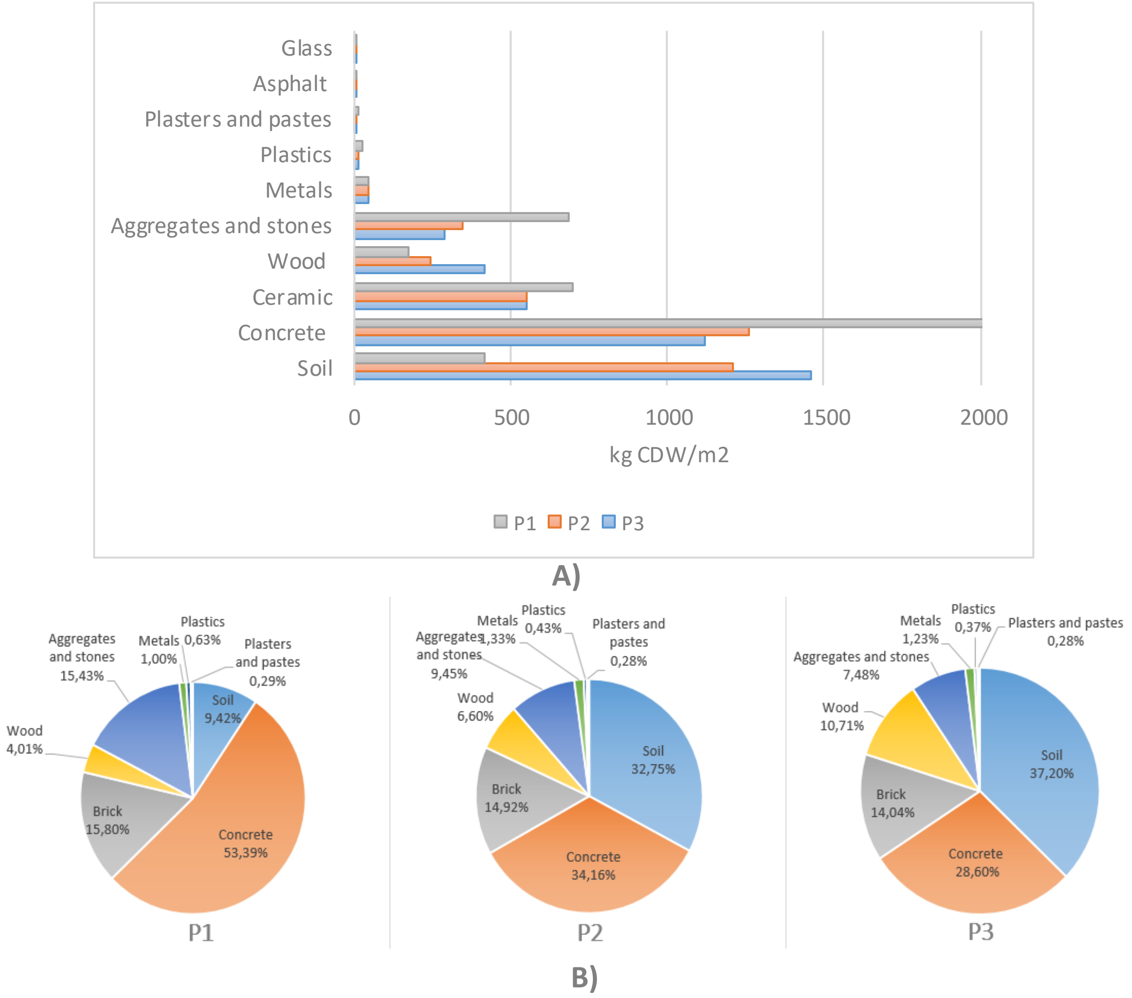


*Figure 4. **A)** Total of CDW generated during 100 years per floor area. **B)** Percentage of CDW in total BLC by project.*

The use of several environmental indicators simultaneously compares its significance in the life cycle, see Figure 5. It can be seen that in all the projects analysed, energy and incorporated and wasted water are proportional to the total weight of the CDW. The stage where the most impact occurs is during demolition. In the particular case of CO_2 emissions, wood has negative emissions that makes the urbanization total balance negative, too.

The P1 impacts are significantly higher than in the other two cases, in all categories and at all life stages. This is due to the fact that single family buildings need more resources per floor area than multifamily ones.

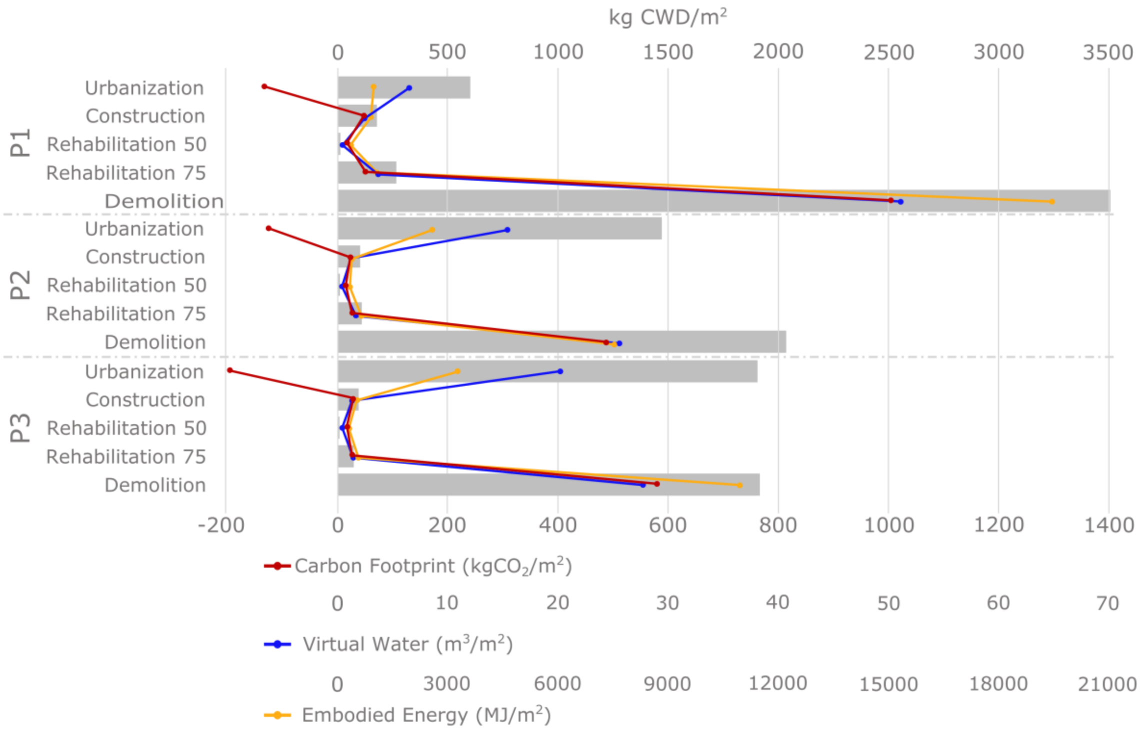


Figure 5. *CDW Environmental impact by project stages.*

Other interesting results are the energy involved in the CDW of urbanization and construction of P1. The higher amount of CDW in urbanization than during construction involves low energy usage. This is due to the large volume of soil in urbanization work, which has low embodied energy per tonne, only that of machines and trucks, because of its nature soil does not require any industrial transformation.

In Table 5, the materials with the highest energy impact are concrete, asphalt and bricks during urbanization. In new constructions, asphalt is substituted by plastic materials. In the retroffiting projects that take place after 50 and 75 years, metals and plastic materials are the most important; and during demolition those of the construction stage are again the highest. The emission pattern is similar except for urbanization, due to the negative emissions of wooden materials.

Virtual water has different controlling materials with high impact such as wood in urbanization, concrete during construction, metals in retrofitting after 50 years and plaster and pastes in buildings after 75 years. At the end of life, concrete has the highest virtual water.

Table 5. *CDW quantities environmental impact by family of materials, with Virtual Water (VW), Embodied Energy (EE) and Carbon Footprint (CF) indicators for projects stages.*

		VW (m^3/m^2)			EE (MJ/m^2)			CF(kg CO_{2eq}/m^2)		
Stage/ CDW generated		P1	P2	P3	P1	P2	P3	P1	P2	P3
Urbanization	Soil	0	0	0	0	0	0	2.96	8.57	10.3
	Wood	0.71	0.98	1.68	0	0	0	-	-	-
	Concrete	0.01	0.01	0.01	1.59	2.80	3.64	0.29	0.51	0.66
	Asphalt	0.00	0.00	0.00	7.68	17.06	20.90	0.23	0.51	0.62
	Brick	0.00	0.00	0.00	1.05	0.97	1.33	0.08	0.08	0.10
	Others	0.49	1.45	1.83	501.83	1,486.	1,877.6	15.97	47.3	59.7
	Total	**1.21**	**2.44**	**3.53**	**512.15**	**1,507.**	**1,903.5**	**-**	**-**	**-**
	Machinery	**5.31**	**12.9**	**16.7**	**425.52**	**1,039.**	**1,341.5**	**24.50**	**58.0**	**74.8**
	TOTAL	**6.51**	**15.4**	**20.2**	**937.67**	**2,547.**	**3,245.0**	**-**	**-**	**-**
Construction	Concrete	0.22	0.12	0.10	67.85	36.29	32.25	12.34	6.60	5.86
	Brick	0.04	0.03	0.03	109.90	87.85	88.01	8.51	6.80	6.82
	Aggregates	0.00	0.00	0.00	9.05	5.03	4.44	0.31	0.17	0.15
	Metals	0.03	0.03	0.03	24.93	28.43	27.73	1.55	1.77	1.73
	Plastics	0.17	0.10	0.08	90.40	50.12	42.96	3.40	1.89	1.62
	Others	0.43	0.07	0.26	437.84	74.94	261.86	13.94	2.39	8.33
	Total	**0.89**	**0.35**	**0.51**	**739.97**	**282.6**	**457.26**	**40,05**	**19.6**	**24.5**
	Machinery	**1.58**	**0.93**	**0.88**	**127.03**	**74.56**	**70.35**	**7.32**	**4.29**	**4.05**
	TOTAL	**2.47**	**1.28**	**1.38**	**867.00**	**357.2**	**527.61**	**47.37**	**23.9**	**28.5**
Rehabilitation 50	Metals	0.21	0.20	0.20	180.11	172.4	174.98	11.20	10.7	10.8
	Aggregates	0.00	0.00	0.00	0.84	0.78	0.80	0.03	0.03	0.03
	Plastics	0.18	0.18	0.18	92.19	92.19	92.19	3.47	3.47	3.47
	Glass	0.00	0.00	0.00	3.10	2.45	2.71	0.13	0.11	0.12
	Cement	0.00	0.00	0.00	0.72	0.72	0.72	0.15	0.15	0.15
	Others	0.04	0.03	0.04	39.57	27.79	39.57	1.26	0.88	1.26
	Total	**0.43**	**0.41**	**0.42**	**316.52**	**296.3**	**310.97**	**16.26**	**15.3**	**15.9**
	Machinery	**0.10**	**0.10**	**0.10**	**8.36**	**7.90**	**8.10**	**0.48**	**0.46**	**0.47**
	TOTAL	**0.53**	**0.50**	**0.52**	**324.88**	**304.2**	**319.07**	**16.74**	**15.8**	**16.3**
Rehabilitation 75	Aggregates	0.02	0.01	0.00	69.01	26.28	17.16	2.36	0.90	0.59
	Concrete	0.10	0.04	0.03	30.98	12.18	8.48	5.63	2.21	1.54
	Brick	0.02	0.00	0.00	45.72	11.96	4.94	3.54	0.93	0.38
	Plasters	0.03	0.02	0.02	19.40	15.44	16.75	2.49	1.98	2.15
	Plastics	0.94	0.55	0.59	494.94	288.1	310.57	18.64	10.8	11.6
	Others	0.20	0.17	0.18	200.40	178,5	186.08	6.38	5.68	5.92
	Total	**1.30**	**0.79**	**0.83**	**860.45**	**532.5**	**543.98**	**39.04**	**22.5**	**22.2**
	Machinery	**2.41**	**0.98**	**0.67**	**193.65**	**78.22**	**53.33**	**11.15**	**4.50**	**3.07**
	TOTAL	**3.71**	**1.77**	**1.49**	**1,054.1**	**610.7**	**597.31**	**50.19**	**27.0**	**25.3**
Demolition	Concrete	4.41	2.36	2.09	1,356.9	725.8	645.01	246.7	131.	117.
	Brick	0.64	0.52	0.52	1,831.5	1,464.	1,466.8	141.8	113.	113.
	Aggregates	0.05	0.03	0.02	180.96	100.5	88.88	6.19	3.44	3.04

Metals	0.96	1.10	1.07	829.48	952.9	922.68	51.62	59.3	57.4
Plastics	3.43	1.90	1.63	1,807.9	1,002.	859.20	68.07	37.7	32.3
Others	10.6	1.82	5.48	10,946.	1,869.	5,624.5	348.4	59.5	179.
Total	**20.1**	**7.73**	**10.8**	**16,952.**	**6,115.**	**9,607.2**	**862.8**	**405.**	**502.**
Machinery	**30.9**	**17.8**	**16.8**	**2,480.2**	**1,434.**	**1,350.3**	**142.8**	**82.6**	**77.7**
TOTAL	**51.0**	**25.6**	**27.6**	**19,433.**	**7,549.**	**10,957.**	**1,005.**	**487.**	**580.**
TOTAL IN BLC	**64.3**	**44.5**	**51.3**	**22,616.**	**11,36**	**15,646.**	**987.6**	**429.**	**383.**

Recent studies (Solís-Guzmán et al., 2018) on dwelling construcion determine embodied carbon emissions, which, on average, are 616 kg CO_2 eq / m^2 of floor area, more specifically, P1 is 769 kg CO_2 eq / m^2, P2 is 577 kg CO_2 eq / m^2, and P3 is 576 kg CO_2 eq / m^2. The CF of the CDW, total quantities are summarized in table 5, is smaller than that of the construction stage in projects 2 and 3 which is due to trees in urbanization stage, accounted as wooden material, have a high negative CF. A similar analysis can be performed on embodied energy, the CDW in the building life is 1.50 times higher in average than that of the construction stage, and water footprint is 2.70 times higher.

In all the projects studied, the results display that CDW represents 40% more wasted resources in the construction of dwellings, thereby emphasising that any enhancements made in their management lead to a significant reduction in environmental impact. This is mainly due to construction material durability which needs to be replaced several times during the BLC, and small interventions are not controlled as in new construction or demolition projects which are considered urban solid waste (Royal Decree 105/2008, 2008). In-situ recycling is also crucial for the waste reduction. This can be achieved, for example by re-using soil and crushing concrete and ceramic materials; but for this to happen in construction, it needs to be comprised in the first phase of the project design.

Blengini (2008) results have demonstrated that building waste recycling is economically possible and profitable, and also sustainable from the energy point of view. The recycling potential is 29% and 18% in energy and greenhouse emisions, respectively. Wang et al. (2018) show that recycling can bring an environmental benefit of 1.21 yen per tonne while direct land fill leads to an enviromental cost of 12.0 per tonne.

But, regarding strategies, recycling off-site and incineration, both combined with landfill for the rejected fractions are the ones most commonly applied; re-use or recycling on site is the strategy least applied (Bovea and Powell, 2016).

6. Conclusions

The model evaluates for the first time the embodied impact in CDW during the building life cycle using the projects' cost assessment. The data the data in the bill of quantities of all construction projects that take place along its service life is employed for the calculation. The bill of quantities describes materials, machinery and workforce in construction projects. The ACCD and its WBS are used for budget generation. Fuel consumption by the use of machinery is considered together with the embodied impact on construction waste.

The results display, in all projects calculated, that CDW represents 40% more waste than in the materials employed in the construction of dwellings. The extra amount is mainly due to material durability, some materials need to be replaced several times during the life of a building.

Using a systematic classification of construction works, it is possible to detect the materials with the most impact and when these impacts may occur during the cycle, so that strategies of urban management can be established capable of predicting, according to the age of the buildings, when the CDW will be generated. The waste produced during retrofitting and renovation works are not normally controlled and considered urban solid waste. The latter limit the opportunities for re-using or recycling. The results of this model can be used by authorities to define strategies to encourage recycling in renovation and retrofitting activities.

The strongest aspect of the propose methodology for the quantification of CDW impact in the building life cycle resides in its easy introduction in the construction sector because cost control is already in place by means of the bill of quantities, professionals in the sector are familiarized with the classification systems and serve as vehicle for the introduction of waste assessment. The method proposed adds information to the traditional quantity surveying. But, on the opposite, this is also the main limitation, because the model completely depends on the quality of the project data that is part of the budget.

The social contribution consist on its potential introduction of the concepts of waste quantification, environmental assessment and its control in a simple way that can reach a non-academic public. In the industry, the inclusion of CDW management into the cost control systems can improve the effectiveness of reducing, recycling and reusing strategies by measuring their potential economic and environmental savings.

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