Research article

Actions to reduce carbon footprint in materials to healthcare buildings

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ABSTRACT

Building sector is a major contributor to the emissions of pollutant gases, which are responsible for health-damaging effects of climate change. To quantify and reduce these emissions. This comparative study is presented between two buildings that could have a sanitary or any other type of use. Both buildings have similar characteristics, except for their structures, one made of metal and the other of concrete. The design, structural calculation and three-dimensional dimensioning were performed using Building Information Modeling (BIM). The budget and the product carbon footprint study were also carried out, to calculate the level of emissions of each building. The study determined higher emissions for the metal-structured building, with 621.234 $tCO_2/t_{material}$ compared to 446.707 $tCO_2/t_{material}$ for the concrete building. To reduce these emissions, measures related to the replacement of the previously selected materials, by other materials with lower emission rates and identical functionality were presented, such as the replacement of metal building roof polyurethane, or the composition of cement for the concrete building. Both actions represented a reduction of 84.61% CO_2 emissions for metal envelope building and 31.765% for the concrete structure. The results of this work will help to select more sustainable materials to use in the renovation of existing buildings, or in the construction of new buildings. For example, health-related buildings, currently in high demand, given the current pandemic situation caused by COVID-19.

1. Introduction

Reducing greenhouse gas (GHG) emissions, which are responsible for the effects related to climate change, is one of the biggest challenges facing our society [1, 2, 3, 4]. Despite exceptional decline in global emissions of carbon dioxide (CO_2), one of the main GHGs, during 2020 caused by COVID-19 pandemic [5, 6], long-term projections point to an upward emissions scenario [7], which deviates from targets set by international [8] and national agencies [9].

Of all sectors causing GHG emissions, building and residential sectors [10, 11] are among the most responsible ones, with 36% of total net CO_2 emissions produced in Spain in 2018 [12,13]. Environmental impact of buildings occurs at different stages of their life cycle: planning, construction, operation, renovation and demolition, with operation stage accounting for largest percentage, with approximately 85% of GHG emissions [14, 15], this figure may vary from country to country [16], e.g. 43% in the United States and more than 50% in China [17]. However, the impact of building materials is coming into the spotlight, due to the publication of more restrictive policies by administrations, to promote energy savings in buildings [18, 19].

In order to minimize the environmental impact of the building sector and allow it to evolve in line with sustainability, tools such as carbon footprint measurement have been developed [20, 21, 22], defined as the amount of CO_2 equivalent emissions caused directly and indirectly by an activity, or as the total amount of GHG emissions during the life cycle of a product or service. Life Cycle Assessment (LCA) [23], is one of the widely accepted tools for calculating carbon footprint [24], especially at the product level [25].

There are numerous studies in the literature on the carbon footprint assessment in buildings, which can be classified into two main groups: those aimed at assessing GHG emissions during the extraction of raw materials, the manufacture of components and building materials and those aimed to the transport of materials to the construction site. As an example, Li, X-J. et al. [21], researched the carbon footprint in the materialization phase of precast concrete buildings using a calculation model combined with Building Information Modelling (BIM) technology. The results revealed a significant reduction of carbon footprint per unit area in precast concrete projects. In a similar study, Li, X-J. et al. [22] researched the carbon footprint at the construction stage of precast concrete piles using the LCA method, yielding carbon emissions data for

the construction machinery of 73% of the total, with a strong linear relationship between pile foundation area, foundation cost, number of foundations and total carbon emission during the construction. Following the line of the previous authors regarding the impact of concrete materials, Xiao, J. et al. [26] researched the carbon footprint of two identical high-rise buildings, one made of recycled aggregate concrete and the other of natural aggregate concrete. In the results, the recycled aggregate concrete achieved a decrease of up to 2.175×105 kg CO_2 in carbon footprint, compared to natural aggregate concrete. There are also works wich are not linked to the more traditional materials used in construction, with the aim of investigating new possibilities for reducing the carbon footprint at the material manufacturing stage, such as the research by Scrucca, F. et al. [27], about the use of sustainable materials, such as hemp, due to its good hygrothermal and acoustic insulation properties.

On the other hand, there are works to evaluate GHG emissions from the daily energy consumption of buildings in their operational phase (air conditioning, water supply, lighting, etc.). As an example, Gamarra, A.R. et al. [28] analysed the activities with energy, material and water requirement of two school buildings located in hot climates, assessing the carbon footprint through LCA. They quantified the effects of different improvement measures, such as the implementation of renewable energy sources and the optimisation of energy use, based on energy efficiency measures, by proposing modifications to the luminaries. Also related to the education sector, Clabeaux, R. et al. [29] evaluated the carbon footprint of a university campus using the simplified LCA tool and found the main sources of GHG emissions to be electricity generation (41%), car travel (18%) and steam generation (16%). Similarly, Onat N.C. et al. [30] obtained a carbon footprint percentage for electricity generation of 48% and more than 10% for commuting in residential and commercial buildings in the USA. Kairies-Alvarado, D. et al. [19] also analysed how to reduce the carbon footprint in the operation phase of public buildings and found that it is possible to reduce it by 82%.

The first works (carbon footprint assessment in the construction phase), present the difficulty of quantifying a large amount of data, due to the diversity of materials and machinery used. The second (carbon footprint assessment in the operation phase) present the complexity of quantifying energy consumption, due to the different lifestyles and multiple uses of the building. To solve these problems, the use of new and powerful tools is required [25].

Literature includes works on the carbon footprint of buildings of different types, but in line with the objectives of this study, it is worth highlighting the importance of large buildings, destined for example to the hospital, health, or residential area for the care of the elderly. With the current health crisis caused by the pandemic, the need for the construction of this type of building has increased [31], leading to a significant contribution of GHGs in the different stages of their life cycle [32, 33, 34, 35], focusing attention on the large amount of material resources invested in the construction stage, due to the large size of these buildings in most cases.

Considering therefore as valid this work for its application in buildings for medical, health or any other use, such as teaching or residential for the elderly. As long as it involves the execution of large buildings.

In order to contribute to the simplification of carbon footprint calculation methods through technological tools and with the aim of reducing the main CO_2 contributions of buildings associated with their construction and use, two virtual models of typical buildings of large dimensions valid for various uses.

The first one with a concrete structure and the second one with a steel structure, in order to represent the current scene of these buildings, using the CYPECAD software, "*Generador de porticos*" y CYPE3D 2017 version (CYPE Ingenieros S.A.) [36] for their structural calculation and Autodesk Revit 2020 (Autodesk Inc.) [37] for their subsequent 3D dimensioning using BIM. A comparative study was made of the carbon footprint of both, in the construction and operation stages, in relation to energy consumption, finally determining which type of building is a greater emitter of CO_2, and establishing a series of measures to be adopted to achieve a reduction in these emissions. Unlike other similar works, where the carbon footprint is only analysed in one of the phases of the building's life cycle and/or where existing buildings are analysed, the results of which may be difficult to extrapolate to new buildings, these virtual models are presented, the configuration of which can be extrapolated to healthcare buildings or buildings of other types.

2. Methodology

In order to provide the final measures aimed at reducing the carbon footprint of materials used in the construction of buildings for sanitary use, a comparative study of product carbon footprint (PCF) was previously carried out, based on the methodology for the quantification of PCF, established in the standard UNE-EN ISO 14067:2018 [38].

To carry out this study, the structures, both metallic and concrete, were calculated with the CYPECAD, "*Generador de porticos*" and CYPE3D 2017 version (CYPE Ingenieros S.A.) software [36]. Subsequently, a 3D dimensioning of the buildings was carried out using BIM, with the Autodesk Revit 2020 software (Autodesk Inc.) [37], in order to quantify all the materials used in the construction of the building.

Budgets were drawn up to quantify the costs of the two buildings and an inventory was drawn up with the emissions of each of the materials and items that make up the building, with the aim of identifying which of these were the most polluting, as well as an overall calculation of the emissions of each building. The emissions corresponding to the transport of materials to the building, from a stablished distance of 100 km, were also calculated.

In the end, with the HCP quantification study and the budgets, the improvements in terms of structural modifications and change of materials of the building elements were established, to achieve the carbon footprint reduction target.

The different phases of this work are described below.

2.1. Definition of standard buildings

The structural calculations of the buildings were carried out on the basis of the Technical Building Code, in its Basic Document on Structural Safety [39], establishing the location in the city of Badajoz (06006 – España) and their use as a health care facility (hospital, health centre, or similar). The structural characteristics of both buildings are detailed in Table 1.
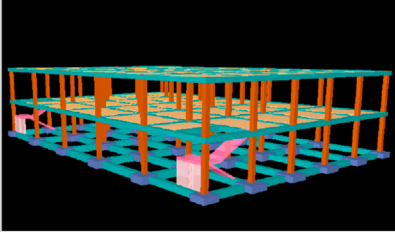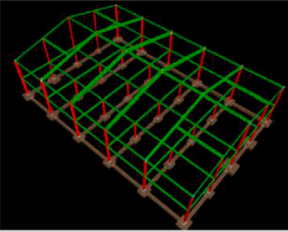
2.1. 3D design and materials

Autodesk Revit was used to make the three-dimensional models of the buildings in order to get an overview of both (Figure 1A and B), to quantify the materials used in their construction, and later, to prepare budgets and an inventory of CO_2 emissions.

As for the materials used, those most used today in this type of construction were selected, obtaining calculations that are representative of reality. The list of materials used for both buildings is detailed in Table 2.

2.2. Measurements and budget

The methodology followed was, firstly, to calculate the measurements of the structural elements, using CYPE - Archimedes software, and those of the construction elements, using Autodesk Revit software. Later, the total budget for both buildings, with their structure and construction elements, was calculated. For this purpose, the unit prices of each item were taken from the CYPE price generator and multiplied by the measurements obtained to calculate the Material Execution Budget (MEB). The comparative manufacturing cost of both buildings will be detailed in the results section.

Table 1. Structural characteristics of buildings.

	Concrete building	Metal building
Structural description	Reinforced concrete with steel bars or meshes	Rolled steel. 6 portal frames and 5 spans
Sizes	27 × 18 × 6 m	27 × 18 × 6 m
Foundations	Insulated feets with tie beams	Insulated feets with tie beams
Pillars	36 units, 6 × 0.30 × 0.30 m	30 units: 2 of 8 m (IPE 200), 12 of 7.5 m (IPE 300), 4 of 7.75 m (IPE 180) y 12 of 3 m (IPE 240)
Beams	0.5 × 0.3 m	50 units: IPE 200 and IPE 240
Frameworks	Prestressed beam	-
Mezzanine floor	Yes, at a height of 3 m	Yes, at a height of 3 m
Roof	Flat roof, 3% slope	Gable roof with a 22.2% slope, 8 m ridge and 6 m wall height. 10.8 m straps (IPE 100).
Picture		
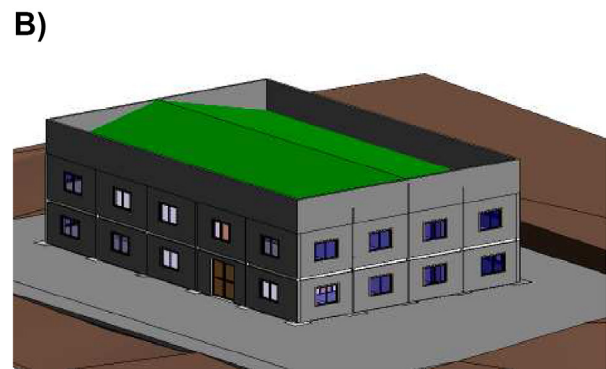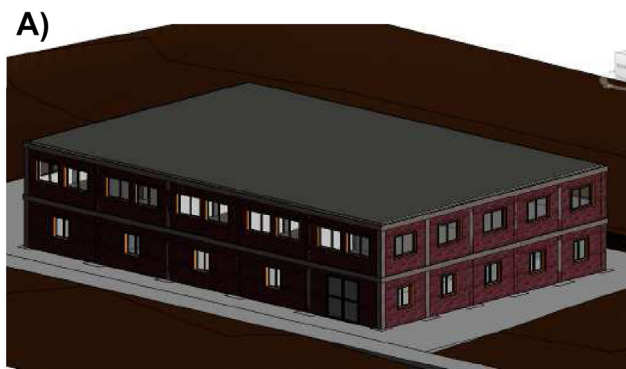
Figure 1. A) Autodesk Revit 3D view of the concrete frame building. B) Autodesk Revit 3D view of the steel structure building.

Table 2. Materials selected for both buildings.

Frameworks	Concrete floor, 0,05 mm thick polyethylene separating sheet and 10 cm thick mass concrete floor screed
Floors	Ceramic tiles of glazing stoneware
External enclosures	Metal building: alveolar plates of prestressed concrete Concrete building: thermoclay block
Internal enclosures	Double hollow ceramic bricks, for cladding, 7 cm thick
Roofs	Metal building: polyurethane Sandwich type panels Concrete building: conventional fixed flooring
False ceiling	Only in metal building: plaster plates with ribbing
Doors	Aluminium and wood
Windows	"Aluplast ideal 4000 cl"

2.3. Calculation of total CO_2 emissions

After carrying out the structural calculations of the buildings, the choice of materials and the budgets, the total emissions in tonnes of CO_2 equivalent (tCO$_2$e) that would be released into the atmosphere in both buildings were calculated. For this purpose, different material emission tables were used [40] detailing the densities of each material and the tCO$_2$e per tonne of material manufactured. The tables are based on the "Creadle-to-gate" methodology, which establishes the limits of the system in terms of emissions, measured up to the exit of the factory. The emissions associated with the transport of the materials were also calculated, establishing a standard distance for all of them of 100 km. The total number of tonnes to be transported, the tonnes that can be transported by each type of vehicle and their emissions were calculated. Finally, the emissions associated with the use of the building with respect to energy consumption were calculated. The results obtained from the product carbon footprint study will be detailed in the results section.

2.4. Actions for carbon footprint reduction

After the total CO_2 emission data were obtained, measures were developed to reduce the carbon footprint, such as: replacement of the sandwich roof insulation, change of the cement composition, replacement of the material of the interior partitions and study of the material for the exterior windows. The influence of these measures on the results was evaluated and conclusions were drawn.

3. Results and discussion

3.1. Building cost comparison

In order to quantify the cost of construction of the buildings and to assess how it could vary through the application of carbon footprint reduction measures, a comparison of the budgets of the structures (Figure 2a) and of the building constructive elements was made, Figure 2b.
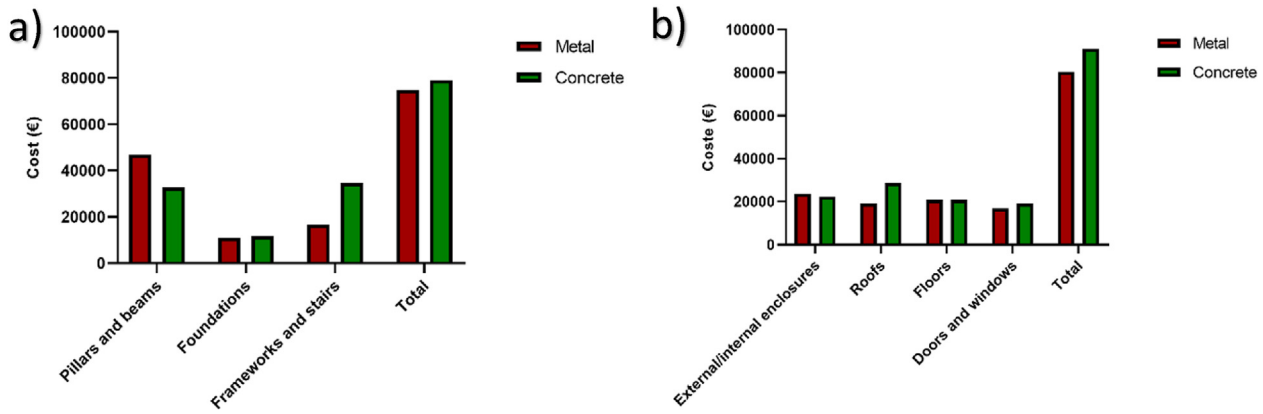
Figure 2. a) Comparison of structure cost – b) Comparison of constructive elements.

The comparison of the structures shows a higher cost of pillars and beams for the steel structure, the costs of the foundations are similar, due to the tie beams and the type of foundations used have been similar. As for the frameworks, the price of the concrete structure is higher due to the roof slab, which does not exist for the steel structure. The structural cost of the concrete building is €4436.42 higher than the metal building.

The comparison of construction elements shows a similar cost of enclosures, partitions and floors, due to the similarity of the materials used. The cost of the flat roof of the concrete building is very high due to its unit price and represents the biggest difference between the two

buildings. The doors and windows differ only because they are larger in the concrete building. The cost of the construction elements of the concrete building is € 10,664.60 higher than the metal building.

3.1. CO_2 total emissions

After inventorying the materials in the measurements and budgets section, the tonnes of CO_2 emitted per tonne of material ($tCO_2/t_{material}$) were calculated and classified according to each type of construction element: quarry materials, concrete blocks, metals, glasses, plastics, woods, insulations, gypsums, concretes and energy.

Table 3. Total CO_2 emission of the metal building broken down by materials.

Metal structure building

Type of construction material	Volume (m^3)	Volume used specifications	Total weight of material (t)	Emissions rate ($tCO_2e/t_{material}$)	Total emissions (tCO_2)
Concrete cleaning layer HL-150/B/20 (Concrete)	48,600	486 m^2 with thickness 0.1 m	93,832	0.170	15,970
Reinforced concrete foundation footing (Concrete)	17,929	17.929 m^3 concrete footing	34,616	0.170	5892
Reinforced concrete tie beam, made of concrete (Concrete)	36,722	36.722 m^3 of concrete in tie beam	70,899	0.170	12,067
S275JR steal in pillars, with single parts made of IPE profiles (Steel: bar)	x	5150.4 kg of steel in pillars	5150	1.400	7211
S275JR steal in beams, with single parts made of IPE profiles (Steel: bar)	x	16,941.56 kg of steel in beams	16,942	1.400	23,718
Internal enclosure sheet of ceramic brick masonry for cladding (Brick)	31,920	456 m^2 with thickness 0.07 m	60,648	0.240	14,556
Heavy prestressed concrete hollow-core slab façade (concrete block)	111,690	657 m^2 with thickness 0.17 m	156,366	0.107	16,731
Sloping roof of insulated sandwich panels (Steel and Polyethylene)	4.98 + 149.40	498 m^2 of panel sandwich: thickness 0.30 (insulation) + 0.01 (sheet metal)	176,292	1.38 + 2.54	402,723
Reinforced concrete structure. Not including impact of pillars (Concrete)	92,875	371.50 m^2 with thickness 0.25 m	179,314	0.170	30,519
Stone paving (Limestone)	97,200	486 m^2 with thickness 0.2 m	213,840	0.090	19,246
Polyethylene separator film (Polyethylene)	0.024	486 m^2 with thickness 0.00005 m	0.022	2.540	0.057
Concrete floor (Concrete)	48,600	486 m^2 with thickness 0.1 m	93,832	0.170	15,970
Adhesive-fixed ceramic tile flooring (General ceramics)	4860	486 m^2 with thickness 0.01 m	11,664	0.700	8165
Continuous plasterboard false ceilings (Plaster)	4860	486 m^2 with thickness 0.01 m	6318	0.130	0.821
Inner hinged door, wooden (203 × 82.5 × 4 cm) (General wood)	0.804	12 doors of 2.03 × 0.825 × 0.04 m	0.402	0.310	0.125
Entrance door to the building, aluminium, "CORTIZO" (Aluminium)	0.608	2 doors of 2.60 × 2.60 × 0.45 m	1643	9.160	15,047
Casement window (General PVC)	7591	34 windows of 1.83 × 1.22 × 0.10 m	10,475	3.100	32,474
		TOTAL	**1,132,255**	**0.549**	**621,290**

To show the emission data obtained in a summarised form and classified according to each type of building, the following tables were prepared: Table 3 shows total CO_2 emission of the metal building, broken down by materials and, Table 4, Total CO_2 emission of the concrete building, broken down by materials.

For emissions related to transport, an average distance for all materials of 100 km was taken. This estimation was made considering that some materials would have to be supplied from further away, while others could be supplied from the location of the building construction site itself. The total number of tonnes to be transported, the tonnes that can be transported by each type of vehicle and the emissions of these vehicles were calculated.

It was, therefore, observed that CO_2 emissions would be lower if more goods could be transported per trip. The transport-related emissions are shown in Table 5 .

Table 5 shows that by increasing the number of materials transported per vehicle by 10 units, CO_2 emissions to the atmosphere were more than halved.

Once the total emissions data was obtained, a comparison was made between the two buildings, in order to determine which type of structure leads higher CO_2 emissions (see Table 6).

The data revealed that, in terms of structure, the biggest difference in emissions was in the frameworks, because the concrete structure has an extra framework for the roof, which does not exist in the metal structure.

Table 4. Total CO_2 emission of the concrete building broken down by material.

Concrete structure building					
Type of construction material	Volume (m^3)	Volume used specifications	Total weight of material (t)	Emissions rate (tCO$_2$e/ t$_{material}$)	Total emissions (tCO$_2$)
Concrete cleaning layer HL-150/B/20 (Concrete)	14,046	140,46 m^2 with thickness 0,10 m	27,119	0.170	4616
Reinforced concrete foundation footing (Concrete)	31,081	31.081 m^3 concrete footing	60,008	0.170	10,213
Reinforced concrete tie beam (Concrete)	10,320	10.32 m^3 of concrete in tie beam	19,925	0.170	2391
Reinforced concrete centring beam (Concrete)	24,670	24.67 m^3 of concrete centring beam	47,630	0.170	8107
Reinforced concrete structure (Concrete)	185,793	743.17 m^2 with thickness 0.25 m	358,710	0.170	61,052
Reinforced concrete, straight, dropped beam (Concrete)	83,860	83.86 m^3 of concrete in beams	161,909	0.170	27,557
Reinforced concrete stair slab (Concrete)	2370	15,8 m^2 with thickness 0.15 m	4576	0.170	0.779
Reinforced concrete rectangular or square cross-section pillar (Concrete)	17,496	17.496 m^2 of concrete in pillars	33,780	0.170	5749
Interior partition sheet made of ceramic brick masonry for cladding (Brick)	28,840	412 m^2 with thickness 0.07 m	54,796	0.240	13,151
External leaf of thermoclay block masonry (General ceramics)	117,120	488 m^2 with thickness 0.24 m	281,088	0.700	196,762
Flat, non-ventilated, walkable roof with fixed screed (Concrete)	58,320	486 m^2 with thickness 0.12 m	112,598	0.170	19,164
Stone paving (Limestone)	97,200	486 m^2 with thickness 0.2 m	213,840	0.090	19,246
Polyethylene separator film (Polyethylene)	0.024	486 m^2 with thickness 0.00005 m	0.022	2.540	0.057
Concrete floor (Concrete)	48,600	486 m^2 with thickness 0.1 m	93,832	0.170	15,970
Adhesive-fixed ceramic tile flooring (General ceramics)	4860	486 m^2 with thickness 0.01 m	11,664	0.700	8165
Interior hinged door, wooden (General wood)	0.737	11 doors of 2.03 × 0.82 × 0.04 m	0.369	0.310	0.114
Entrance door to building, aluminium (Aluminium)	0.608	2 doors of 2.60 × 2.60 × 0.045 m	1643	9.160	15,047
Double casement window (general PVC)	6698	30 windows of 1.83 × 1.22 × 0.10 m	9243	3.100	28,653
Double casement window (general PVC)	2084	14 windows of 1.22 × 1.22 × 0.10 m	2876	3.100	8914
		TOTAL	**1,495,626**	**0.299**	**446,707**

Table 5. CO_2 emissions related to the transport of materials from buildings.

Concrete building						
Distancie (km)	Means of transport (quantity that can be transported)	Emissions rate (gCO$_2$e/ passenger•km)	Emissions per vehicle (tCO$_2$e)	Total amount to be transported (t)	Required vehicles (unit)	Total emissions (tCO$_2$)
100	Diesel van (3,5 t)	250.92	25.09	659.76	189.00	**4,742,44**
100	Diesel truck (34 t)	1011.06	101.11	659.76	189.00	**2022.12**
Metal building						
Distancie (km)	Means of transport (quantity that can be transported)	Emissions rate (gCO$_2$e/ passenger•km)	Emissions per vehicle (tCO$_2$e)	Total amount to be transported (t)	Required vehicles (unit)	Total emissions (tCO$_2$)
100	Diesel van (3.5 t)	250.92	25.09	575.54	165.00	**4140.23**
100	Diesel truck (34 t)	1011.06	101.11	575.54	17.00	**1718.80**

Table 6. Comparison between the emissions of the two buildings.

Structure emissions (tCO$_2$/t$_{material}$)			Constructive elements emissions (tCO$_2$/t$_{material}$)		
Item	Metal	Concrete	Item	Metal	Concrete
Foundation, frameworks and stairs (Common in both)	64.44	88.15	External enclosure	16.73	196.76
Pillars and beams	30.92	33.30	Roof	402.72	19.16
			Other elements (Common in both)	106.40	109.31
Total	**95.37**	**121.46**		**525.85**	**325.24**

Although the emissions rate of steel beams and pillars is much higher than those of concrete, the emissions are similar, due to the smaller amount of steel required in the construction of metal structures. Regarding the construction elements, the biggest difference lies in the external enclosures and the roof. Sandwich panel and thermoclay block are highly polluting and account for a high percentage of emissions. As for the rest of the construction elements, there are hardly any difference, as the same materials have been used and in similar quantities, with a slight appreciable difference in the use of more or less material depending on the square metres. This comparison shows that the building type with the highest emissions is the metal structure, with 621.234 tCO$_2$/t$_{material}$, compared to 446.707 tCO$_2$/t$_{material}$ for the concrete building.
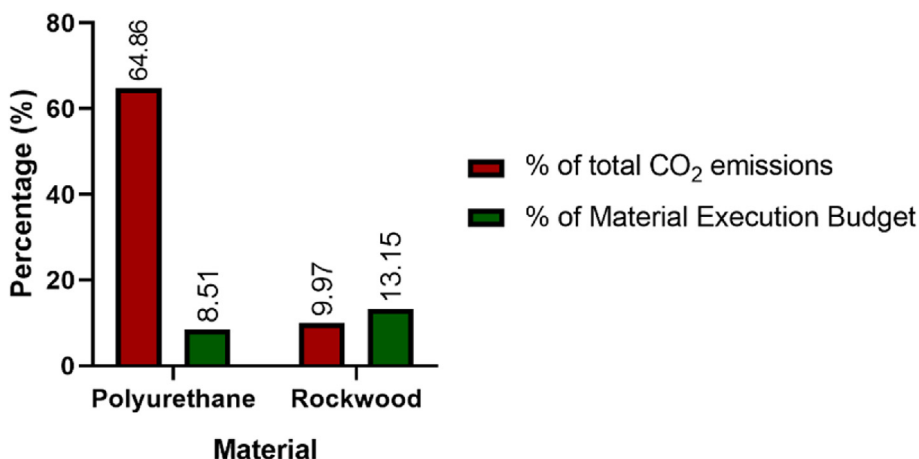
3.2. Carbon footprint reduction actions

3.2.1. Sandwich panel insulation replacement

As a first action, it was proposed to replace the insulation type of sandwich roof, as it was responsible for 64.85% of the total emissions of the metal building. The sandwich roof is composed of two galvanised steel sheets on the outside and polyurethane insulation on the inside. In order to reduce the value of these emissions without altering the functionality, the polyurethane was replaced by rockwool. Rockwool offers characteristics such as: fire protection, thermal insulation, impermeability and good acoustic insulation. Its lifespan can be compared to that

Table 8. Estándar concrete components (94% clínker).

Components	Proportion (%)	Density (t/m^3)	Emissions (tCO$_2$e/t$_{material}$)
Portland cement	13.34	1.50	0.95
Water	6.66	1.00	0.00000034
Sand	26.67	2.24	0.0051
Gravel	53.33	2.00	0.079
Total (concrete)	100	1.93	0.170

Table 9. Modified concrete components (50 % clínker).

Components	Proportion (%)	Density (t/m^3)	Emissions (tCO$_2$e/t$_{material}$)
Cement 50-50	13.34	1.50	0.544
Water	6.66	1.00	0.00000034
Sand	26.67	2.24	0.0051
Gravel	53.33	2.00	0.079
Total (concrete)	100	1.93	0.116

of a building, as it does not degrade over time. In addition, the final product contains a high percentage of recycled content, which can vary between 70% and 90% [41].

Table 7 details the variation of the data with material substitution. The emission rate of rock wool is 1.12 tCO$_2$/t$_{material}$ compared to 2.54 tCO$_2$/t$_{material}$ for polyurethane insulation. This, together with the fact that its density is up to 18 times lower, reduces emissions from the initial 402.72 tCO$_2$ emitted by the roof, to 61.97 tCO$_2$ with the rock wool, keeping constant the 53.6 tCO$_2$ associated with the metal sheets of the sandwich panel. After applying this measure, there was a reduction in roof emissions of 84.61%. Variation data for both CO$_2$ emissions and the impact on the EMP are shown in Table 7. Figure 3 shows the change in budget and CO2 emissions due to material changeover.

3.2.2. Cement composition change of the concrete structure

Cement results from the decomposition of limestone and other calcareous materials. This decomposition produces clinker, a granular

Table 7. Results of emission reductions in roof insulation.

Results of emission reductions in roof insulation

Insulation type	Weight (t)	Material emissions (tCO$_2$/t$_{material}$)	Total CO$_2$ emissions (tCO$_2$)	CO$_2$ emissions reductions (%)	Total cost (€)	Total cost increase (%)
POLYURETHANE	137,45	2,54	402,72	**84,61**	13,212.04	**54,5**
ROCKWOOL	7,47	1,12	61,97		20,413.02	

Figure 3. Change in budget and CO$_2$ emissions due to material changeover.

Table 10. Results of the modification of concrete components.

Concrete type	Emissions ($tCO_2e/$ $t_{concrete}$)	Amount of concrete used	Concrete building emissions (tCO_2)	Reduction of CO_2 emissions
Traditional	0.170	920,086	156,415	49,685
Modified	0.116	920,086	106,730	
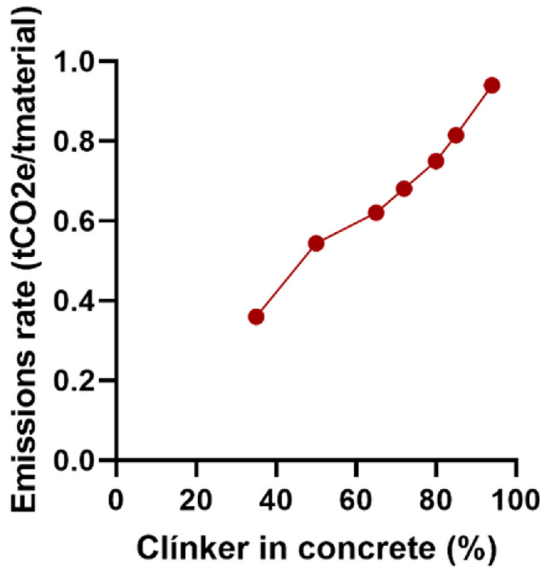
Figure 4. Variation of emission rate with respect to clinker variation in concrete.

material wich is the main component of common cement, known as Portland cement. Portland cement in Spain, used in most buildings, contains approximately 94–95% clinker, being the remaining 5% other additives. The problem of cement production lies in the production process of obtaining the clinker, which requires a heating process of about 1400 °C, in which carbon is released, which when combined with air produces CO_2, which is emitted into the atmosphere. To these emissions must be added those emitted by the kilns, which use large amounts of energy to reach these temperatures and therefore also generate CO_2.

The remaining percentage of cement formation is usually done with granulated blast furnace slag, which determines the production yield and can achieve a higher ecological benefit by using a lower percentage of clinker, thus achieving lower CO_2 emissions and lowering the costs of energy generation for cement production. Maintaining at all times the strength requirements of the concrete [42, 43].

After analysing the emissions associated with cement, a change in cement composition was considered to study the potential benefits, in terms of emission and cost reductions. To this end, a study was carried out with a 94% clinker composition in the cement, which is detailed in Table 8.

Subsequently, modifications were made, starting with 94% Portland cement clinker, and the characteristics and emissions of the new concrete were obtained, starting with 50% Portland cement, as detailed in Table 9.

After the modification of the cement composition, see Table 10, a new concrete was obtained with a reduction in CO_2 emissions of 31.765%, a percentage that is relevant considering the large quantities of concrete used in construction. The building with a concrete structure, with this change in composition, went from emitting 156.415 to 106.73 tonnes of CO_2, which means a total of 49.685 tonnes less CO_2 emitted.

Figure 4 shows the variation of the concrete emission rate when the clinker percentage is varied. The variations were made from 94%, the common percentage of Portland cement, to 35%, as the minimum percentage to which the clinker can be reduced while maintaining the properties of the concrete [44].

3.2.3. Replacement of internal enclosures material

The reduction of emissions through the replacement of the building's interior partition materials was also studied, analysing the available options on the market, and comparing them with each other. The initial material used was ceramic brick masonry, as it is the most common material currently used in this type of construction elements. The total emissions corresponding to the partitioning of this material are 13.13 tonnes of CO_2 [45].
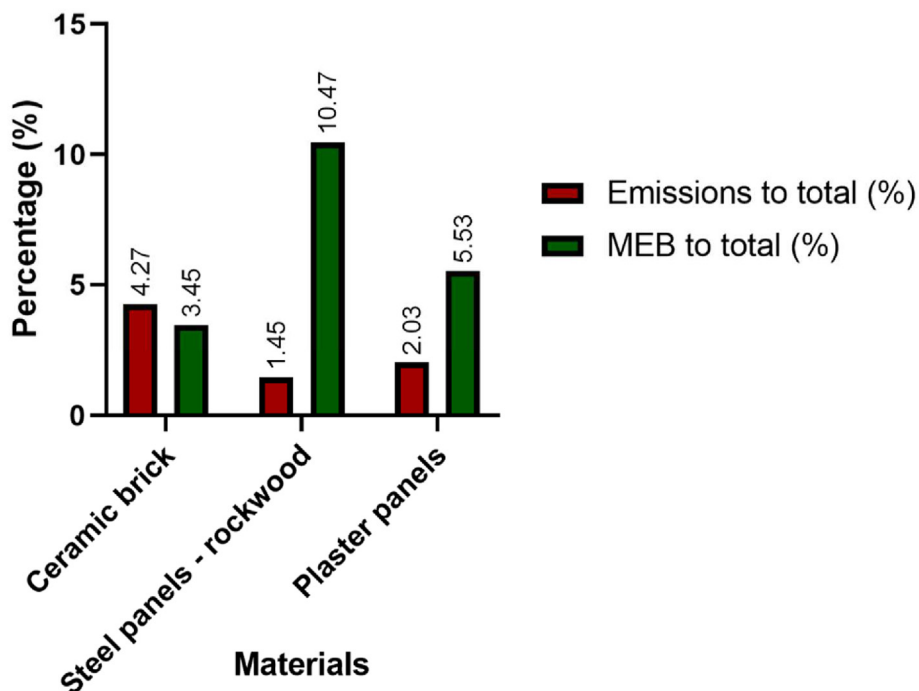
Figure 5. Variation in budget and emissions by type of internal enclosures.

A comparison of this material was carried out with: tongue and groove steel partition panels with rockwool insulation and glass fibre reinforced gypsum board interior partitions. The comparative study revealed the results shown in Figure 5.

From the study it can be extracted that the sectorial steel and rockwool panels present a decrease in CO_2 emissions regarding to ceramic bricks of 2.82% and an increase in the MEB of a significant 7.02%, and this solution can be rejected due to the large increase in the MEB. On the other hand, plaster panels represent a reduction in CO_2 emissions with respect to ceramic bricks of 2.24%, a smaller reduction than that produced by steel and rockwool panels, and an increase in the MEB of 2.08%, this being an assumable increase and, therefore, considering plaster panels as an useful material to replace traditional ceramic bricks.

4. Conclusions

A comparative study was carried out between two similar buildings. They can be used for sanitary use or for any other use. One of the buildings in concrete structure and the other in a metal structure, to determine the carbon footprint of the materials used.

To determine the carbon footprint, the buildings were first designed, and their structures calculated. A 3D dimensioning of the buildings was carried out using BIM, with which the materials used in the construction of the building were quantified. Budgets were drawn up to quantify the costs of the two buildings and an inventory was drawn up with the emissions of each of the materials and items that make up the building.

The results revealed that the building type with the highest emissions is the one with metal structure, with 621.290 $tCO_2/t_{material}$, compared to 446.707 $tCO_2/t_{material}$ for the concrete building.

Analysing the results from a more localised perspective in the purely structural elements (foundations, pillars, and beams), it should be noted that metal structures are less polluting than concrete structures. Although steel has higher emissions rate than concrete, with a rate of 1.4 tCO_2/t_{steel} and 0.17 $tCO_2/t_{concrete}$.

This is because metal structures use fewer tonnes of this material and are quicker to build, so overall they have a lower environmental impact.

After knowing the emissions data, measures were proposed to reduce these emissions through the replacement of the materials used. Such as the replacement of the insulation material of the sandwich panels used for the roof of the metal building, which resulted in a reduction of 84.6% in roof emissions and an increase of 4.64% in the MEB.

The composition of the cement used in the concrete structure was also modified, decreasing the percentage of clinker to 50%. Which generated a decrease in CO_2 emissions related to the concrete structure of 31.765%.

Finally, the substitution of interior enclosure materials was studied, comparing ceramic brick with steel and rockwool panels and plaster panels. With this latter one being considered as the best option for replacing ceramic brick in terms of emissions/price reduction.

As future lines of improvement, a study is considered including more emission reduction measures such as: supplying heating through renewable sources, supplying sanitary hot water through renewable sources such as geothermal energy, the use of biomass in boilers, establishing external thermal insulation systems, the replacement of metal roofs with wood and the use of special low emissivity or solar control glass.

Declarations

Author contribution statement

Juan Pablo Carrasco-Amador, Alberto Castaño-Liberal, Manuel Matamoros-Pacheco: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

José Luis Canito-Lobo, Jesús Manuel Rodríguez-Rego: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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