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Environmental Impact Assessment of Construction Waste Recycling versus Disposal Scenarios Using an LCA-BIM Tool during the Design Stage

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Abstract: The scientific community has revealed the environmental benefits of recycling construction waste (CW) versus its disposal, and its contribution to circularity. The Life Cycle Assessment (LCA) method enables the environmental impact of CW management to be quantified and facilitates the comparison of recycling versus alternative disposal scenarios. However, due to its complexity, LCA is seldom used by technicians during the design phase, which constitutes a crucial stage in the prevention of environmental impacts. This paper therefore proposes an LCA-based tool, integrated into the Building Information Modelling (BIM) methodology, that helps designers to automate the environmental assessment of recycling versus disposal. The CW-LCA-BIM tool uses impact factors obtained from an LCA model applied to CW and was applied to the structural system of a building in Spain. Up to 99% of the non-hazardous waste was recyclable or reusable. The management of three types of recyclable waste was assessed: concrete (27.2 t), plastics (4.2 t), and steel (1.5 t). Recycling is shown to be the best option since it prevents 1.4 times (14.6 t) the emissions of the disposal scenario and saves 85 times (148.5 GJ) its energy consumption. This tool can be developed in other waste management systems and infrastructures. It can be useful both for designers for the reduction of the environmental impact of their buildings, and for policy managers for waste-prevention policies.

Keywords: Life Cycle Assessment (LCA); construction waste (CW); Building Information Modelling (BIM); environmental impact; recycling; disposal; landfilling; concrete structure

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1. Introduction

The generation of construction and demolition waste (CDW), together with the use of resources in the construction industry, presents a worldwide problem [1]. In the European Union (EU), the construction sector is the main source of waste generation, accounts for more than a third (35%) of all waste generated [2], and is the main consumer of natural resources in that it consumes approximately 50% of all extracted material [3]. Faced with this situation, initiatives and strategies to promote CDW recycling and circularity have been implemented in recent years. The EU rules, for example, aim not only to ensure that CDW is managed in an environmentally sound way, but also to contribute towards the circular economy. The new Circular Economy Action Plan [4] is thereby one of the main building blocks of the European Green Deal [5], which focuses on the sectors that use the most resources and on where the potential for circularity is high, such as construction and buildings. Nevertheless, the level of recycling and material recovery of CDW varies greatly across the EU: from less than 10% to over 90% [6]. Hence, recycling rates remain far from the target of recycling 70% of CDW (excluding soil) set for 2020 by the European Waste Framework [7]. A major barrier to the circular principles is the lack of appropriate design methodologies to enable the better use of CDW [8]. In fact, in the light of the circular economy, the provision of methods and tools to evaluate and subsequently enhance product performance has become a significant issue, albeit still barely addressed [9].

The design phase is a crucial stage in improving on-site waste management, since not only does building design determine the types and quantities of waste generated, but it also dictates the level of recyclability of the waste on site. Moreover, Life Cycle Assessment (LCA) [10,11] is a method that can measure the environmental impact caused by waste management, and hence enables the comparison of alternative CDW management scenarios. In the field of CDW, LCA has been used in scientific studies, mainly to assess alternative End Of Life (EOL) scenarios [12,13], with only a few studies focused on other phases of the life cycle, such as the construction phase. Although the EOL is the main source of CDW in many countries, such as the USA, where demolition waste (DW) represented more than 90% of total CDW debris generation in 2018 [14], in other countries, such as Spain, new construction in 2019 incurred a higher incidence of CDW (85%) than did demolition (10%) and rehabilitation (5%) [15]. In both cases, design methodologies are needed that include the prediction of the environmental impact from early design phases [12], since these phases facilitate the implementation of corrective measures before the design is complete [16].

However, LCA application by technical designers has been limited due to its complex and time-consuming properties [17,18]. In this vein, Building Information Modelling (BIM) has become a powerful tool for the management of building information [19–21] and for the automation of calculations during the design stage [16,21]. In the field of CDW, BIM has been applied with several approaches: (i) to predict CDW generation [22–25]; (ii) to estimate the CDW [26] and the environmental impact prevented [27] through clash detection; (iii) to support waste minimization, management, and control [28–32]; and (iv) to facilitate the adoption of the circular economy in the construction industry [33–37]. However, the application of LCA and BIM to the field of CDW has remained limited. As shown in Table 1, there are LCA studies [38–44] applied to CDW that include disposal and recycling scenarios but with few integrated approaches in the design tools. A BIM tool [45] has been developed to simulate alternative management scenarios but it focuses on DW generated in the EOL. Therefore, the lack of approaches and design tools for the assessment of the environmental impact of CDW management in general and especially that of construction waste (CW) has motivated the interest and timeline of this study.

Table 1. LCA studies that evaluate recycling and demolition scenarios in construction and demolition waste. BIM integration.

Study	CW	DW	LCA	Recycling	Disposal	BIM
[38–42]		X	X	X	X	
[43,44]	X	X	X	X	X	
[45]		X	X	X	X	X
Proposed CW-LCA-BIM tool	X		X	X	X	X

CW. Construction waste generated in the construction phase; DW. Demolition waste generated in the End-Of Life phase; LCA. Life Cycle Assessment; BIM. Building Information Modelling.

In order to fill this research gap, this paper proposes a CW-LCA-BIM tool the main contribution of which is that it enables designers to automate the evaluation of the environmental impact of alternative CW management scenarios, using the project's own design tool (i.e.,Audodesk Revit 21.1.1, Autodesk Inc., San Rafael, California, USA). The tool is based on a BIM-integrated plug-in to quantify CDW [46] and on environmental impact factors obtained from an LCA model applied to building waste [47]. A case study in Spain is provided to show the usefulness of the CW-LCA-BIM tool. Recycling and disposal scenarios for the management of the CW generated by a structural system of a residential building are compared in the early design stages. The CW-LCA-BIM tool informs the designer both of the potentially recyclable waste and of the environmental benefits achieved by its recycling, thereby promoting the circularity of materials in the construction phase of buildings. The paper first presents the materials and methods necessary for the development and application of the CW-LCA-BIM tool, and subsequently reveals the results obtained with its application to the case study as well as the discussion and conclusions derived from the major findings.

The following research questions (RQ), regarding general gap issues and far removed from professional practice during the design of the building, are intended to be answered with the tool:

RQ1. During the design phase, is it possible to obtain the impact reduction achieved with the recycling versus disposal scenarios of CW, without being an LCA expert and without time consumption?
RQ2. Is CW recycling always the most beneficial option with respect to CW disposal?
RQ3. Which environmental impact categories are most influenced by CW recycling?
RQ4. Which CW and building elements have the greatest impact on CW management and which CW benefits the most from recycling?

2. Results and Discussion

The structural system was modelled in BIM with an LOD of 300 as shown in Figure 1. The information of each building element was included in their respective BIM-Objects to quantify CW as explained in [46]. The CW-LCA-BIM tool allowed the designer to classify the building elements into five main groups: (i) the foundation slab (60 cm reinforced concrete slab); (ii) the walls (30 cm reinforced concrete walls); (iii) the pillars (reinforced concrete and steel pillars); (iv) the beams (embedded and dropped reinforced concrete beams); and (v) the floors (both 30 and 35 cm reinforced concrete waffle slabs with expanded polystyrene cassettes and concrete decks).

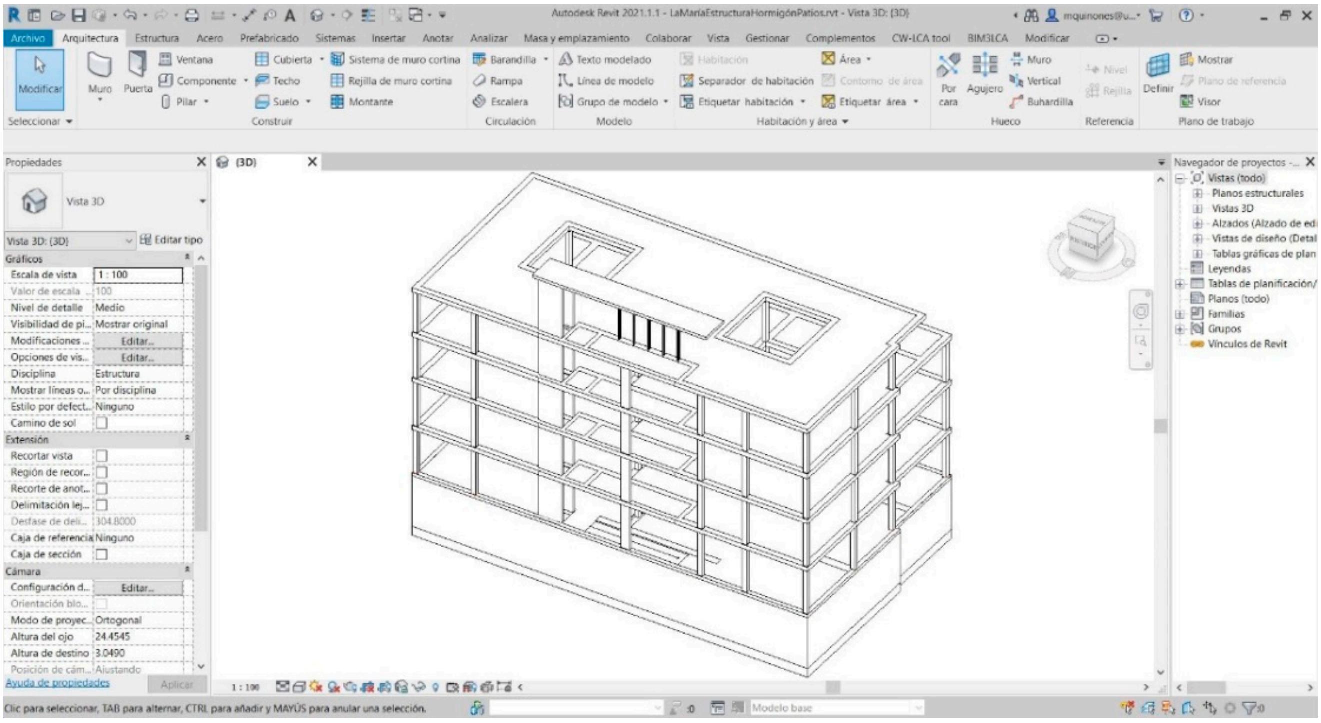
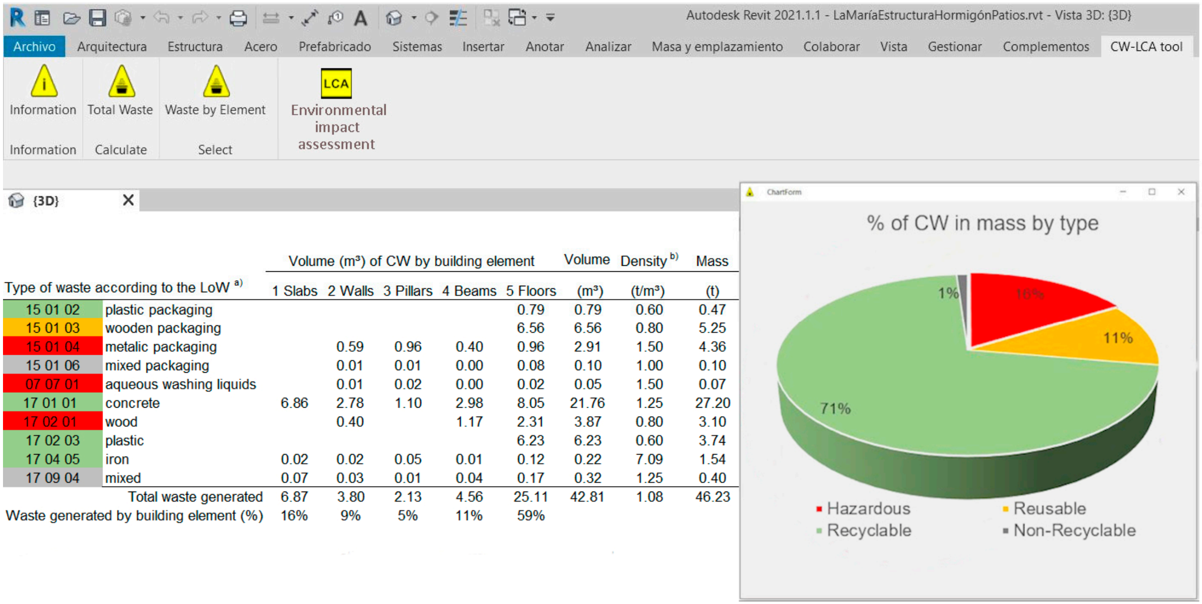


Figure 1. Structural system of "La Maria" modelled in BIM.

Ten main fractions of CW (excluding soil) were identified and quantified in terms of volume (m^3) and mass (t), as shown in Figure 2, structured in groups of building elements. The main sources of CW were (in descending order of mass): (i) concrete leftovers due to its manufacture and pouring on site; (ii) wooden pallets used to supply the waffle slab caissons; (iii) metal cans to contain the form release agents; (iv) cuts and pieces of the polystyrene waffle slab caissons; (v) timber formwork from the concrete slabs; (vi) steel from reinforcement cuts and remains of metal formwork; (vii) plastic film to protect the waffle slab caissons; (viii) mixed waste, unavoidable, to be separated on site; (ix) mixed packaging that was unavoidable, to be separated on site; and (x) release agent residues.



Type of waste according to the LoW [a)]		Volume (m³) of CW by building element: 1 Slabs	2 Walls	3 Pillars	4 Beams	5 Floors	Volume (m³)	Density [b)] (t/m³)	Mass (t)
15 01 02	plastic packaging					0.79	0.79	0.60	0.47
15 01 03	wooden packaging					6.56	6.56	0.80	5.25
15 01 04	metalic packaging		0.59	0.96	0.40	0.96	2.91	1.50	4.36
15 01 06	mixed packaging		0.01	0.01	0.00	0.08	0.10	1.00	0.10
07 07 01	aqueous washing liquids		0.01	0.02	0.00	0.02	0.05	1.50	0.07
17 01 01	concrete	6.86	2.78	1.10	2.98	8.05	21.76	1.25	27.20
17 02 01	wood		0.40		1.17	2.31	3.87	0.80	3.10
17 02 03	plastic					6.23	6.23	0.60	3.74
17 04 05	iron	0.02	0.02	0.05	0.01	0.12	0.22	7.09	1.54
17 09 04	mixed	0.07	0.03	0.01	0.04	0.17	0.32	1.25	0.40
	Total waste generated	6.87	3.80	2.13	4.56	25.11	42.81	1.08	46.23
	Waste generated by building element (%)	16%	9%	5%	11%	59%			

Figure 2. Identification and quantification of recyclable CW fractions. [a)] European List of Waste [48]; [b)] National Ratios Generation of Waste Study from Construction and Demolition [49].

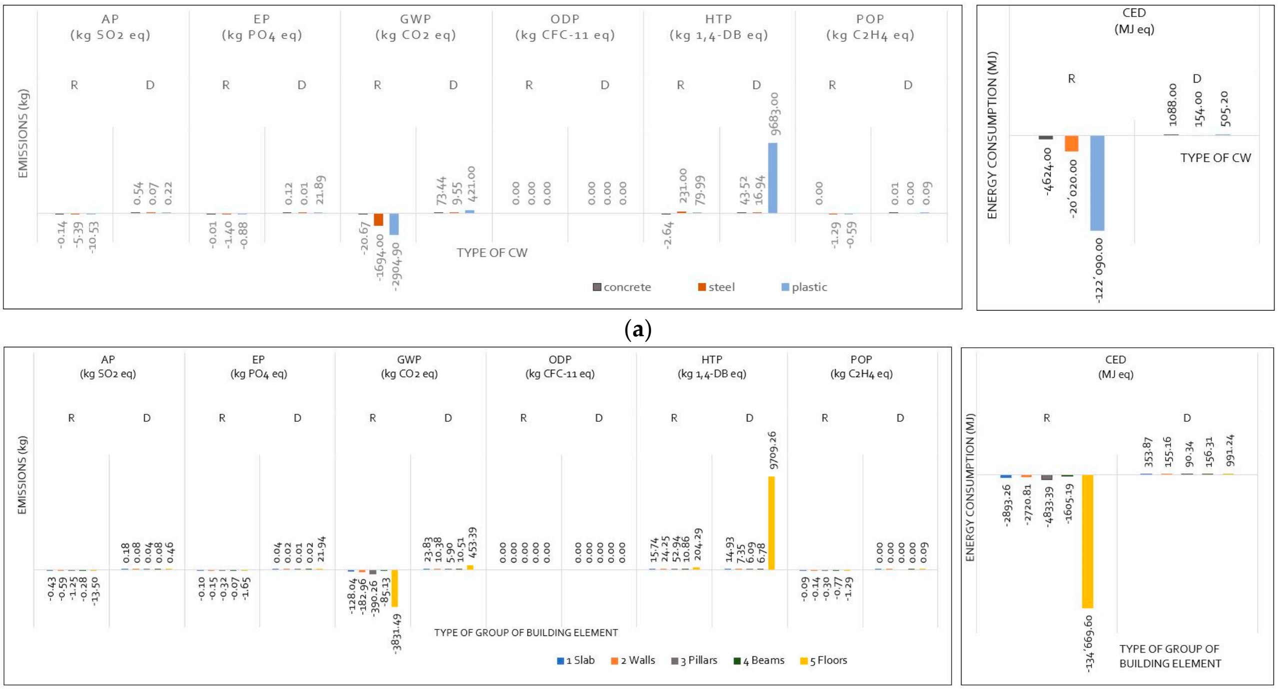
In order to obtain the variable types (*i*) and quantities (*Q*) of recyclable CW, each fraction was classified into four groups according to the preferred management option, as shown Figure 2.

i. Hazardous waste (16%) (in red): (i) timber formworks and (ii) metal cans contaminated by release agents; and (iii) release agent residues, which must be separated and removed by a specialized waste manager in accordance with Spanish regulations [50].
ii. Reusable waste (11%) (in orange): (i) wooden pallets that are usually stockpiled on site and removed by the same supplier of the materials.
iii. Non-recyclable waste (1%) (in grey): (i) mixed waste and (ii) mixed packaging, the recycling of which is economically and technically unfeasible since their heterogeneous mixtures may be difficult to separate on site as explained in [47].
iv. Recyclable waste (71%) (in green), variables "*i*" and "*Q*": (i) concrete (27.2 t); (ii) plastics (4.2 t); and (iii) steel (1.5 t).

Subsequently, two alternative scenarios were simulated in the CW-LCA-BIM tool:

i. Recycling scenario (R), in which each recyclable fraction is separated on site and transported to its corresponding recycling plant by an authorized manager (see Figure S1). These recycling plants would produce the by-products: recycled aggregates, recycled steel, and recycled plastic, considering the processes explained in [13,47];
ii. Disposal scenario (D), in which each recyclable fraction is separated on site and transported to its corresponding landfill (concrete to the landfill of inert waste; and steel and plastics to the landfill of non-inert waste) by an authorized manager (see Figure S1); considering the processes explained in [13,47].

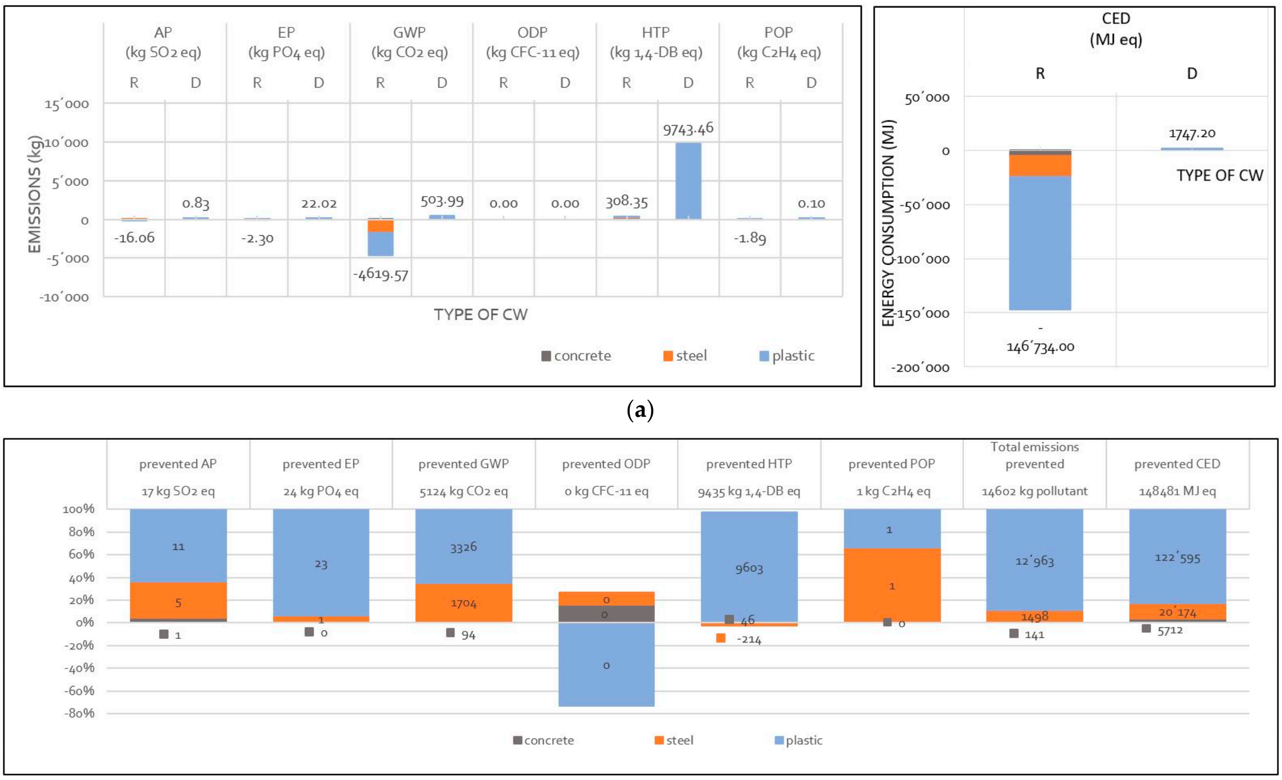
For each scenario, the tool quantified the environmental impacts (*I*) by considering the impact factors (*Fi*) shown in Table 1. These impacts were obtained for each type of CW (Figure 3a), for each type of group of building elements (Figure 3b), and globally for the entire building system (Figure 4a). Finally, the tool provided a graph showing the reduction of impacts, prevented emissions, and energy savings achieved in the recycling scenario (Figure 4b).



(**a**)

(**b**)

Figure 3. Environmental impacts in recycling (R) versus demolition (D) scenarios; (**a**) per type of CW; (**b**) per building element.



(**a**)

(**b**)

Figure 4. (**a**) Total environmental impacts in the concrete structure system in recycling (R) versus demolition (D) scenarios. (**b**) Prevented emissions and energy savings achieved in recycling scenario (R) with respect disposal scenario (D).

2.1. Case Study Validation and Answers to the Research Questions (RQ)

The tool provides estimates as would be used in the design stage to simulate scenarios before the building was constructed. The reliability of the CW estimates and accurate data acquisition are discussed in [46,51]. Nevertheless, it is verified that the three types of recyclable CW obtained (see Figure 2) are included in the ratios of CW generation in new residential buildings in Spain [49]: (i) concrete (0.017 t/m^2), in the range 0.010–0.034 t/m^2; (ii) plastics (0.003 t/m^2), in the range 0.001–0.005 t/m^2; and, although steel (0.001 t/m^2) is below the ratio of mixed metals (0.002–0.007 t/m^2), this fraction is expected to be higher as it would be complimented with other metals (aluminum, copper) of other building systems (carpentry, plumbing). However, it was found that the steel waste expected to be generated due to steel reinforcement cuttings (1.1 t) (output data) represented 1.2% of the reinforcement steel considered in the project budget (input data, 91.1 t), which is an acceptable loss percentage for construction work in Andalusia [52]. Moreover, the fractions of concrete and plastics are likely to be higher once other waste sources are included in other building systems.

The environmental impacts prevented were ascertained without the aid of an expert in LCA, thereby addressing RQ1. The most time-consuming step for the designer was the modelling of the BIM-Objects. Once modelled, the technician obtained the results by clicking on the corresponding buttons on the tool.

Regarding RQ2, disposal was identified as the scenario that produces the highest impact for all types of waste and categories (see Figure 3a), except for plastic in ODP (insignificant category), and for steel in HTP, where the recycling scenario would be less beneficial. This result is in line with the literature, since most studies have demonstrated the reduction of environmental impacts of recycling with respect to disposal [40,44,53–55], although other work reports that recycling is not always beneficial [56,57].

Regarding RQ3, the tool identified GWP and HTP as the categories with the greatest impact on the amount of emissions and showed the relevance of energy consumption (see Figures 1 and 2a). This issue is a consequence of the impact factors obtained and discussed in [13,47]. As Table 1 shows, 1 ton of deposited concrete waste, for example, generates 2.70 kg CO_2 emissions and consumes 40 MJ of energy, whereby the impact is much higher for the non-petrous fractions of steel (6.20 kg CO_2, 100 MJ) and plastics (100 kg CO_2, 120 MJ). Another study estimated impacts for 1 ton of deposited mixed CDW of 4.12 kg CO_2 emissions and 62.91 MJ of energy [58]. Moreover, the largest emission reductions were achieved in HTP (9.4 t) and GWP (5.1 t) followed by the EP (0.02 t) and AP (0.02 t) categories, and the energy savings in the CED category (148.5 MJ), as shown in Figure 4b. GWP, GHG emissions and Climate Change are the most evaluated impact categories in LCA [59]. HTP was also identified as the most significant category in [53].

Figures 1 and 2 show how the tool addressed RQ4. The most polluting option would be plastic disposal (10.1 t), followed by concrete disposal (0.12 t) and steel disposal (0.03 t), and the most energy-consuming option would be concrete disposal (1 MJ) followed by plastic disposal (0.5 MJ) and then steel disposal (0.2 MJ) (Figure 3a).

As shown in Figure 4b, the tool identified the floors, followed by the foundation slab, the beams, walls, and pillars as the most polluting and energy-consuming group of building elements. The reason is twofold. On the one hand, the floors and slabs are the main source of waste: 75% of all waste (see Figure 2). On the other hand, the floor slabs generated a large amount of plastic (3.74 t) due to cut-outs in the EPS cassettes. Nevertheless, in any building element, the deposit of its corresponding waste would be the least beneficial option and recycling would be the best option, since the recycling of the waste generated by floors and slabs prevents the most emissions and achieves the highest energy savings (13.4 t and 138.9 GJ), followed by the other three groups of elements (0.6 t and 9.6 GJ) (Figure 4b).

Finally, the incidence of the impacts prevented by steel, and plastic recycling, above other types of waste such as concrete and stone, has been highlighted in other studies such as [54]. As shown in Figure 4b, the waste whose recycling would be the most beneficial is that of plastic (prevents 13.0 t of emissions and saves 122.6 GJ), followed by steel (prevents

1.5 t of emissions and saves 20.2 GJ), and, to a lesser extent, concrete (prevents 0.1 t of emissions and saves 5.67 GJ). Although the literature points to the greater benefit of steel recycling compared to that of plastics (e.g., [53]), this study found greater environmental impact reductions with the recycling of plastics. One reason is that the amount of plastic waste (4.2 t) represented almost three times the amount of steel waste (1.5 t) and therefore represented a higher incidence of recycling. In another building [47] where the amount of steel (14.7 t) and plastics (17.5 t) waste was similar, a greater reduction of impacts in the GWP category was detected with steel recycling (16.2 t) versus plastics recycling (13.8 t), using the same impact factors. Moreover, other tools use impact factors applied to municipal solid waste, and result in similar trends. In the WARM tool [60], recycling 1 ton of steel (cans) prevents 1.8 times the GHG emissions prevented by recycling 1 ton of plastic (PET, HDPE), while recycling plastic saves 2.1 times the energy consumption saved by recycling steel. In the proposed tool, these values are 1.4 and 2.3 (extracted from Table 2).

Table 2. Environmental impact factors [(a)], recycling impact factor (F_R), and disposal impact factor (F_D) for each recyclable CW fraction in the case study.

	AP ($kg\ SO_2eq$) /t Waste		EP ($kg\ PO_4eq$)/ t Waste		GWP ($kg\ CO_2eq$)/ t Waste		ODP (kg CFC-11eq)/ t Waste		HTP (kg 1,4-DBeq)/ t Waste		POP ($kg\ C_2H_4$)/ t Waste		CED (MJeq)/ t Waste	
LoW Code [(b)], Type of CW	F_R	F_D	F_R	F_D	F_R	F_D	F_R	F_D	F_R	F_D	F_R	F_D	F_R	F_D
17 01 01 concrete	-5.3×10^{-3}	2.0×10^{-2}	-4.1×10^{-4}	4.3×10^{-3}	-7.6×10^{-1}	2.7×10^{0}	-6.2×10^{8}	3.5×10^{-7}	-9.7×10^{-2}	1.6×10^{0}	-1.8×10^{-4}	5.1×10^{-4}	-1.7×10^{2}	4.0×10^{1}
17 04 05 steel	-3.5×10^{0}	4.3×10^{-2}	-9.1×10^{-1}	8.2×10^{-3}	-1.1×10^{3}	6.2×10^{0}	-4.0×10^{-6}	7.0×10^{-7}	1.5×10^{2}	1.1×10^{1}	-8.4×10^{-1}	1.2×10^{-3}	-1.3×10^{4}	1.0×10^{2}
17 02 03/15 01 02 plastic	-2.5×10^{0}	5.3×10^{-2}	-2.1×10^{-1}	5.2×10^{0}	-6.9×10^{2}	1.0×10^{2}	1.3×10^{-5}	8.9×10^{-7}	1.9×10^{1}	2.3×10^{3}	-1.4×10^{-1}	2.1×10^{-2}	-2.9×10^{4}	1.2×10^{2}

Environmental impact categories: Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Human Toxicity Potential (HTP), Photochemical Oxidation Potential (POP), Cumulative Energy Demand (CED). (a) Obtained from [13,47,61]; (b) European List of Waste (LoW) [48].

2.2. Implications of Findings

The proposed tool assesses the environmental impacts caused by CW management, which form part of the embodied impacts of the building. Although materials and construction (embodied carbon) are responsible for 11% of total building impacts and building operations for 28% [62], embodied carbon can be as relevant as operational carbon [63]. For example, Spain, is expected to achieve national climate neutrality and 97% of renewable energy in the total energy mix by 2050 [64], which could radically reduce the incidence of operational impact emissions over the life cycle of the building. However, after the total reduction of operational impact emissions, embodied carbon will continue to grow significantly as a proportion of total remaining emissions [63,65]. Therefore, efforts should now focus on reducing embodied carbon emissions [65]. Strategies to make buildings net-zero energy and zero carbon constitute a key part of the global strategy [66] for long-term decarbonization and must become the mainstream form of building construction in all economies to achieve net zero emissions by 2050 [62]. In order to reach this goal, it is necessary to develop and implement tools into the design software itself to help predict these impacts in early design stages [16].

Therefore, the proposed tool is implemented in BIM and predicts the potential recyclable CW generated due to the selected building elements, as well as the potential environmental benefits of its recycling. In the case study, only 16% of CW was identified as hazardous waste, the vast majority being non-hazardous (84%). A total of 99% of non-hazardous waste would indicate a high potential for recycling or reuse. This percentage is well above the current practice in Spain, where 75.13% of non-hazardous CDW is recovered [67]. In the case study, only 1%, corresponding to an unavoidable fraction of mixed waste, was considered non-recyclable due to the difficulty of its separation on site: its major environmental impact is shown in [47].

The designer became aware of the benefits achieved with the recycling scenario. As shown in Figure 4b, the recycling scenario would remove 14.6 t of pollutants from the system, improving human health by obviating 9.4 t of 1,4-DB eq emissions and contributing to decarbonization, by preventing 5.1 t of CO_2 eq emissions. To a lesser extent, it would contribute to the enrichment of the freshwater ecosystem with nutritional elements, and to the deacidification by preventing 0.02 t PO_4 eq emissions and 0.02 t SO_2 eq emissions. Furthermore, the recycling scenario would save 148.5 GJ of energy consumption over the disposal scenario. It can be concluded that recycling is the best option, as it prevents 1.4 times the emissions of the disposal scenario and saves 85 times the energy consumption of the disposal scenario.

Furthermore, the results provided by the tool would enable policy makers to detect hot spots in the recycling of materials in a given location in order to accelerate the implementation of recycling and practice of the circular economy. For example, by detecting those materials and products where the benefits of recycling remain lower than the impacts of landfill, the tool could help shift this situation towards a more circular scenario. Therefore, the tool, in addition to contributing to the implementation of LCA from the design stage, would contribute to improving circularity in the construction sector through the digitalization of the AECO sector via the BIM methodology.

2.3. Limitations and Future Work

In order to estimate the environmental impacts of CW management, certain simplifications have been considered. For example, the tool used generic instead of specific impact factors, since the case study is less than five kilometers (by road) from the reference building for which the generic impact factors were calculated and distances to infrastructure were taken into account (see Figure S1). To refine the results, it would be necessary to obtain specific impact factors or to use corrective factors depending on the distances. It is precisely this process that would limit the application of the method given its higher complexity. In addition, the three types of recyclable waste were considered to be clean waste. It was assumed that the system of selective collection and separation on site enables the collection of clean waste before it is mixed with other waste. In addition, the EPS (polystyrene) generated by the slab cassettes used the same impact factor as that of the plastic film (polyethylene). For each type of plastic, a specific impact factor should be used.

Most studies on LCA that are applied to waste evaluate waste management options once the waste is generated. Future approaches should explore the beneficial environmental effects of waste prevention scenarios. Moreover, the field of DW has been more widely addressed in the literature than that of CW. The estimation of DW, in which 100% of the building is waste, is more predictable than the estimation of CW, in which only a percentage of the materials supplied to the site becomes waste. In CW, packaging waste is also generated: a waste difficult to foresee during the design phase. However, in Spain, for example, construction work has incurred a higher incidence than has demolition work to date, and although the trend is moving towards refurbishment, tools that assess the environmental impact of new buildings are still needed.

In the field of civil engineering, there are advances in the application of other recycled materials in other construction elements, such as the use of recycled rubber in paving roads [68,69]. In this vein, the tool could be applied to other types of construction, such as roads, tunnels, and industrial facilities. To this end, it will be necessary to design new BIM objects related to the construction systems of these types of civil work, e.g., asphalt paving and drainage systems. These BIM objects should include information related to CW generation and the environmental impact of its management. In this way, the library of BIM objects could be enriched and completed over time with the incorporation of: (i) other construction typologies; (ii) other materials, including recycled and reused materials; (iii) data from other lesser-known phases, such as those of use and maintenance; and (iv) other socio-economic indicators and impact categories affected by CW management, such as the economic cost of its management.

Finally, since the tool relates design decisions (materials, construction techniques, etc.) to environmental data (recycling rates, types and quantities of recyclable waste, environmental impact of waste management, emissions, energy consumption, carbon footprint, etc.), it could be employed to compare and simulate alternative design decisions in real time. For example, it could be applied in order to investigate the effects of prefabrication (compared to on-site construction) on both the recycling rate of waste in buildings and the effects on the decarbonization of the waste management system. Albeit most effective during the early design phases to simulate alternative design solutions, the tool could also be applied in the detailed design phase to quantify and report final impacts. In this vein, further applications of the tool to other building typologies, building systems, and building phases will be necessary in order to verify the usefulness of its implementation, including application in other geographical contexts.

3. Materials and Methods

3.1. Basic Assumptions

This study focuses on construction waste (CW) generated on new construction sites. Waste generated in other phases of the building's life cycle, such as the use phase and the demolition, lies outside the scope of this work. The functional unit is defined as "the management of 1 ton of the 'i' fraction of CW potentially producible at a given construction site" [13]. Two alternative management scenarios are considered—the recycling scenario and the disposal scenario—the definitions of which are in accordance with the European Waste Framework Directive [7]:

i. 'Recycling' means any recovery operation by which waste materials are reprocessed into products, materials, or substances whether for the original or other purposes. This includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. This is used in the recycling scenario.
ii. 'Disposal' (also called landfill, elimination, or dumping in the literature) refers to any operation which is not recovery even where the operation has, as a secondary consequence, the reclamation of substances or energy. This is used in the disposal scenario.

According to the waste management hierarchy [7], recycling should be used when the waste cannot be prevented or prepared for reuse and disposal should be used as a last resort when the waste cannot be recovered. This study focuses on CW that can potentially be recycled, hereinafter referred to as recyclable CW. Other management options, such as incineration or preparation for reuse lie beyond the scope of this study.

3.2. Steps

Figure 5 shows the five steps of the method and the variables obtained in each step.

Steps 1 to 4 develop the CW-LCA-BIM tool and Step 5 applies the tool to a case study. In order for the waste generated during the construction of buildings to be recycled, it is necessary to foresee the types and quantities of recyclable CW expected to be generated. This information enables the planning for its separation and selective removal to the corresponding waste treatment infrastructures during the construction phase of the building. Step 1 therefore consists of estimating the types (i) and quantities (Q) of recyclable CW during design by means of a BIM tool for CW quantification [46]. Each type of recyclable CW is considered as either recycled, in the recycling scenario, or deposited, in the disposal scenario, according to the existing infrastructures in the context of the construction site, called the waste management system. The method is based on impact factors (Fi), which depend on the location of this infrastructure in relation to the construction site. These factors are considered in Step 2 and can be obtained from an LCA model to evaluate waste prevention and non-prevention scenarios [47]. Note that the tool will include non-prevention scenarios (recycling and disposal). Subsequently, in Step 3, the environmental impacts (I) of each option can be quantified once the Q, and F_i factors are ascertained. The factors, variables, and mathematical formulations of these three steps are integrated into BIM software in Step 4, so that the calculation can be included in the design process and can be performed effortlessly. Finally, in Step 5, the CW-LCA-BIM tool is applied to a case study to demonstrate its usefulness.

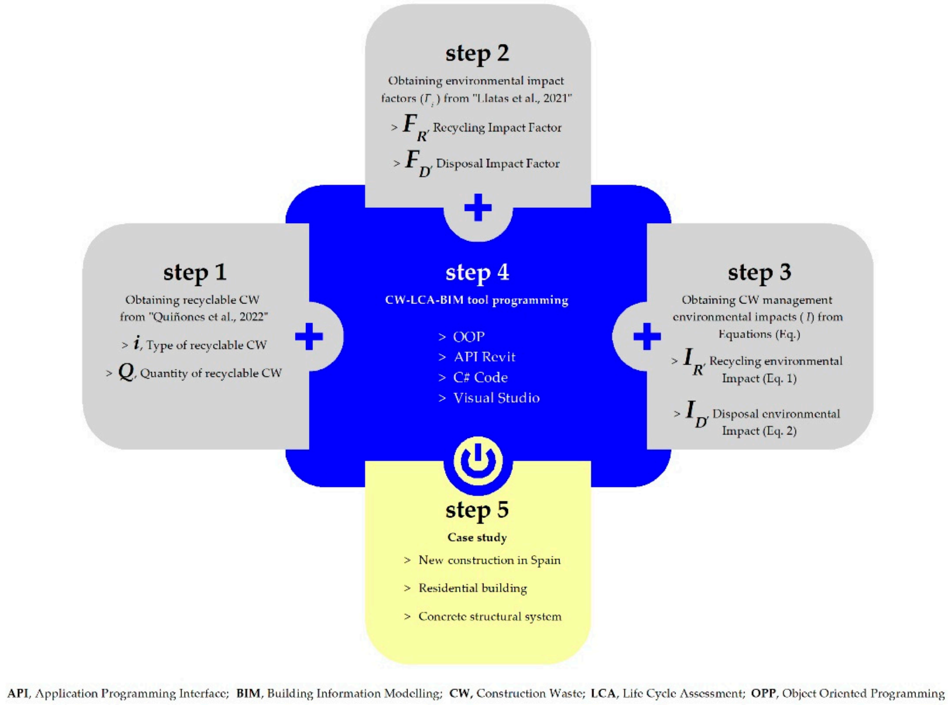


Figure 5. Flowchart of the developed methodology. Recyclable CW from "Quiñones et al., 2022" [46]. Environmental impact factors from "Llatas et. al., 2021" [47].

3.2.1. Step 1: Quantifying the Types and Quantities of Recyclable CW in BIM

Several studies have shown the relationship between the design that covers the construction solutions, materials, and technologies used in buildings and the types and quantities of waste generated [70–72]. The types and quantities of waste generated can be ascertained from the building design: manually, using waste quantification models [51,73]; semi-automatically, in various BIM platforms (Allplan 2021.02, Nemetschek AG, Munich, Germany; Archicad 24, Graphisoft, Nemetschek AG, Munich, Germany; Audodesk Revit 21.1.1, Autodesk Inc., San Rafael, California, USA) [22,25,74]; or automatically, such as in BIM (Revit) [23,24,46]. Specifically, certain studies [46,74] integrated the quantification model [51] into BIM, so that automated CDW quantification can be carried out by the designer without effort nor time consumption.

The proposed CW-LCA-BIM tool is based on the BIM tool for CW quantification [46] in such a way that once the building systems are modelled in BIM with a minimum LOD of 200, the designer automatically attains: (i) the types and quantities of CW listed according to the European List of Waste (LoW) [48]; (ii) the source of the CW; (iii) the CW generated by each building element or system; (iv) hazardous and non-hazardous CW; and (v) CW originated by breakage and losses (remains), in addition to packaging waste and soils.

The CW is then classified into four groups depending on its management: (i) hazardous CW, which must not be mixed with other waste; (ii) reusable CW, which should be prepared for reuse; (iii) recyclable CW, which should be recycled if it is technically and economically feasible on site; and (iv) non-recyclable CW due to the technical and economic unfeasibility of recovery. Thus, the variables "i" (types of recyclable CW) and "Q" (quantity of recyclable CW) can be ascertained. Moreover, detailed information on the CW can be obtained per building element (e.g., beams, pillars, walls), per building system (e.g., structure, masonry, roofing), and for the entire building through the total addition of the CW of these building elements. Since the quantities of CW are obtained by volume (m^3), and the impact factors obtained in Step 2 are applied to the mass of CW (t), the CW densities used in Spain [49] are applied to ascertain the quantity of CW by mass (t). This information can be displayed through Bar Graphs for better visualization. This step was integrated in Step 4 into BIM (see Section 3.2.4).

3.2.2. Step 2: Implementing the LCA-Based Environmental Impact Factors in BIM

The environmental impact factors (F_i) can be obtained from an LCA-based model that allows for the evaluation scenarios of prevention versus those of non-prevention of CW [47]. The proposed CW-LCA-BIM tool focuses on the non-prevention scenarios of recycling and disposal. The four phases of the LCA methodology [10,11] were followed to obtain the impact of managing 1 ton of each type of CW for each environmental impact category (GWP, PA, EP, etc.) using the CML 2000 [75], and the Cumulative Energy Demand (CED) methodologies. SimaPro software v.7.1, PRé Sustainability B.V. (Amersfoort Netherlands), was employed to quantify impact. Other methodological issues as well as assumptions were conducted in [13,47,61]. For example, the zero-burden assumption principle [76] was applied. Therefore, the system boundaries included downstream processes and omitted upstream loads since they are equal in both scenarios (recycling and disposal). The impact considered the main processes once the waste was generated: (i) waste collection; (ii) selective separation; (iii) transport to the treatment facility; and (iv) impact due to waste processing. In the case of recycling, the loads from the manufacture of natural materials that had been replaced by recycled materials were eliminated from the system. This makes the recycling option in general more beneficial since it removes burdens from the system.

The waste management system of a site, in which the infrastructure for managing each type of waste is located, plays a key role. It conditions the impacts, mainly due to waste transportation from the construction site to the waste treatment site. The impact factors were therefore obtained for an imaginary construction point located at the center of this system, called the Reference Building (RB). From the RB, the distances to each infrastructure were taken and generic impact factors were calculated in such a way that, for any construction site located within the scope of this system, these generic impact factors can be applied. This strategy simplifies the calculation, since the LCA is applied only once to obtain generic impact factors instead of obtaining specific impact factors for each construction site. Two impact factors are defined:

i. F_D is the final environmental impact produced by the disposal of 1 ton of each type of CW according to each impact category (AP, EP, GWP, etc.). This factor corresponds to $F_{\Omega D}$ Downstream Impact Factor of Disposal in [47];
ii. F_R is the final environmental impact produced by the recycling of 1 ton of each type of CW according to each impact category (AP, EP, GWP, etc.). This factor corresponds to $F_{\Omega R}$ Downstream Impact Factor of Recycling in [47].

These impact factors were quantified in the unit of measurement of each impact category indicator (e.g., kg CO_2eq in the case of GWP) and were included in the tool database in order to quantify impacts in the next step. They were calculated for the waste management system of Seville as analyzed in [13,47,61], where the case study building is located (see Figure S1), and are the factors that have been included in the CW-LCA-BIM tool. This step was integrated into BIM (see Section 3.2.4) in Step 4. Table 2 shows the generic impact factors considered for the recyclable CW in the case study. As noted, most of the recycling impact factors (F_R) are negative, which a priori points to a greater benefit.

3.2.3. Step 3: Quantifying the Environmental Impacts in BIM

Once the quantities (Q) of each type (i) of recyclable CW in tons and the impact factors (F_i) of 1 ton for each management option are ascertained, then the total impact (I) can be obtained using the following equations. Equation (1) obtains the impact of CW recycling

(I_R). Equation (2) obtains the impact of CW disposal (I_D). These equations have been derived from the Equations (1)–(4) conducted in [47].

$$\boldsymbol{I}_R^j = \sum_i^n \boldsymbol{Q}_i \times \boldsymbol{F_R}_i^j \quad (1)$$

$$\boldsymbol{I}_D^j = \sum_i^n \boldsymbol{Q}_i \times \boldsymbol{F_D}_i^j \quad (2)$$

where:
$\boldsymbol{I}_R^j$ is the total recycling impact of the environmental impact category "*j*";
$\boldsymbol{I}_D^j$ is the total disposal impact of the environmental impact category "*j*";
$\boldsymbol{Q}_i$ is the quantity in tons of the fraction "*i*" of recyclable CW generated on site;
$\boldsymbol{F_R}_i^j$ is the environmental impact of the category "*j*" of 1 ton of the recycled CW "*i*";
$\boldsymbol{F_D}_i^j$ is the environmental impact of the category "*j*" of 1 ton of the disposed CW "*i*".

Quantification can be carried out automatically from the Revit template. This step was integrated into BIM in Step 4 (see Section 3.2.4).

3.2.4. Step 4: Programming the CW-LCA-BIM Tool

A BIM design platform, Revit [77], was selected to implement the tool that uses the C# programming language with the Microsoft Visual Studio 2019 code editor, and the Classes and Methods available in the Revit Application Programming Interface (API) [52]. The API provides a set of tools, definitions, and protocols that allow new software to be developed and integrated into the Revit application, thereby extending its capabilities. Once the building systems have been modelled through the BIM-Objects and the CW is quantified in terms of building elements and coded according to the LoW [48] using the Add-in [45], the tool then operates as follows:

i. First, the designer classifies the building elements by grouping them according to their main function (e.g., walls, pillars, beams). This step can be carried out manually; however, by default, the CW-LCA-BIM tool classifies the building elements according to the *Base de Costes de la Construcción de Andalucía* (BCCA) [52]. This step enables the environmental impact of each group of building elements to be evaluated and compared;
ii. Second, the CW-LCA-BIM tool allows the designer to classify CW into 4 main groups according to their main management option: (i) hazardous waste (e.g., wood contaminated with release agents, paint cans, solvent residues); (ii) reusable waste with little or no treatment (e.g., wooden pallets, super-plus construction materials); (iii) recyclable waste (e.g., concrete/ceramic waste and those that can be assimilated to urban solid waste such as paper, cardboard, plastics, and metals); and (iv) non-recyclable waste (e.g., mixed waste). By default, the tool advises the designer of the most common option for each type of waste generated. This step enables the identification of recyclable waste;
iii. Third, once the types and quantities of recyclable waste have been identified, the tool, by default, evaluates their recycling versus their disposal. However, the designer could compare other scenarios by selecting only those types of waste that would be recycled.

Note that the basis of the tool is the BIM-Objects library, the main function of which is to store and manage the data of the building elements during design.

3.2.5. Step 5: Applying the Tool to a Case Study

The case study is a real 1638.65 m^2 multi-family housing building, called "La María", developed by a Public Company, the Municipal Housing Company in Seville (EMVISESA) [78] (see Figure 6). The structure consists of concrete pillar-and-beam frames and concrete waffle slabs. A concrete slab serves as foundation and there are concrete basement walls. The building is located within the area of the Seville waste management system analyzed in [47], as shown in Figure S1 (see supplementary data).

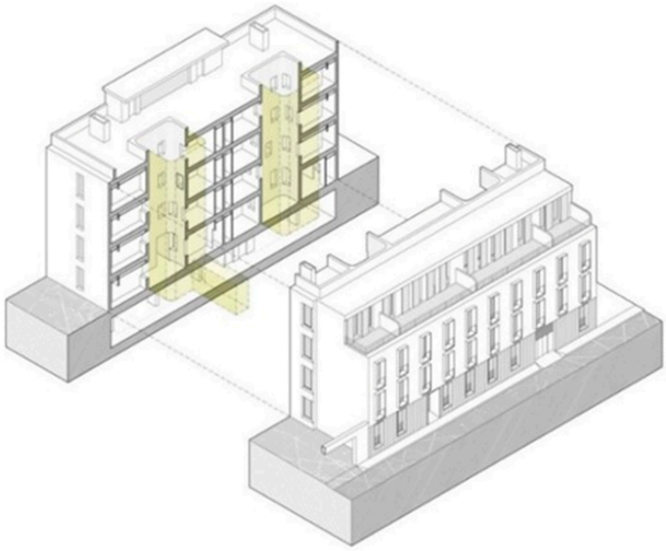


Figure 6. Case study: residential building "La María", Seville, Spain.

The selected building system is representative, since in Spain the construction of residential buildings is the main construction typology (60%) (see Table 3), and the reinforced concrete structure is the main structural typology (68%) used in buildings (see Table 4).

Table 3. Surface area in Spain per type of construction work carried out in 2019. Spanish Ministry of Development (2022) [15].

Type of Construction Work	Thousand m^2	Percentage
New building for residential use	15,614	60%
New building for non-residential use	6424	25%
Demolition work	2745	10%
Rehabilitation work	1325	5%

Table 4. Type of vertical structure in newly constructed buildings built in Spain in 2019. Spanish Ministry of Development (2022) [15].

Type of Vertical Structure	Number of Buildings	Percentage
Reinforced concrete	20,123	68%
Load-bearing walls	4275	14%
Metallic	3711	12%
Mixed and others	1776	6%

4. Conclusions

The transition to a circular and decarbonized construction model, with a special focus on embodied carbon, presents a major challenge. The role of designers is key and the implementation of BIM methodology in the AECO sector provides an opportunity to integrate LCA-based methods into professional practice to help improve the circularity and decarbonization of buildings. Therefore, this study presents the CW-LCA-BIM tool whose principal innovation is that it automates the quantification of the environmental impact of CW management scenarios within the Revit BIM modeler in real-time. The tool was applied during the design phase of a residential building structure, and has provided the following answers to the starting research questions:

(i) Although an LCA expert is required to develop the tool, it is possible to obtain the results during the design without an LCA expert and without time consumption, as RQ1 queried;
(ii) Four groups of CW were obtained: hazardous waste (16%), reusable waste (11%), non-recyclable waste (1%), and recyclable waste (71%);
(iii) The management of the following three types of recyclable waste was assessed: concrete (27.2 t), plastics (4.2 t), and steel (1.5 t);
(iv) Although recycling would be the best option for the entire structural system since it could prevent 14.6 t of emissions (1.4 times that of the disposal scenario) and could save 148.5 GJ of energy consumption (8.5 times that of the disposal scenario), recycling would not always be the most beneficial option with respect to CW disposal for all types of CW and categories, as queried by RQ2;
(v) The recycling scenario would be less beneficial for plastic in ODP, a relatively insignificant category, and for steel in HTP;
(vi) The environmental impact categories most influenced by CW recycling would be those related to the climate emergency, GWP, and energy consumption, in addition to HTP, with a greater influence on human health, as queried by RQ3;
(vii) RQ4 revealed that the CW management that would have the greatest impact would be that of plastic disposal (which emits 10.1 t and consumes 0.5 MJ) and concrete disposal (which emits 0.12 t and consumes 1 MJ), followed by steel disposal (which emits 0.03 t and consumes 0.2 MJ). RQ4 also revealed that the most beneficial CW management would be that of recycling plastic (which prevents 13.0 t of emissions and saves 122.6 GJ), followed by recycling steel (which prevents 1.5 t of emissions and saves 20.2 GJ) and, to a lesser extent, recycling concrete (which prevents 0.1 t of emissions and saves 5.67 GJ).
(viii) The building elements that would have the greatest impact on CW management would be the horizontal structural elements (floors and foundation slab), followed by the vertical structural elements (walls and pillars);
(ix) Finally, CW recycling would contribute towards decarbonizing the building by eliminating 5.1 t of CO_2 eq emissions from its embodied carbon.

The CW-LCA-BIM tool could help designers to report, quantify, compare, and simulate alternative design solutions in order to identify and select those with higher CW recycling rates and greater environmental benefits in their CW management. Designers could introduce improvements in their projects by exploring possible corrective measures based, for example, on the identification of the most suitable materials and construction techniques for waste recyclability, and on the analysis of its contribution to the decarbonization of the building. The results obtained could also help to plan control strategies for the optimization of CW management on site, such as the forecast of recycling, selective sorting, and appropriate treatment.

The tool is firmly aligned with EU strategies and policies, such as the Green Deal and the Circular Economy, thereby contributing to the transition towards circular and decarbonized construction.

Future studies should address more design tools, applications, case studies, and benchmark values, the results of which can be used by policy makers to explore material recycling hot spots.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling7060082/s1, Figure S1: Location of "La María" in the waste management system of the city of Seville.

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