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Life cycle assessment of a residential building with cross-laminated timber structure in Granada-Spain

Análisis del ciclo de vida de un edificio con estructura de madera contralaminada en Granada-España

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ABSTRACT

A residential building with cross-laminated timber structure in Granada (Spain) was analyzed using the life cycle assessment methodology, life cycle energy analysis and sensitivity analysis to changes in efficiency of operating energy, materials database, transport distances and different scenarios for C&DW. The environmental impacts of the materials and construction production and embedded energy were relatively significant. The global warming impact category was very low due to the CO2 sequestration of wooden materials. Sensitivity analysis revealed that the most significant reduction in environmental impact was achieved through improvements in energy efficiency, high uncertainty in the impacts of the environmental product declaration, the low effect of long-distance transport on the overall impact and the feasibility of the objective of recovery of the Waste Framework Directive by 2020 (above 70%).

Keywords: Life Cycle Assessment (LCA), wooden building, life cycle energy analysis, transport of construction materials, construction and demolition waste.

RESUMEN

Se ha estudiado un edificio residencial con estructura de madera laminada en Granada (España) con la metodología de análisis del ciclo de vida, análisis energético del ciclo de vida y análisis de sensibilidad a cambios en la eficiencia energética durante el uso, bases de datos, distancia del transporte y diferentes escenarios para los residuos. Los impactos ambientales de las etapas de producción de materiales y construcción, así como la energía embebida fueron relativamente significantes. El valor del calentamiento global ha sido muy bajo debido al secuestro de CO2 por la madera. El análisis de sensibilidad ha revelado que la mayor reducción se consigue con la mejora de la eficiencia energética, la alta incertidumbre en los impactos de las declaraciones ambientales de producto, el escaso efecto del transporte de larga distancia sobre los impactos totales y la viabilidad de conseguir el objetivo de valorización de la Directiva Marco para el horizonte 2020 (mayor del 70%).

Palabras clave: *Análisis del ciclo de vida (ACV), edificio de madera, análisis de la energía del ciclo de vida, transporte de materiales de construcción, residuos de construcción y demolición.*

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1. INTRODUCTION

Nowadays, climate change mitigation is considered a priority topic in many research studies being conducted around the world. Similarly, the environmental impacts produced by our daily activities are constantly being assessed. In this area, the construction sector is one of the three fields of consumption responsible for 70-80% of the environmental impacts of private consumption, along with food and drink, and private transportation (1).

In the last few years, several studies have assessed the environmental impacts of buildings using the Life Cycle Assessment (LCA) methodology. LCA is a widely accepted technique for evaluating environmental impact quantitatively. However, unfortunately, the high variability in building construction and the different methods used for the LCA make it more difficult its application to entire buildings. The complexity of the analysis lies in the absence of truly comparable data about buildings, as there are many factors which directly influence the results of the impact, such as the geographical location, the building size, the scope of the study performed, the phases of the life cycle covered, the calculation methodology used, the way to evaluate the transport of the materials or the maintenance of the building, the years that we consider regarding the useful life of the building in the use phase, etc. (2,3).

This methodology is applied to the construction industry in two different ways, one for specific building materials and component combinations as in (4), and the other for individual buildings, reviewed by (2,5,6,7,8,9,10,11,12). Some of these studies focus specifically on life cycle energy analysis (LCEA), reviewed by (9,13), or carbon footprint, without taking into account other environmental aspects.

Most published LCA studies of timber constructions have been undertaken in developed countries and in colder regions. Consequently, heating has been the main source of energy demand in those studies. On the other hand, design priorities are different for temperate climates, as cooling and ventilation are also important (14).

Some LCA of residential buildings have been published in Southern Europe, with moderate climates and mainly with masonry construction: Peuportier (15) compared three types of house with different specifications located in France; Mercader (16) estimated the embodied energy of 10 subsidized buildings in Seville (Spain) and also the embodied CO2 (16,17); González and García Navarro (18) estimated CO2 emissions based on the embodied energy for three dwellings in central Spain; Ortiz et al. (19) applied LCA to a typical Spanish Mediterranean house located in Barcelona; Rosselló-Batlle et al. (20) assessed the variations in the embodied energy and thermal energy demand of a single-family house in Spain, taking into account the change of building typology and a series of façades, roofing systems and window frames; Monteiro and Freire (21) considered a single-family house in Portugal with seven alternative exterior wall types; Bastos et al. (5) presented a life-cycle energy and Greenhouse Gas analysis of three representative residential building types in Lisbon (Portugal); Gaspar and Santos (14) performed a life cycle energy analysis for intervention on an old detached house in Portugal; Stazi et al. (22) assessed three types of energy-efficient envelopes and their effect on energy consumption, comfort level and environmental sustainability in a Mediterranean area of Italy; and Lolli et al. (23) compared the sustainability of the design and construction process, in terms of environmental impacts, of a single-family house built with natural materials (wood and straw infill) in Rome and a corresponding virtual one built with concrete, bricks and polystyrene.

Special mention should be made of the extensive research on LCA of residential buildings carried out by the Joint Research Center (JRC) involving the analysis of the most representative buildings for the UE-25 (1). The results showed that "significant environmental improvements can be expected only when the substitution leads to the use of wood products instead of more conventional products (concrete, reinforced concrete, sand-lime and bricks)". This conclusion is in agreement with several authors about the use of wood construction material in colder regions which will, in general, result in lower energy and CO2 balances from cradle to grave than when concrete is used, although the precise values of the energy and CO2 balances of building materials depend upon many factors (24,25,26,27,28,29,30). However, this conclusion is nuanced by (31), who found that wooden frames cause lower CO2 emissions given the prevailing energy system.

In addition to the environmental impacts of wooden buildings in a temperate climate, where heating requirements are lower and cooling is important, some other gaps require attention like the potential benefits in terms of the potentially harmful effect of transporting wood panels from a long distance. Other interesting concern is the feasibility of accomplishing the valorization objectives of the Waste Framework Directive (WFD, Directive 2008/98/EC). The target of the WFD is to achieve 70% (by weight) of construction and demolition waste (C&DW) by 2020 for preparation for re-use, recycling and other material recovery, including backfilling operations using non-hazardous C&DW to substitute other materials. It should be noted that the recycling rate of C&DW in Europe shows significant variations among countries. The specific situation of C&DW in Spain shows that important amounts of C&DW are generated annually, but the recycling rate is much lower than in other European countries (32,33,34).

In order to contribute to the above concerns, a comprehensive LCA of a newly constructed wooden building in Granada (Southern Spain) was performed, including LCEA and analyses of sensitivity to changes in efficiency of operating energy, materials inventory, changes in transport distances and different end-of-life (EOL) scenarios.

2. MATERIALS AND METHOD

Given the lack of environmental data of wooden constructive systems in temperate climates, it was necessary to undertake an accurate study. The LCA methodology was used to calculate the environmental impacts of a wooden building located in Spain. LCA was performed in accordance with the guidelines provided by ISO 14040:2006 (35) and ISO 14044:2006 (36). The software application SimaPro® ver. 8.0.3.14 was used.

2.1. Description of the wooden dwelling

The building studied is a multi-family dwelling between party walls. It is in the old quarter of the city of Granada and has a main façade that faces southeast, but with relatively few hours of sun due to the size of the street. The plot area is 147 m2, but the building covers 112.86 m2 and the rest is organized in two inner patios. The plot geometry and the construction system of the adjacent buildings party walls made it necessary to look for a structural system that allows the maximum useful area. In addition, the poor quality of the land also required a lightweight structural system that made it possible to reduce the loads on the foundations. As a result, a wooden structure was used to construct this building.

It is a four-story building (Fig. 1) consisting of the ground floor for access and commercial areas, and three floors with two apartments per level. The topmost "roof" floor has only the stairs for access and the rest of the space is organized into two terraces used to house the air conditioning facilities. The total area of the building is 370.91 m2 of useful area and 450.78 m2 of built-up area. The energy consumption calculation does not consider the area of the commercial spaces.

To solve the problems of the foundations, the building has a reinforced concrete slab supported by concrete wells, with an average depth of between 3 and 3.5 m in order to reach the resistant substrate. This kind of foundation is unconventional and mainly due to the poor quality of the land on which the building rests. One of the characteristics of a wooden building is its low weight with respect to concrete ones, and thus it is unusual to use this kind of foundations for this building. For this reason, and in order to have more standardized data without excessively distorting the volumetric data of the concrete in further comparisons with other buildings, we have corrected the data for the LCA calculation. Keeping the floor dimensions of the wells, approx. 1.5 x 1.5 m, we have considered one quarter of the depth (approx. 0.9 m) in order to have a more standardized solution. Regarding the foundations, we also need to highlight the fact that, because of the poor quality of the land, it was necessary to carry out land improvement with compacted layers of graded aggregate. In consequence, the amount of aggregate employed is higher than usual in this building.

The differentiating factor of this building is the use of a prefabricated cross-laminated timber structure instead of what is a more conventional solution in Spain, namely a reinforced concrete structure with brick walls, or the traditional solution with load-bearing walls made of solid brick or natural stone. Interior and exterior walls, roofing, stairs and also floor slabs form part of the structure and are made of wood in this building. This structure is reinforced both inside and outside for the adequate thermal and acoustic comfort of the building. Therefore, all the building above-ground is made with dry construction systems, and reinforced concrete is only used for the foundations.

The main constructive elements of the building taken into account were:

- Roofs (around 110 m2): both, the flat and the sloping roofs, are composed mainly of a solid timber floor with waterproofing and insulation (rock wool, 80 mm).
- Main façade (around 225 m2): solid timber wall with external insulation (extruded polystyrene, 100 mm), internal insulation (rock wool, 50 mm) and reinforcement with prefabricated plasterboard.
- Floors (around 255 m2): solid timber floor with insulation underneath.
- Patio façade (around 150 m2): solid timber wall with external insulation (extruded polystyrene, 100 mm) and internal prefabricated plasterboard.
- Party wall between buildings (around 265 m2): solid timber wall with internal rock wool insulation (50 mm) and a thermo-reflective aluminum insulation (4 mm). Also internal prefabricated plasterboard.
- Surface finishing materials. These materials and their transport are included for the full building calculation.

2.2. Goal and scope definition

The goal of this LCA is to assess the environmental issues of timber in a residential building. For this reason, the modules A (materials production and constructions, MPC) and C (End-of-life) of the standard EN 15978 (37) were included in this LCA. Additionally, the module HVAC energy (B6) was also included. Other processes like maintenance, repair, replacement and refurbishment work (B1-5) were not included because no differences in surface finishing materials were expected with respect to masonry construction. For the same reason, water during the use phase was not included (B7).

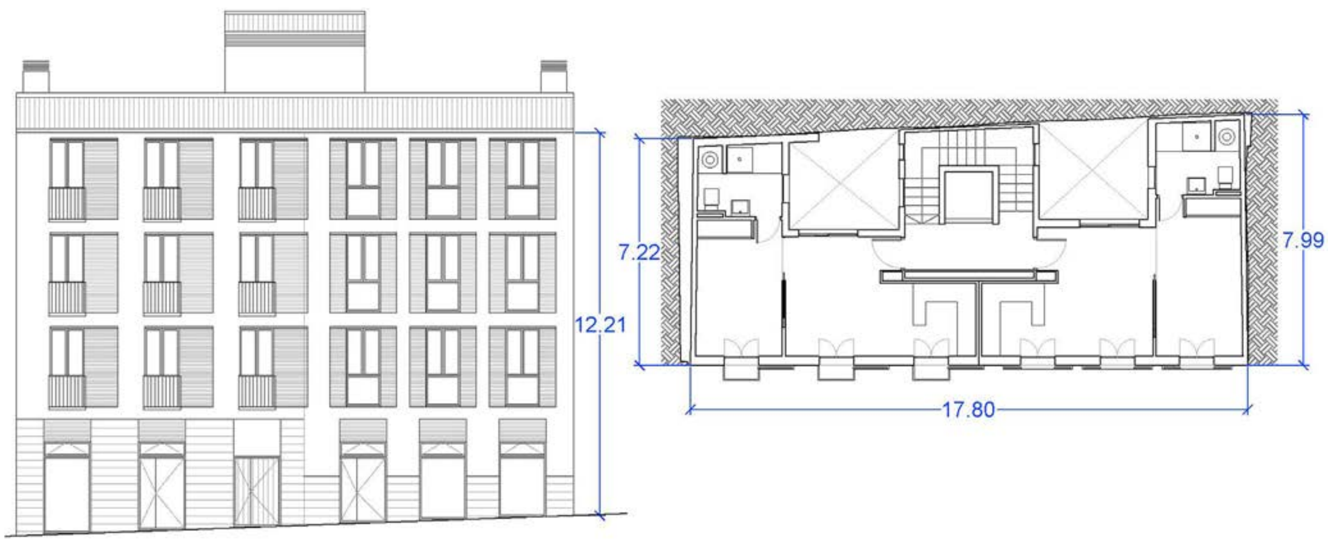

Figure 1. Main façade and layout.

The functional unit selected was one square meter of gross floor area (GFA) considering 50 years of service. This period of service is stablished in the Environmental Product Declaration of the cross-laminated timber panels used to build the structure, according to the requirements of the European technical approval ETA-06/0138.

All impact categories included in EN15978 were selected: Global warming (GWP) [Kg CO2 eq], Depletion of the stratospheric ozone layer (ODP) [CFC-11 eq], Acidification (AP) [Kg SO2 eq], Eutrophication (EP) [Kg PO4 eq], Formation of tropospheric ozone photochemical oxidants (POCP) [Kg C2H4 eq], Abiotic resource depletion for elements (ADPE) [Kg Sb eq] and Abiotic resource potential of fossil fuels (ADPF) [MJ]. Evaluation was performed with the CML-IA baseline v.3.02 method (38). Furthermore, the cumulative energy demand (CED) v1.09 was added (39), as this is of special interest for life cycle energy analysis.

2.3. Life cycle inventory

The Executive Architecture Project of the building was the basis on which to collect the necessary data for the inventory. More than 45 materials were considered and subsequently grouped in 10 categories with the next percentage of weight: concrete and mortar, 45.82%; aggregates and natural stone, 22.15%; wood, 15.82%; gypsum plasterboard, 7.31%; steel, 2.45%; ceramics, 2.43%; insulation, 2.06%; glazing, 0.98%; aluminum, 0.53% and plastics, 0.46%. The total weight was 437.44 tons (0.97 t/m2).

As expected, weight per square meter was lower for wood construction than in masonry construction (14,17), with values of 1.50 t/m2 and 2.18 t/m2, respectively.

The transport was also considered as a separate life cycle stage including the impact for each material according to the type of truck and the distance traveled; all these data were extracted from the Executive Architecture Project.

The attributional Ecoinvent 3.0 database (40) was used to work out the impact categories of both, inputs and outputs. Exceptionally, in the cases of the rock wool insulation, the aluminum profiles for windows and the structural wood panels, it was possible to obtain the data from their Environmental Product Declarations (EPD) (41,42,43), considering for them the same system boundaries used in the life cycle inventory from the Ecoinvent database (from cradle to gate).

During the construction stage of the building, which is completely framed in wood, 1878 kWh of electricity, 9000 liters of diesel and 10 m3 of water were consumed.

Amounts of construction waste were estimated based on statistical data, except waste wood. It has to be noted that the dwelling was built with a non-conventional construction system, similar to a prefabricated construction system, because the structural timber panels came perfectly modulated and ready to be installed. For cross-laminated timber, a waste percent reduction was assumed to be about 50% that of a conventional construction system, although the reduction could be higher (44).

Thermal energy consumption during the use phase was collected from the Executive Architecture Project. In accordance with Spanish legislation, the Calener VyP software application was used to obtain the energy demand data (45). Each apartment has a heating pump with COP (coefficient of performance) and EER (energy efficiency ratio) values of 2.4 and 1.81, respectively. Hot water is obtained with an electric heater.

Electric energy for cooking and lighting was obtained from statistical data for the Mediterranean region (46). The total amount of energy is shown in Table 1.

The data from "1 MJ Electricity, low voltage, production ES, at grid" of the Ecoinvent database were used with a carrier conversion factor of 3.35. All the energy during the use phase was expressed as primary energy.

Construction and demolition waste was supposed to be disposed of in an inert landfill, except hazardous waste, which was submitted to an authorized agent for treatment. Soils and rocks from excavation were reused as filling materials for other construction projects and only their transport impact was included. The average distance to the waste treatment and disposal facility was estimated to be 80 km.

Decomposition of wood products "was assumed to be insignificant, as the near absence of moisture and the absence of highly degradable waste (e.g., food waste) in C&DW landfills significantly limits the onset of anaerobic decay" (47).

Finally, it was assumed that the energy used for demolition of the case study building was 10 kWh/m2 (GFA) from diesel fuel (48).

2.4. Scenarios

Five scenarios were considered. The first scenario corresponded to the baseline values, Sc1, and the energy during the use stage considered was only for HVAC. The second scenario, Sc2, was an efficiency improvement in the HVAC system (a heating pump with ratios of 4.5 for COP and 4 for EER). Materials with impact categories provided by their EDP were changed in the scenario Sc3 by life cycle inventories (LCI) from Ecoinvent database ("Rock wool packed at plant/CH" for insulation material and "Plywood outdoor use at plant/RER" for cross laminated timber). The fourth scenario, Sc4, was related to reducing long distances. Finally, the fifth one included a potential end-of-life based on the WFD.

3. RESULTS AND DISCUSSION

3.1. Total life cycle assessment

Impacts from cradle to grave are shown in Fig. 2. Impacts of the materials production and construction stage are divided into materials production, construction, transport to construction and construction waste. Total values for each impact category are expressed as baseline in Table 2 (Scenario Sc1).

In Fig. 2, end-of-life impacts were lower than 6% in all impact categories. The materials and construction stage was of greater relevance, with a value of more than 28%. The lowest value for this stage was in the GWP impact category. It has to be noted that the negative values of GWP during this stage were due to the CO2 sequestration of the wooden materials,

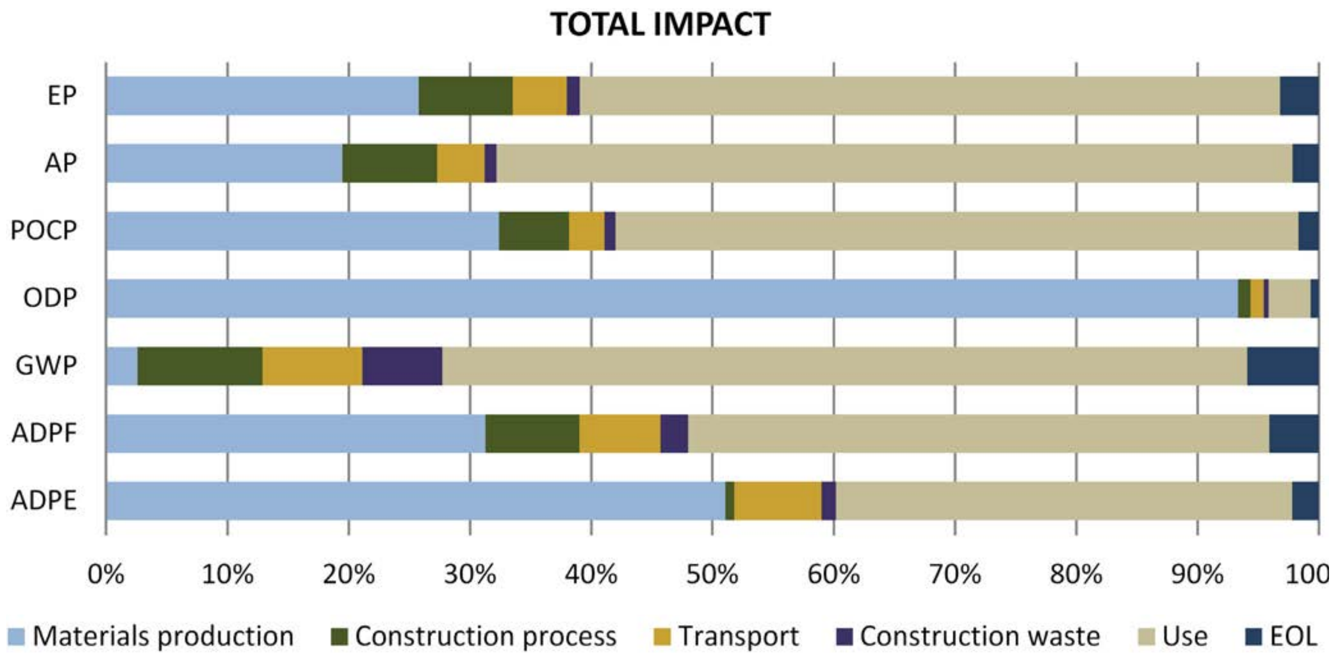

Figure 2. Life cycle impacts of the wooden building. Scenario Sc1 or baseline.

also portrayed in Fig. 3. The Environmental Product Declaration of the wooden panels considers an atmospheric carbon sequestration of 1.85 kg CO_2 for each kg of dried wood.

A point to consider was the impact produced by the transport of materials and the construction process. In the case of the AP impact category, the two accounted for 12% and 24% of the MPC stage, respectively. Specifically, wood transport represents 83% of the impacts caused by all transport of materials.

Fig. 3 shows the impact of materials production. Aluminum and steel were two of the materials that cause relatively severe impacts, although their importance by weight is limited. Aluminum is only 0.53% by weight, yet it is responsible for 29% of the acidification impact, 25% of the eutrophication

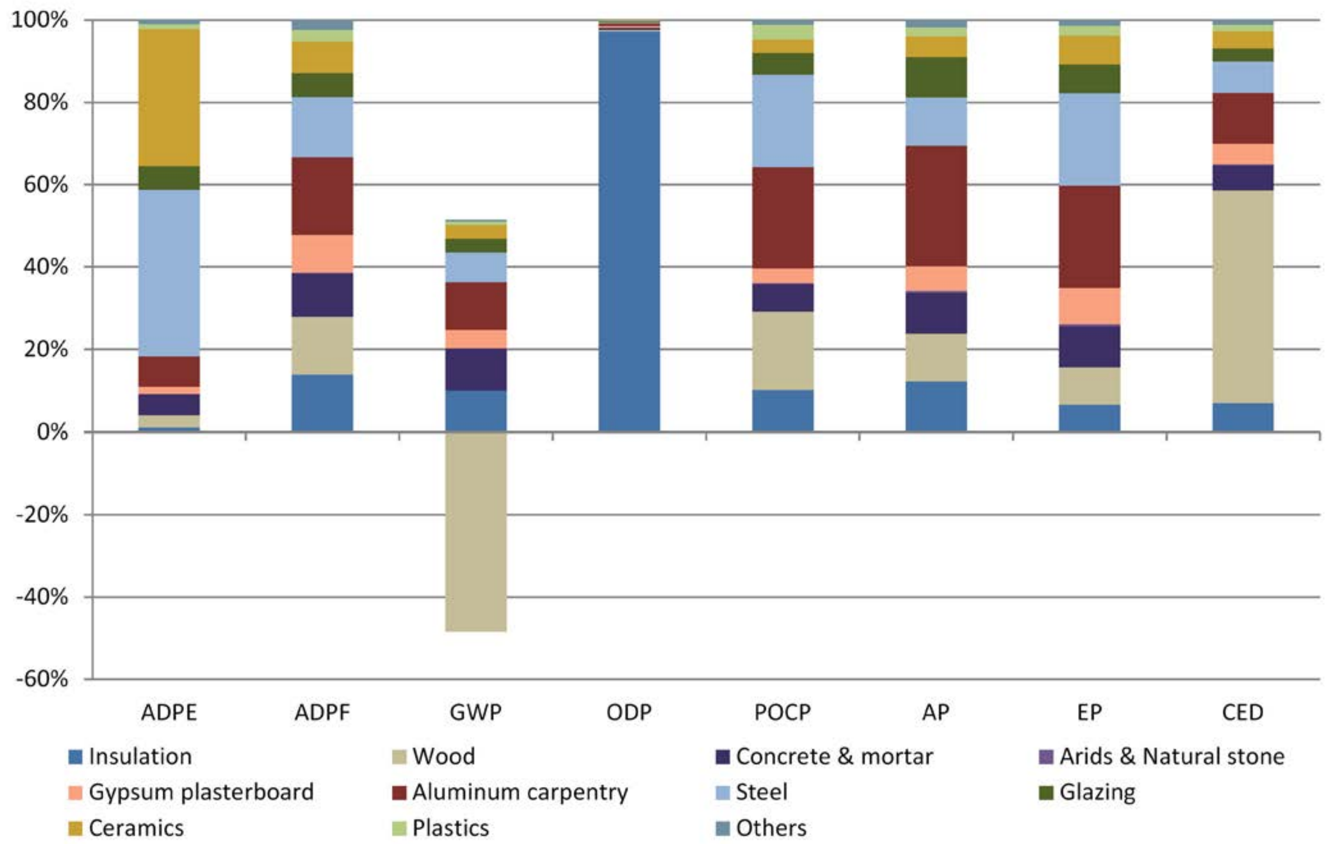

Figure 3. Category impacts of the materials production phase.

impact and 25% of the photochemical creation impact. Expanded polystyrene, included in Fig. 3 as an insulation material, was almost solely responsible for the impact in the ODP category.

3.2. Life cycle energy analysis

The life cycle energy of the building is the sum of all the energies incurred in its life cycle; embodied energy, operating energy and end-of-life energy. "Embodied energy is the energy utilized during the manufacturing phase of the building. It is the energy content of all materials used in the building and technical installations, and the energy incurred at the time of erection/construction and renovation of the building. The energy content of materials refers to energy used to acquire raw materials, and in manufacture and transport to the building site" (9). The detailed life cycle energy analysis is included in Table 1.

In conventional buildings, the average energy consumption depends on the operating (80–90%) and the embodied energies (10–20%), whereas demolition and other process energy represents a negligible or small share (13). The normalized life cycle energy use of conventional residential buildings falls within the range of 540–1440 kWh/m2 per year (9). Embodied energy, detailed in Table 1, is relatively higher (37%) and the total life cycle energy is lower than the values reported as average in the literature.

Table 1. Life Cycle Energy Analysis for the wooden building (MJ/m2) during 50 years of life.

Stage	Process	Primary energy (MJ/m2)	
Embodied energy	Materials production without feedstock	5306	
	Feedstock energy	2986	
	Transport materials	853	
	Construction process	960	
	Waste management	286	
			10391
Operating	HVAC	9172	
	Hot water	4198	
	Cooking	1758	
	Lighting	1707	
			16829
End-of-life energy	Waste management		508
Total (MJ/m2)			27728
Total (MJ/m2 per year)			554.6
Total with only HVAC in use (MJ/m2)			20071

This fact is due to the higher values of the materials energy. CED in Fig. 3 shows the embodied energy without considering transport, construction process or construction waste. In this case, embodied energy includes feedstock energy, which is not always included as embodied energy in the literature (13). Feedstock energy is significant for wood and plastic materials, but especially for wood in this building, which accounted for 52% of the materials energy if feedstock was included (see Fig. 3) or 26% if feedstock was not included.

The first conclusion from Table 1 was the relatively high value of the embodied energy with respect to the total life cycle energy and even more with regard to the HVAC energy (13,31). It has to be noted that cooling and ventilation were included in HVAC energy. On the other hand, EOL energy was almost insignificant, 2%.

3.3. Sensitivity analysis

Changes in transport and EOL scenario were analyzed together with the environmental aspect most meaning (HVAC energy) and also with changes in the database of materials with potentially high uncertainty (4,49). The results are shown in Table 2. The greatest improvement was clearly obtained with scenario Sc2. This result is in good agreement with the literature (9,13). The greatest worsening corresponded to the replacement of the EDP data for the structural wood panels with those from the Ecoinvent database (environmental changes of the rock wool were insignificant, lower than 0.6%). In this scenario, the only impact category improved was GWP. Therefore, if the LCI from Ecoinvent were considered, the embodied energy would be higher than operation energy. Variability could be linked to different manufacturers, production processes, recycled content of the materials, but also to database assumptions (49).

During the life cycle inventory and for each material input, the distance from its manufacturing supplier to Granada was estimated. The largest distance was for structural wood panels, which came from Austria (2400 km), due to the lack of culture about the use and production of cross-laminated timber in Southern Spain. All the loads and transport specifications were defined in the Executive Architecture Project and, in the same way, three trucks with different capacities (>32 t, 16-32 t, 3.5-16 t) were selected from Ecoinvent 3.0.

In order to estimate the potential negative effect of long-distance transport of wood panels, a sensitivity analysis was performed supposing wood panels could be obtained from potential local suppliers (located at 80 km). The same criterion was applied to all other materials with traveling distances higher than 500 km (plasterboard system and waterproofing

Table 2. Sensitivity analysis. Scenarios Sc2-5 are referenced respect Sc1 or baseline. Values of baseline expressed by m2 of gross floor area.

		ADPE kg Sbeq	ADPF MJ	GWP Kg CO2eq	ODP Kg CFC-11eq	POCP Kg C2H4eq	AP Kg SO2eq	EP Kg PO4eq	CED MJ
Sc1	Baseline	0.00190	11829	652	0.00079	0.29	6.72	1.57	20071
Sc2	Improvement by energy use	18.0%	22.9%	31.7%	1.7%	26.9%	31.4%	27.6%	21.8%
Sc3	Change in LCI	−27.7%	−30.8%	26.2%	−2.5%	−22.2%	−14.1%	−28.3%	−39.3%
Sc4	Improvement by local transport	6.2%	5.8%	7.1%	0.9%	2.5%	3.4%	3.9%	3.7%
Sc5	Improvement by disposal > 70% valorization	2.3%	8.0%	-33.6%	0.6%	15.6%	4.8%	9.3%	5.0%

materials). This change reduced the amount of transport by 88% (expressed in t.km). Environmental impacts were very slightly reduced, and the highest reduction (7.1%) was in the GWP impact category as shown in Table 2.

Valorization rate for Spain is not clear due to the high percentage of uncontrolled C&DW, not included in the official statistics (50), although much lower than WFD target. Some values reported in the literature are: 14% in 2009 (33), 38.9% in the period 2011-2015 (51). Therefore, an initial scenario (Sc1) was supposed as being one in which all the C&D debris was disposed of in a landfill with the exception of hazardous waste, which was treated by an authorized agent.

Scenario Sc5 was defined with the aim of achieving a minimum target of 70% (by weight) of C&DW. The EOL impacts of Sc1 and Sc5 are shown in Fig. 4. In Sc5 a consequential approach was followed. The choice of methodological approach (attributional or consequential) has a strong influence on the uncertainties of the EOL of construction materials (52). "The consequential approach is present when substitution is applied to avoid allocation in the disposal stage. This means that by-products of the disposal process are assumed to replace a product manufactured by alternative means, and that environmental impacts thereby avoided are credited to the system under study. Instead, the attributional approach is present when the cut-off method is applied to allocate the environmental impacts to either construction or the by-products of the disposal process, which means that only impacts directly caused by a product are allocated to that product".

One potential valorization option for each C&DW fraction (according to their LER Code) was selected from the literature in Sc5 (33,53,54) as shown in the column "Avoided product" of Table 3 and explained below. These avoided products were the ones substituted with the disposal process.

Potential valorization rates were obtained mainly from (33). Fractions of non-hazardous waste that were not valorized were landfilled and hazardous waste was incinerated. Energy for waste processing to facilitate recuperation or recycling of each fraction was taken from (55).

Recycling concrete waste has a good application in order to produce suitable aggregates which, having been conveniently treated in the recycling facility, can be of great advantage by decreasing the use of virgin raw aggregate and by reducing the volume of this waste requiring disposal at landfills (32). The recycled product obtained is a mixture of coarse aggregate (65–80%) and fine aggregate. The grain structure of the recycled coarse aggregate could be appropriate for all concrete applications, whereas using recycled fine aggregate for concrete will probably represent an increment in water consumption, and simultaneously it will reveal a reduction in mechanical resistance and in workability. Consequently, using sizes smaller than 4 mm is not suitable to produce new concrete. For this reason, in Scenario Sc5 a potential valorization rate of 75%, included within the range of coarse aggregate, was selected.

The potential contamination of wood waste with hazardous substances is a crucial point which establish its suitability for recycling or for material recovery, or if it must to be reduced to ashes in specially designed plants. If no hazardous substances are present, C&D wood waste can be processed into high added value products such as medium density particle boards, fiberboards or even wood-plastic composites with a high share of recycled materials. This is by far the main application for recycled wood (33). In accordance with the EPD of the structural timber used in this building, no hazardous substances are present and this material was supposed to be recovered to manufacture particle boards with a conservative valorization rate of 0.8. As shown in Fig. 4, the GWP benefits of recycling wood products were limited due to the already low greenhouse footprint of wood products production. Similarly, (58) analyzed the use of wood as nonwood substitutes and wood-wood substitution concluded that main savings were achieved through the replacement of other materials and the energy production in the end, but not with a cascade-like use of wood.

Metal is by far the most recyclable and profitable material due to the fact that there is a very mature market for metal recycling around the world. A recycling rate of 0.8 was assumed and the avoided product was pig iron (54).

Table 3. Characteristics of Scenario Sc5 (Scenario 5: Fulfillment of Waste Directive 2020).

LER CODE	Waste fraction	Amount	Valorization rate	Avoided product
17 01	Concrete, bricks, tiles and ceramics	307935	0.75	Aggregates for road construction or backfilling (33)
17 02 01	Wood	69120	0.8	Wood fiber
17 02 02	Glass	4278	0.8	Glass raw materials and melting energy (56)
17 02 03	Plastic	2136	0.3	PVC
17 03	Bituminous mixtures	949	0	
17 04	Metals	15821	0.8	Pig iron (54)
17 05	Soil and stones		0.7	
17 06	Insulation	3150	0.3	Fiber for new ceiling tiles (57)
17 08	Gypsum-based construction material	31958	0.3	Gypsum Stone (33)
17 09 03*	Other containing hazardous waste	796	0	
17 09 04	Other non-hazardous waste		0.3	Aggregates for backfilling
	Total	436142		
	Total non-hazardous	434397	0.72	

"Gypsum is a completely and endlessly recyclable material that is able to close the material loop. Unfortunately, a large proportion of gypsum waste, including building plaster, gypsum blocks and plasterboard waste, is currently being landfilled worldwide. Following the need to reduce the volume of C&DW sent to landfill and to increase the efficiency of using resources, the use of recycled gypsum is expected to grow in the coming years" (59). When the collection gypsum products comes from demolition or refurbishment projects, they may be contaminated with other materials such as screws, paper, wood, paint and isolating materials among others, which might signify recycling difficult. For this reason, the valorization rate selected was only 0.3 and it was assumed that gypsum stone was avoided.

Mineral wool waste is currently recycled by processes including reuse in ceramics, cement or fiber-based composites, tiles, and soilless cultures. "Mineral wool isolation materials recovered from moisture-damaged buildings may contain actinobacteria and fungi. On the other hand, mineral wool waste reveals similar properties to newly manufactured mineral wood when it is recovered from constructions without moisture damage. Some hazardous substance categorization systems classify mineral wool waste as a potentially carcinogenic substance if the soluble component index is above 18% and the diameter of the fibers is <6 μm. Nevertheless, the risk of health hazards from mineral wool fibers is very low" (57). Mineral wool was supposed to be recovered as fiber for ceiling tiles with a valorization rate of 0.3.

Recycling plastic is difficult if the waste is mixed with other plastics or contaminants. The possibility of reaching a high level of recycling plastic is restricted because of the degradation in properties of old plastic, henceforth virgin plastic must be added in the process. In Scenario Sc5, it was assumed that 30% of plastic was recycled and avoided raw PVC was assumed due this being the most plentiful plastic in the building assessed.

Glass cullet from C&DW could be a feedstock in glass production instead of conventional raw materials. In Scenario Sc5, avoided products were estimated from the ratios of (56): the potential energy saving considered was 1.5 MJ/ kg of cullet added. It was assumed that the fuel saved was natural gas. "Up to 20% of the volume of the commodities for primary glass manufacture was lost as gases during melting, mainly as CO_2 from decomposition of carbonates". Therefore, 1.2 ton of primary feedstock (composed of sand, soda and limestone) was replaced, and emission of 0.2 ton CO_2 was avoided when 1 ton of cullet was added to production.

Table 3 shows that the valorization objective of the WFD by the 2020 horizon is feasible. Moreover, Vefago & Avellaneda (60) concluded that wooden structures have a higher index of deconstruction recyclability than steel and concrete structures.

Scenario Sc5 clearly improved the environmental impact in all impact categories with respect to Scenario 1 (Table 2) except in GWP, because the manufacturing process required recovering wood as fiber increases CO_2 emissions from electricity and fuel consumption and avoids the use of raw wood, which could sequestrate more CO_2. This result is in agreement with the conclusion reached by (47).

Improvements in the POCP and EP impact categories were significant, with total reductions of 15.6% and 9.3% respectively, mainly produced by recycling metals. Fig. 4 clearly shows the beneficial effect of recycling metals, with negative values in all impact categories. Furthermore, the environmental impacts of concrete and plastics were also reduced in Scenario Sc5.

4. CONCLUSIONS

This paper presents the life cycle assessment from cradle to grave of a newly constructed wooden building in Granada (Southern Spain), including life cycle energy analysis, sensitivity analysis to changes in efficiency of operating energy, changes in materials database, changes in transport distances and different scenarios for C&DW.

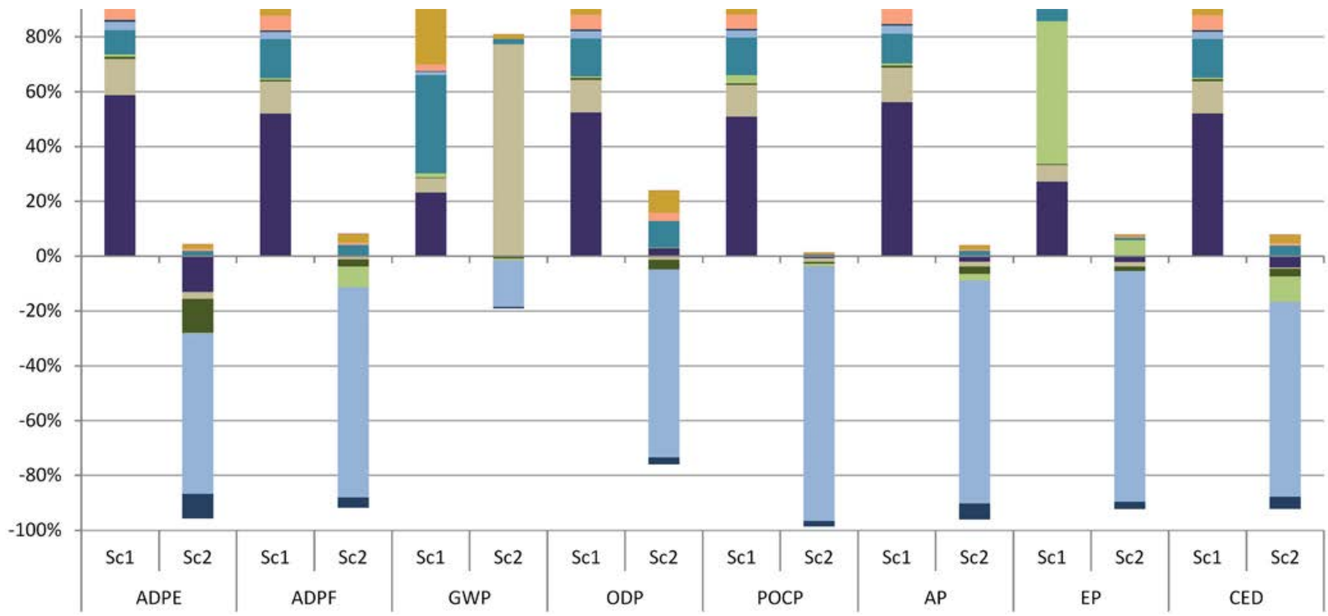

Fig. 4. EOL relative environmental impacts. In horizontal axis, the impact categories for Sc1 (Scenario 1: Landfill) and Sc5 (Scenario 5: Fulfillment of Waste Directive 2020).

Environmental impacts in the materials and construction stage were relatively significant, with values higher than 28% of the total impact in all impact categories included in EN15978. Embodied energy is relatively higher (27728 MJ/m2 and 37% of LCAE) and the total life cycle energy is lower (554.6 MJ/m2.year) than the values reported as average in the literature. The GWP impact category was very low due to the CO_2 sequestration of wooden materials (652 kg CO_2-eq/m2).

Good environmental results were significantly reduced if data from EPD for CLT was changed by data from Ecoinvent database (with worsening to 39% in CED), although an improvement in GWP was reached (26%).

Regarding the transport of wood panels from a long distance, the repercussion was not very significant within the total calculation of the life cycle assessment. The change from long distance to local supplier reduced the amount of transport by 88% (expressed in t.km). However, environmental impacts were very slightly reduced; the highest reduction (7.1%) was in the GWP impact category.

Valorization objective of the Waste Framework Directive for the 2020 horizon (higher than 70%) would be feasible with this new wooden building. In this scenario, the values in all impact categories except in GWP were improved. The improvement in the POCP and EP impact categories was significant with total reductions of 15.6% and 9.3% respectively, mainly from recycling metals.

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