Sustain Sci (2017) 12:65–85
DOI 10.1007/s11625-015-0342-4

ORIGINAL ARTICLE

Optimization of CO_2 emissions in the design phases of urban planning, based on geometric characteristics: a case study of a low-density urban area in Spain

J. Roldán-Fontana[1] · R. Pacheco-Torres[1] · E. Jadraque-Gago[1] · J. Ordóñez[1]

Received: 5 March 2015 / Accepted: 17 September 2015 / Published online: 14 October 2015

Abstract When environmental impact analysis is included in the design phase of engineering projects, this lowers the cost of strategic actions that must be performed to minimize possible environmental damage in later project phases (Construction Process Stage, Use Stage, and End-of-Life Stage). In the case of family housing, efforts to optimize energy consumption will not be successful if initial urban planning stages are not taken into account. The objective of this research was to use Life Cycle Assessment (LCA) as a method of evaluating the environmental impact of urban planning. For a surface area of 100,000 m^2, six housing development alternatives were analyzed for the following housing profiles: (i) single-family detached house; (ii) single-family semi-detached house; and (iii) high-rise apartment buildings of 40, 20, 10, and 5 floors. The results for this case study indicated that in the building construction stage, the activities that produced the greatest environmental impact were those related to the foundation, frame elements, and siding of the buildings. More specifically, these activities were responsible for 55–68 % of the CO_2 emissions produced during this stage. In contrast, in the urbanization phase, the most harmful activities were linked to earth-moving and paving, which generated 63–75 % of the emissions in this stage of the project. Furthermore, this study highlights the importance of using steel and cement with a low environmental impact as well as of creating green spaces with an environmentally friendly design. The results obtained show that the steel and concrete used in the building construction stage were responsible for 30–52 % of all of the CO_2 emissions during this phase.

Keywords Energy consumption · Building shape · CO_2 emissions · Life cycle Assessment · Urban planning

Handled by Yoshiyuki Shimoda, Osaka University, Japan.

✉ J. Ordóñez
javiord@ugr.es

[1] Department of Engineering Construction and Project Management, University of Granada, Granada, Spain

Introduction

According to the United Nations, "sustainable development is development that meets the needs of the present without compromising the viability of future generations to meet their own needs" (World Commission on Environment and Development 1987). Even though the term sustainable building is frequently used in books and articles, it still lacks a clear definition.

In order to evaluate the environmental impact of building constructions, this research used Life Cycle Assessment (LCA), which can be defined as follows:

"Process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing; transportation and distribution; use, re-use, maintenance; recycling; and final disposal" (Society of Environmental Toxicology and Chemistry 1993).

A more detailed description of how to perform Life Cycle Assessment is provided in the ISO 14040 and ISO

Table 1 Life cycle stages of a building as proposed in the CEN/TC 350 Standard

Stage	Module
(I) Product stage	Raw material supply
	Transport
	Manufacturing
(II) Construction	Transport
Process stage	Construction/installation on-site processes
(III) Use stage	Maintenance
	Repair and replacement
	Refurbishment
	Operational energy use: heating, cooling, ventilation, hot water and lighting
	Operational water use
(IV) End-of-life stage	Deconstruction
	Transport
	Recycling/re-use
	Disposal

14044 Standards (European Committee for Standardization 2006a, b). In the case of building construction, the CEN/TC 350 proposes the four stages given in Table 1 (European Committee for Standardization 2008).

LCA methods have long been used for the environmental evaluation of product development processes in other industries. Although their application to the building construction sector is fairly recent, numerous studies have been published that incorporate LCA in construction decision-making (Singh et al. 2011). In recent years, LCA has been used mostly to evaluate the production of materials. However, the development of user-friendly interfaces now facilitates its application to other domains. For example, it can be used to compare various possible building sites, different projects in an architectural competition, architectural and technical solutions for retrofit, end of life processes, etc. (Peuportier et al. 2013). Singh et al. also provides references that applied LCA to the environmental evaluation of building materials, construction systems and process evaluation, and databases related to the construction industry (Singh et al. 2011). Currently, the traditional model of Life Cycle Analysis is evolving towards a more comprehensive Life Cycle Sustainability Analysis (LCSA) (Guinée et al. 2011).

One of the problems highlighted by different authors involves the value or indicator selected to evaluate the environmental damage produced in the building construction stage. Various studies focus on the ecological footprint or impact of this activity as expressed in kilograms of CO_2 (González and García Navarro 2006). For example, Cuéllar-Franca et al. studied the three most common housing profiles in the U.K. by using the following indicators of ecological damage: (i) acidification potential (AP); (ii) abiotic depletion potential (ADP); (iii) ozone layer depletion potential (ODP); and (iv) terrestrial ecotoxicity potential (TETP) (Cuéllar-Franca and Azapagic 2012). The environmental damage indicator used in our research was the level of CO_2 emissions in kg. In the construction sector, various studies focus on LCA as applied to single buildings (Mithraratne and Vale 2004; Paulsen and Sposto 2013). Ordóñez and Modi analyzed the geometry of a building and its relation to the energy demand as measured in CO_2 emissions (Ordóñez and Modi 2011).

The main goal of this research was to optimize energy consumption, as measured in CO_2 emissions, in regards to the building materials used in a housing development. For this purpose, LCA was applied to the building construction process with a focus on the housing profiles and structures in the housing development project.

The manuscript is organized as follows: firstly, an overview of previous studies on embodied energy and carbon emissions of building materials is provided. Secondly, the methodology is expounded. In consonance with urban conditions, a set of six urban solutions is described. Then, the building materials involved are estimated, and the carbon emissions associated to each urban solution are evaluated. After analysis and discussion of the results, some final conclusions are drawn.

Overview on embodied energy and carbon emission of building materials at design stage

In the wake of increasingly restrictive laws regarding the environmental impact of buildings (European Parliament 2010, 2012), a deeper knowledge of how to reduce the embodied energy of construction materials is essential. Commonly, studies on the environmental impact of buildings focus on operational energy, and may neglect the embodied energy of the building materials (Perkins et al. 2009; Waldron et al. 2013; Davila and Reinhart 2013; Bardhan 2011; Perkins et al. 2009). A comprehensive definition of what embodied energy comprises is “the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building” (Ding 2004). A more detailed discussion of embodied and operational energy is given in (Cabeza et al. 2013).

The management of building materials entails the advantage of being under the control of the designer. Hence, it is a useful tool for reducing environmental impact, whereas control during the operating stage is beyond the designeŕs control. Previous research on the embodied energy and CO_2 emissions of building materials generally consider isolated buildings (Wen et al. 2014; Porhin and Adriana 2013; Mercader et al. 2012). In such cases the design of urban layout is ignored, despite its known effect on the quantity of building materials used (Waldron et al. 2013). Urban planning defines the quantity of materials involved to build the necessary networks and supply services. Therefore, it makes sense to face the challenge from an urban scale perspective, considering different building types.

Although little research has been done in this direction (World Commission on Environment and Development 1987), valuable references should be highlighted. Perkins et al. compared the Life Cycle Energy Consumption and emissions of three different housing types: city centre apartments, inner suburb dwellings and outer suburban dwellings (Perkins et al. 2009). Among the dwellings types studied, the authors found that inner suburban households show a lower embodied energy index. A variation of 33–37 % on the embodied energy is possible depending on the case study.

Also in this regard, Waldron et al. developed a methodology for estimating embodied and operation energy use at an urban scale in the design phase (Waldron et al. 2013). Three urban layouts were considered (high-rise, middle-rise, low-rise) with the same characteristics for different building uses, although roads and service infrastructures were not taken into account. The methodology was based on innovative software developed by the Low Carbon Research Institute. The authors pointed out the need of a deeper understanding of other elements that act on the built environment (such as structures, foundations and services structures), as they account for a large amount of the embodied energy of the urban development.

Rickwood et al. released the embodied energy rate per unit of inhabitable area for different high rise buildings (Rickwood et al. 2008). Compared to detached houses, the minimum embodied energy rate was found in a three- story building, yet this rate increases with building height. Davila et al. performed an evaluation of embodied energy in buildings in three levels: single building geometry; urban parametric geometry and urban lifecycle analysis (Davila and Reinhart 2013). In each scenario, three different façade compositions were evaluated.

Typically, the study of embodied energy of building materials goes hand in hand with the estimation of associated carbon emissions. The research by Paulsen et al. shows a scrutiny of material distribution at the design stage (Paulsen and Sposto 2013). An estimation of potentials on carbon savings is effected for developing more sustainable projects for social housing, as part of a governmental initiative. Along the lines of assessing different building types, Jeon et al. looked into CO_2 emission embodied from construction materials at the building construction stage of residential apartments considering different floor areas (Jeong et al. 2012). The quantity distribution of the most highly emitting materials and their CO_2 emissions were evaluated. Based on LCA, González et al. grouped by chapters and compared, at design stage, the carbon emissions of building materials from a low environmental impact building and a conventional one (González and García Navarro 2006).

Apart from developing more knowledge on the distribution and emissions of materials, recent efforts have been dedicated to developing new building materials with a lower environmental impact (Cabeza et al. 2013).

It is evident that considerable efforts have gone into quantifying embodied energy and carbon emissions of building materials at the design or construction stage. Still, the materials necessary for providing a network and service supply are generally not taken into account, thus overlooking the effect on the embodied energy and carbon emissions associated for different building types and urban layouts. In this regard, the study here presented introduces an innovative approach in which: (a) different building typologies are considered; and (b) the building materials derived from services and infrastructures necessary for urbanizing the plot are also considered.

Methodology

In the first stage, the housing development and building profiles were designed. Then, the frame structures of the buildings and the earth-moving for streets were calculated. Also included in the analysis were the networks for water supply, sewage, electricity, gas, and telephone service.

Once this research had determined the construction work units in the housing development and the emission levels produced, a set of indicators were used to evaluate and compare the environmental impact of the different alternatives. The stages in this study were the following:

Stage I

- The set of housing profiles was defined in consonance with urban conditions.
- The profiles were characterized and designed for each type of urban planning.

Stage II

- The building structures were calculated and the construction work units were measured.
- The CO_2 emissions were estimated for the work units comprising each building type.

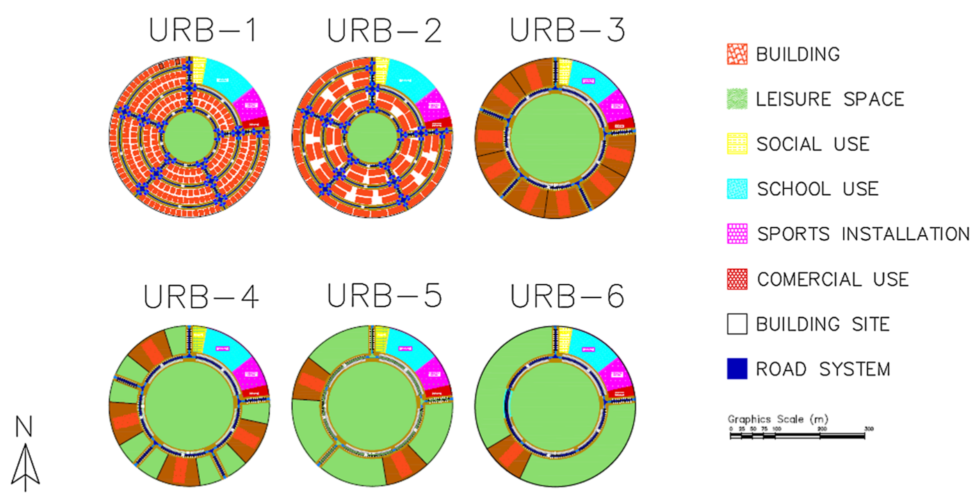


Fig. 1 Diagram of the housing development with six alternatives: single-family detached house (URB-1); single-family semi-detached house (URB-2); eight 5-floor apartment buildings (URB-3); four 10-floor apartment buildings (URB-4); two 20-floor apartment buildings (URB-5); and one 40-floor apartment building (URB-6)

– The installations and civil engineering work were calculated for the sample of housing development profiles.
– The construction materials corresponding to the land urbanization process were measured and their potential environmental impact was quantified as CO_2 emissions.

Stage III

– These results gave the curve of the total emissions, which represented the environmental impact of the land development and the building construction process as a whole.
– This made it possible to obtain the optimal set of conditions that minimized CO_2 emissions in the construction stage of the housing development.

This research study evaluated the level of CO_2 emissions for the six housing development profiles, as reflected in Stage I, the Product Stage (A1–A3) and also for Stage II, the Construction Process Stage (A4–A5). The processes included in this stage are the following: raw material supply (A1); transport (A2); manufacturing (A3); transport (A4); and construction/installation on-site processes (A5).

The results obtained permit the integration of ‘green’ strategies during the conceptual design phase of the building project. When such strategies are implemented in the early stages of a building’s life cycle, their cost is significantly lower than at later stages (Wang et al. 2006).

Definition of the shape parameters. Planning, urbanization, and building construction.

For the purposes of our research, the project design conditions for the housing development were the following:

- Circular-shaped land plot with a green area and/or leisure area at the center of the circle (see Fig. 1)
- Land plot located in the city of Granada (Spain) in compliance with city regulations, technical requirements, etc.

Figure 1 shows a sketch of the spatial distribution of the different urban configurations studied. In compliance with existing regulation, a minimum proportion of the plot of land to be urbanized must be devoted to public uses: leisure use (>10 % of total plot area); social use (3 m^2 built/per dwelling), school use (12 m^2 floor/per dwelling); sports installation (6 m^2 floor/per dwelling); and commercial use (1 m^2 built/per dwelling) (Ministerio de Obras Públicas y Urbanismo 1978).

In Fig. 1, different colours represent the proportion of the total plot area considered devoted to these uses. Buildings (orange colour) occupy different proportion of the total plot area, depending on the urban configuration. It can be seen that in URB-1 and URB-2 (both single-family solutions) the area occupied by buildings is considerably higher than in the other cases.

The baseline data were the following:

- Total surface area of the plot: 100,000 m^2
- Buildable area[1]: 0.5 m^2/m^2
- Parking spaces: 1 per dwelling located on the underground levels

The following housing types were designed and calculated: (i) single-family detached house; (ii) single-family semi-detached/terraced house; (iii) high-rise apartment buildings of 40, 20, 10, and 5 floors. Different configurations of these building types produced the sample of housing development profiles that were analyzed in this research. Each design had a different number of buildings based on the initial premise that the above-ground built

[1] Buildable area was defined as m^2 of roofing divided by m^2 of buildable land surface.

area was 50,000 m^2. The underground surface was not regarded as housing surface and was used for garage and parking spaces. The following profiles were analyzed:

- URB-1. Housing development of single-family detached houses.
- URB-2. Housing development with single-family semi-detached houses.
- URB-3. Housing development with eight 5-floor high-rise apartment buildings and one underground level for garage and parking spaces.
- URB-4. Housing development with four 10-floor high-rise apartment buildings and two underground levels for garage and parking spaces.
- URB-5. Housing development with two 20-floor high-rise apartment buildings and four underground levels for garage and parking spaces.
- URB-6. Housing development with one 40-floor high-rise apartment building and eight underground levels for garage and parking spaces.

The design of each of these alternatives was in compliance with national and regional laws in Spain for urban planning and construction. These regulations are clearly stated in the Land Act (Ministerio de Vivienda 2008), in the regulations that implement this act (Ministerio de Obras Públicas y Urbanismo 1978) and in the Spanish Technical Building Code (Ministerio de Fomento 2003).

For the case of the apartment building, the floor plan (Fig. 2c), was the same for all of the high-rise buildings. Consequently, profiles URB-3, URB-4, URB-5, and URB-6 only vary in regards to the number of apartment buildings as well as to the number of floors and levels above and below ground. In this manner, the total built surface area (50,000 m^2) remains constant. The number of underground levels was calculated such that there was one parking space per dwelling.

With regards to each housing development profile, Table 2 shows the building characteristics, and Table 3 lists the urban planning features.

Frame calculation of the buildings

The foundations and frame elements of buildings are the main source of environmental impact during the buildings' life cycle. This is due to the fact that the construction materials (mainly steel and concrete) are the highest contributors of CO_2 emissions (Varun et al. 2012).

Once the floor plan and height of the buildings were defined, their foundation and structural elements were calculated in order to specify the construction work units. This made it possible to obtain the amounts of concrete (m^3) and steel (kg) used. The buildings were designed with a slab foundation and the structural framework was composed of columns and concrete waffle slabs.

The following model was used to calculate the building frame. The frame was made up of bar-type elements (i.e., columns, beams, and floor slabs) as well as finite triangular elements that model the walls. The stresses on these bar elements were calculated with a matrix stiffness method. Accordingly, the relation between the stresses and deformations of the bar elements was assumed to be linear with six degrees of freedom per node. For each element, there was a relation between the stresses acting on it and the displacement, based on the relation, $f = K \times D$, where K is the stiffness matrix of the element, and D is the displacement of the nodes. This method was used to formulate and resolve the equation system or stiffness matrix of the frame, thus obtaining the displacements of the nodes due to the set of loads. The stresses on the nodes could then be obtained, depending on the displacements, $\{F\} = [K] \times \{d\}$. This calculation was performed with the software program, CYPECAD® (CYPE Ingenieros S.A. 2012).

The values of the actions considered for the dimensioning of the frame elements were the following:

- Gravity load floor: 1.9 kN/m^2 (partition walls: 100 kg/m^2 + dead loads: 0.9 kN/m^2= 1.9 kN/m^2).
- Gravity load roof : 2.4 kN/m^2 (roofing: 2.4 kN/m^2).
- Live load: 3.0 kN/m^2.
- Snow: 1.0 kN/m^2.
- Wind velocity: 26 m/s.

Once the frame structure had been calculated, the quantities of steel and concrete per m^2 were obtained for each of the building profiles. Results are plotted in Fig. 3. The vertical left axis indicates the amount of concrete used in the foundation and frame elements of each housing profile, expressed in m^3 of concrete by each m^2 of built area. The dotted line (vertical right axis) plots the amount of steel involved in those activities (in kg/m^2 of built area).

This section included a description of the case study of this research. In consonance with urban norms, six different urbanization layouts were defined, and the floor plan of each is depicted. Construction systems, building materials and frame calculation are also described. Hence, this section offers an overview of different urban layouts and their implications for building design and, consequently, future results.

Calculation of the emissions due to the construction of the buildings

The CO_2 emissions were calculated with the information from different databases that provided the values of the CO_2 emissions for the various components of the construction work units. Emissions due to operation stage of the building are not included in this study. Those databases

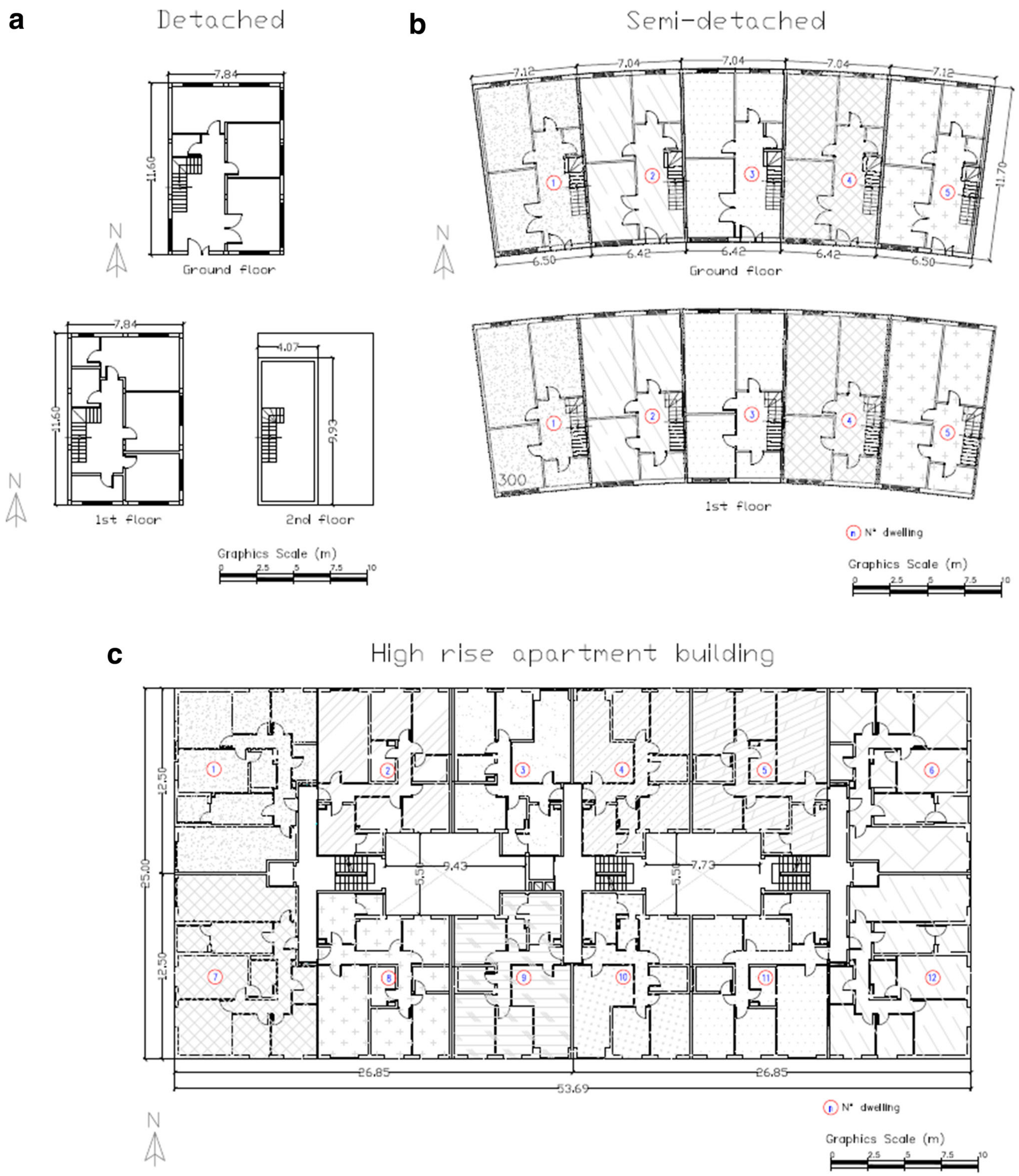


Fig. 2 **a–c** Floor plan distributions of each of the case study

used as information sources to obtain the CO_2 emissions were the following: Inventory of Carbon and Energy (ICE) (Hammond and Jones 2011), the Environmental Product Declaration (EPD) provided by the manufacturers, and the database of the Instituto de Tecnología de la Construcción of Catalonia (ITEC 2012). These databases have been previously used in similar studies (Zabalza Bribián et al. 2009; Solís-Guzmán et al. 2013).

Table 2 Housing profile characteristics

Profile	No. of floors above ground	No. of floors below ground (parking)	Surface of building units above ground (m^2)	Surface of building units below ground (m^2)	Total surface of building units (m^2)	No. of buildings per profile	Total No. of dwellings per profile	Total built surface above ground (m^2)
Detached	2+ tower	1	222.00	85.00	307.00	225	225	50,000.00
Semi-detached	2	1	770.00	374.00	1144.00	65	325	50,000.00
5-floor apt. building	5	1	6250.00	1342.00	7592.00	8	60	50,000.00
10-floor apt. building	10	2	12,500.00	2685.00	15,185.00	4	120	50,000.00
20-floor apt. building	20	4	25,000.00	5369.00	30,369.00	2	240	50,000.00
40-floor apt. building	40	8	50,000.00	10,739.00	60,739.00	1	480	50,000.00

The profile of the material quantities used varies depending on the building case study. A description of material distribution is included in Table 4. Columns 1 and 2 contain the materials that are most commonly used in abundance (based on total mass), grouped by task (González and García Navarro 2006). The major materials are: concrete, steel, wood, ceramic brick, mortar, plaster, natural stone, ceramic tile, paintings, insulation materials (mineral wool, polythene, bitumen, asphalt sheet) and synthetic pipes (PVC and polyethylene). Column 3 includes some clarifications on the specific element assessed. The embodied energy of each material by unit (in MJ/kg) is shown in column 4, and its equivalent in CO_2 emissions (in $kgCO_2/kg$) is included in column 5.

The following columns include the total quantity of each material (in tonnes) derived in each case study. For comparative purposes, we give the total material quantities necessary to build all the buildings in each urbanization solution (see Table 3) to build the total considered surface area (50,000 m^2).

The most common materials are concrete, ceramic brick, mortar and ceramic floor tile. Steel, painting and synthetic pipes must be highlighted due to their high embodied energy and carbon emission rates. These results are in accordance with (Paulsen and Sposto 2013; Jeong et al. 2012).

Some differences are appreciable in material distribution by building type. In the case of materials involved in foundations and structure (concrete and steel), there is a noteworthy effect of (a) spatial distribution; and (b) structural requirements. Although single-family houses do not require massive quantities of steel and concrete, the need to build a vast number of houses to cover the studied area makes them a high-consuming solution. In the case of high-rise buildings, due to foundation requirements, URB-6 (the tallest one) consumes more structural materials. Single-family housing (detached and semi-detached) shows a major consumption of materials involved in external and internal walls (ceramic brick) and claddings (ceramic floor tile, painting).

In global terms, single-family solutions consume more material quantities than do high-rise solutions because a higher number of units is needed to cover the area. However, the effect of a massive structural material requirement in very high rise buildings must be considered.

The CO_2 emissions, as calculated with the information from the different databases, led us to determine the embodied energy for each material and its equivalent CO_2 emissions, based on the type and weight of the material, including its packaging.

Complex products were decomposed into simple materials in order to determine their embodied energy and emissions values. Each work unit was composed of materials, manpower, and machinery. Table 5 shows the emissions ($kgCO_2$) produced during the manufacture of various construction materials.

In the transport and construction phases, the criteria used were those of the CYPE database (CYPE Ingenieros S.A. 2012). It was thus considered that for the A4 module in the Construction Process Stage, construction materials were transported in diesel-powered trucks with an average load and fuel consumption per kilometer and kilogram of the material transported. The values obtained depended on the distance travelled and whether the scope was local, regional, national, or international.

In the case of the A5 module (construction/installation on-site processes), we considered the embodied energy and emissions produced by the machinery, auxiliary equipment, and waste transportation to the landfill. As an example, Table 6 shows the construction units necessary and the cost (€) of the on-site manufacturing and placement of 1 m^3 of concrete foundation slab with a strength of

Table 3 Urban planning characteristics

			LAND DIVISION CATEGORIES	Detached (URB-1) Surface [m²]	Detached (URB-1) No. of dwellings	Semi-Detached (URB-2) Surface [m²]	Semi-Detached (URB-2) No. of dwellings	5-floor building (URB-3) Surface [m²]	5-floor building (URB-3) No. of dwellings	10-fl. apt. building (URB- Surface [m²]	10-fl. apt. building (URB- No. of dwellings	20-fl. apt. building (URB- Surface [m²]	20-fl. apt. building (URB- No. of dwellings	40-fl. apt. building (URB- Surface [m²]	40-fl. apt. building (URB- No. of dwellings
PLANNING OF THE SECTOR	USEFUL LAND	RESIDENTIAL LAND. BASIC UNIT	Block 1	3,231.08	14	3,231.08	20	10,104.50	120	10,104.50	120	21,077.20	240	43,022.61	480
			Block 2	5,219.85	23	5,219.85	30	10,104.50	120	10,104.50	120	21,077.20	240		
			Block 3	3,407.67	15	3,407.67	25	10,104.50	120	10,104.50	120				
			Block 4	3,231.08	14	3,231.08	20	10,104.50	120	10,104.50	120				
			Block 5	5,219.85	23	5,219.85	30								
			Block 6	3,407.67	15	3,407.67	25								
			Block 7	3,231.08	14	3,231.08	20								
			Block 8	5,219.85	23	5,219.85	30								
			Block 9	3,407.67	15	3,407.67	25								
			Block 10	3,231.08	14	3,231.08	20								
			Block 11	5,219.85	23	5,219.85	30								
			Block 12	3,407.67	15	3,407.67	25								
			Block 13	4,100.54	17	4,100.54	25								
			TOTAL RESIDENTIAL LAND USE	51,534.94	225	51,534.94	325	40,418.00	480	40,418.00	480	42,154.40	480	43,022.61	480
	PUBLIC LAND CONCEDED	MINIMUM MODULES OF RESERVATIONS FOR ALLOTMENTS	Allotted land: Land allotment for commercial use	1,151.10		1,151.10		1,151.10		1,151.10		1,151.10		1,151.10	
			Allotted land: Land allotted for social use	1,511.13		1,511.13		1,511.13		1,511.13		1,511.13		1,511.13	
			Allotted land: Land allotted for school use	6,043.59		6,043.59		6,043.59		6,043.59		6,043.59		6,043.59	
			Allotted land: Land allotted for sports installations	4,167.86		4,167.86		4,167.86		4,167.86		4,167.86		4,167.86	
			Total Land Allottedl	12,873.68		12,873.68		12,873.68		12,873.68		12,873.68		12,873.68	
			Leisure space	10,000.37		10,000.37		31,052.56		31,052.56		31,052.56		31,052.56	
			Total land use for leisure areas	10,000.37		10,000.37		31,052.56		31,052.56		31,052.56		31,052.56	
		TOTAL LAND RESERVED FOR ALLOTMENTS		22,874.05		22,874.05		43,926.24		43,926.24		43,926.24		43,926.24	
		ROAD SYSTEM	Parking		164		164		385		385		433		427
			Road	25,591.01		25,591.01		15,655.76		15,655.76		13,919.36		13,051.15	
		TOTAL LAND USE FOR THE ROAD NETWORK		25,591.01		25,591.01		15,655.76		15,655.76		13,919.36		13,051.15	
		CEDED PUBLIC LAND		47,313.96		47,313.96		58,430.90		58,430.90		56,694.50		55,826.29	
	TOTAL LAND DESIGNATED FOR BUILDING			100,000.00											

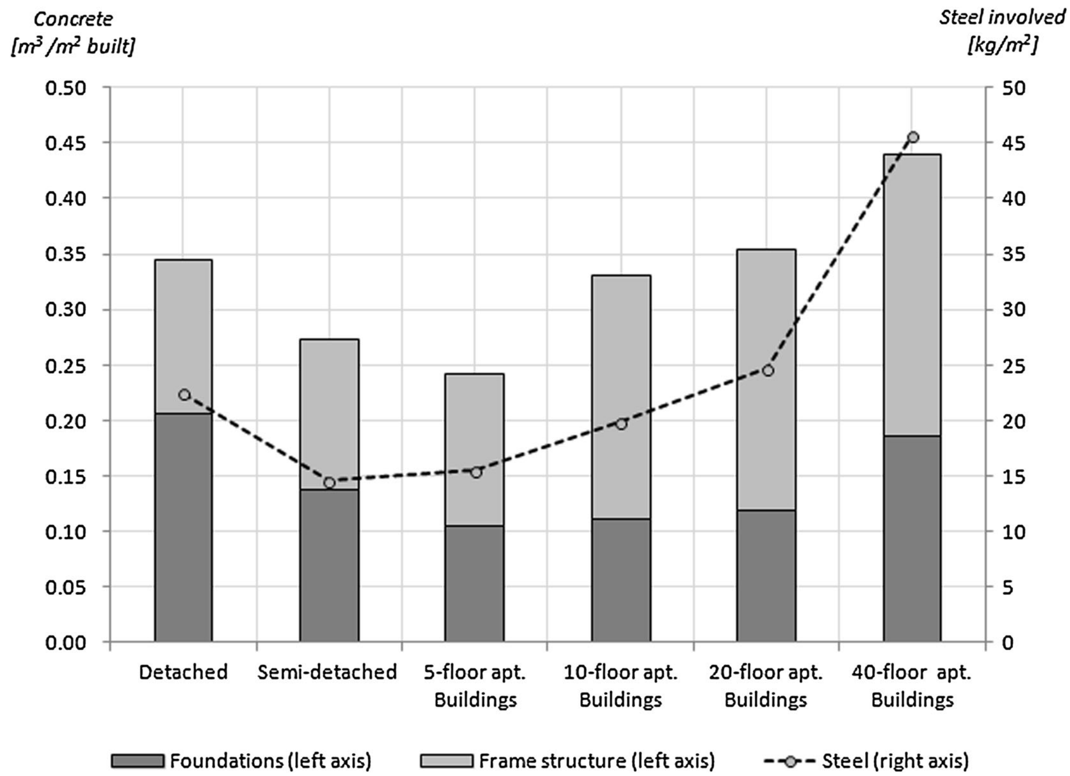


Fig. 3 Quantities of concrete and steel in the frame elements of the building profiles

25 N/mm^2 and 40.1 kg/m steel reinforcement per m^3 of concrete.

After calculating the quantity of the elements in each work unit (see Table 4), their emission value was obtained based on the following criteria:

- Emissions produced by the materials as specified by the database information.
- Manpower with no CO_2 emissions.
- Fuel consumption.

As an example, Table 7 shows the total CO_2eq (kg) for the manufacture and placing of a foundation slab made of steel and concrete.

Once the CO_2 emission values were calculated for the work units in each of the previously mentioned categories, measurements were performed to obtain the total CO_2 emissions (kg CO_2/m^2) for each of the housing profiles. The results were the following: (i) single-family house (402.73); (ii) single-family semi-detached house (365.77); (iii) 5-floor apartment building (363.58); (iv) 10-floor apartment building (376.09); (v) 20-floor apartment building (394.47); and (vi) 40-floor apartment building (461.36).[2]

[2] These values do not include the emissions from the interior development of the land plot.

Figure 4 shows the CO_2 emissions (kgCO_2/m^2) for each construction work unit category and housing profile. The construction work units were classified in the following categories: (1) earth-moving; (2) foundations; (3) frame elements; (4) façades; (5) partition walls; (6) installations; (7) insulation and waterproofing; (8) roofing; (9) siding; (10) signs and equipment; (11) interior development of the land plot; and (12) waste management.

For example, for a 5-floor apartment building, the foundations, frame elements, and façades account for 53.1 % of the emissions (see Fig. 5). Not surprisingly, these parts of the building are largely composed of concrete and steel. Various authors indicate that work units manufactured with concrete, cement, and steel (i.e., the structure, frame elements, envelope, and masonry) are the source of most of the CO_2 emissions during the building construction (González and García Navarro 2006; Varun et al. 2012). Asif et al. concluded that concrete was responsible for a high percentage of the embodied energy and associated environmental impacts generated by housing construction (Asif et al. 2007).

A more in-depth analysis of the materials in the work units shows that the steel required for the structure of the 5-floor apartment building was responsible for 25.06 % of the total emissions, and that the concrete in the structure was responsible for 20.86 %. When 6.85 % from the mortar was added to this total, this signified that almost

Table 4 Amount of major construction materials required for building each case studied

Task	Material	Specific element	Embodied energy by unit (MJ/kg)	CO_2 emissions ($kgCO_2/kg$)	Quantity (tonnes)					
					URB-1	URB-2	URB-3	URB-4	URB-5	URB-6
Foundations	Concrete	Mass concrete for reinforced concrete	1.0578	0.0991	30,942.45	30,714.97	17,266.30	16,740.59	17,661.72	26,239.82
	Steel	Raw steel and reinforced concrete	35.3239	2.8240	718.88	660.14	410.69	314.20	337.82	876.39
	Wood	Formwork	3.0447	0.0905	344.80	307.65	62.52	60.43	61.54	145.23
Structure	Concrete	Reinforced concrete	1.0578	0.0991	20,859.30	29,839.81	22,594.35	32,855.77	34,780.46	35,743.58
	Steel	Raw steel and reinforced concrete	35.3239	2.8240	811.35	811.59	756.22	1040.76	1328.19	2050.02
	Wood	Formwork	3.0447	0.0905	117.47	110.98	98.54	101.96	106.82	107.09
External wall	Ceramic brick		4.5444	0.3408	9541.48	4743.77	3546.07	3456.08	3414.54	3435.98
	Mortar		1.2144	0.1133	3201.98	1678.64	1742.23	1384.81	1286.61	1245.45
	Natural stone	Stone coping	0.2244	0.0232	107.59	82.27	115.17	104.72	101.41	80.33
	Steel	Raw steel	35.3239	2.8240	25.10	23.19	20.19	20.19	20.19	20.39
	Ceramic wall tile		10.3374	0.7750	7.14	3.55	2.52	2.52	2.52	2.55
	Additive	Water-repellent additive	99.8158	14.7500	5.85	2.91	2.07	2.07	2.07	2.09
	Aluminum	Aluminum frame	160.3404	23.5454	4.04	7.57	20.52	16.11	16.11	15.90
Partitions	Ceramic brick		4.5444	0.3408	8062.48	3208.32	5240.35	5240.35	5240.35	5240.35
	Mortar, plaster		1.2144	0.1133	2543.63	1084.33	1697.42	1697.46	1697.42	1697.42
Claddings	Mortar, plaster		1.2144	0.1133	10,063.35	8126.92	7198.41	7979.62	8136.39	7840.37
	Ceramic floor tile		10.3374	0.7750	5693.68	5386.11	5173.10	5124.78	4831.42	4831.42
	Painting		70.0000	2.9100	140.04	138.80	62.86	62.86	62.89	62.89
Roof	Mortar, plaster		1.2144	0.1133	3616.65	4428.71	1774.27	772.24	437.53	220.72
	Ceramic floor tile		10.3374	0.7750	1233.92	1509.05	650.82	302.81	148.46	74.23
	Ceramic brick		4.5444	0.3408	155.46	189.66	75.76	48.84	19.71	10.03
Insulation	Mineral wool	Mineral wool insulating	15.2690	1.3909	217.35	281.11	213.45	189.50	185.91	149.19
	Polythene		77.0081	11.3952	79.28	91.14	76.24	59.50	55.91	54.94
	Bitumen	Modified bitumen	10.0700	1.4747	28.50	30.99	15.05	10.48	7.28	5.68
	Asphalt sheet	Synthetic rubber	44.4167	6.5033	0.70	1.94	1.37	1.24	1.18	1.15
Piping	Synthetic PVC pipe	General PVC	80.3374	11.8650	56.29	66.06	95.93	101.93	50.97	48.15
	Synthetic polyethylene pipe	Low density	77.3367	11.4217	6.85	6.81	10.31	10.46	10.74	11.68
		Total			98,585.60	93,536.99	68,922.70	77,702.28	80,006.17	90,213.02

Sources: Inventory of Carbon and Energy (Hammond and Jones 2011), database of the *Instituto de Tecnología de la Construcción* (ITEC 2012), Environmental Product Declaration (EPD)

Table 5 Emissions generated by single elements in the construction work units

Materials	Density (kg/m^3)	Embodied energy (MJ/kg)	Carbon data (kgCO_2/kg)	Unit	Carbon data (kgCO_2/unit)
Steel	7850	3.81	2.82	kg	2.82
Concrete	2340	1.06	0.1	m^3	231.83
Mortar (M5)	1650	1.58	0.15	m^3	242.91
Cement	1880	7.34	0.68	m^3	1284.04
Wood (beech)	510	3.04	0.09	m^3	46.04
Baked clay	850	4.29	0.32	m.u.	528.27
Sand	1800	0.12	0.01	m^3	11.91
Plaster	1200	3.34	0.3	m^3	356.38
PVC	1380	80.34	11.86	ml	16.05
Expanded polystyrene	24	101.08	14.92	m^2	3.58
Aluminum	2700	160.34	23.55	m^2	317.86
Glass	2490	19.34	1.15	m^2	11.41
Bitumen	2400	10.07	1.47	m^2	3.54

Sources: (Hammond and Jones 2011); ITEC 2012) and the Environmental Product Declaration given by manufacturers

Units: baked clay 1 unit 24 cm × 11.5 cm × 7 cm; PVC pipe with a diameter of 200 mm and a thickness of 4.9 mm; expanded polystyrene with a thickness of 1 cm; aluminum with a thickness of 5 mm; glass with a thickness of 4 mm; bitumen with a thickness of 1 mm

Table 6 Cost of the on-site manufacturing and placement of 1 m^3 of foundation slab made of HA-25 concrete and 40.1 kg/m steel reinforcement per m^3 of concrete

Concept	Quantity	Unit	Cost per unit (€)	Total cost (€)
Hard plastic separator for foundations	5.00	unit	0.12	0.60
Corrugated steel bars, UNE-EN 10080 B 500 S, manufactured with various diameters and placed on site	40.10	kg	0.89	35.69
HA-25/B/20/IIa concrete mixed at a plant and placed with a concrete bucket skip	1.05	m^3	65.83	69.12
Smooth PVC pipe for flow tubes (various diameters)	0.01	m	6.23	0.06
Concrete vibrator (3 m)	0.34	h	4.61	1.58
Skilled construction worker	0.14	h	18.33	2.55
Unskilled laborer	0.14	h	17.08	2.37
Total direct cost				111.97

Table 7 Total CO_2eq (kg) for the manufacture and placing of a foundation slab made of HA-25 concrete and 40.1 kg steel per m^3 of concrete

	Amount	Unit	Emissions in CO_2 equivalent (kg)			
			A1–A2–A3	A4	A5	A1–A2–A3–A4–A5
Materials						
Steel	40.10	kg	112.28	1.00		
Concrete	2415.00	kg	236.09	3.17		
Machinery						
Diesel	1.02	dm^3			2.79	2.79
Auxiliary					0.02	0.02
Construction wastes						
Transport to landfill	25.78	kg			0.08	0.08
Total CO_2 emissions (kg/m^3)			348.37	4.18	2.88	355.43 kg eq CO_2/m^3

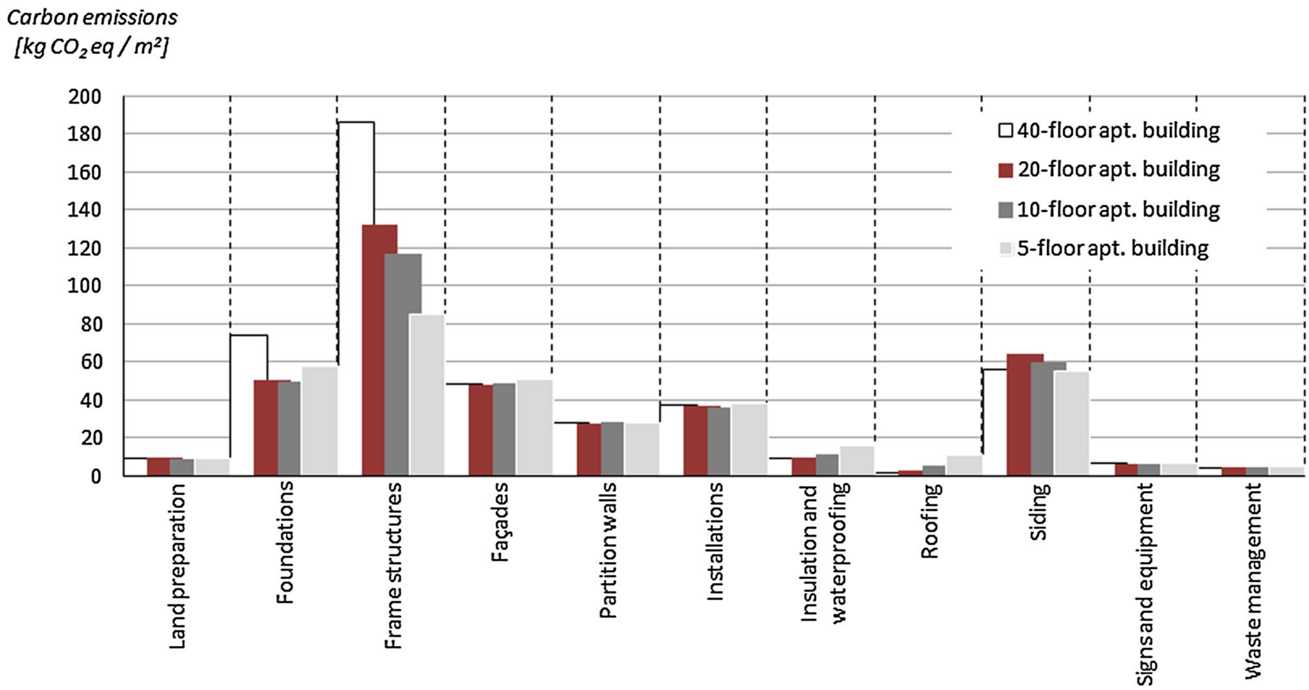
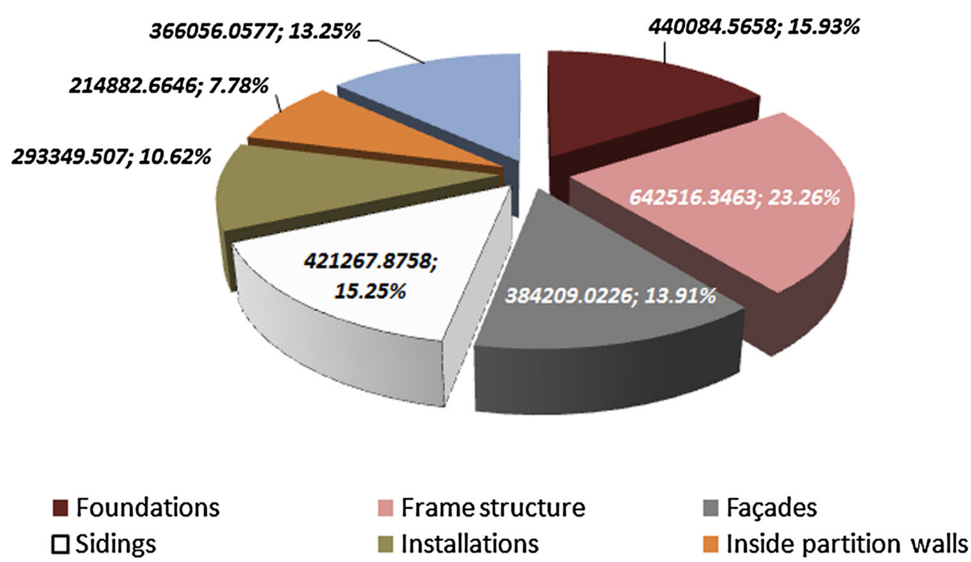


Fig. 4 CO_2 emissions ($kgCO_2/m^2$) for each construction work unit category and housing profile

Fig. 5 Distribution of the CO_2 emissions ($kgCO_2$) for a 5-floor apartment building



half of the CO_2 emissions were due to construction materials made with cement and steel. Figure 6 shows the emissions generated by the on-site manufacture and placing of the materials used to build a 5-floor apartment building.

In this section, the details of the carbon assessment procedure were provided. Table 4 depicts material quantities for each case study. Differences in material distribution across urban configurations can be found. The total CO_2 emissions (kg CO_2/m^2) for each of the housing profiles were obtained (Fig. 4).

Calculation of the installations within the area of the housing development

For each of the six housing development alternatives in our sample (see Fig. 1), we designed a road network as well as the following installations: water supply system, sewage

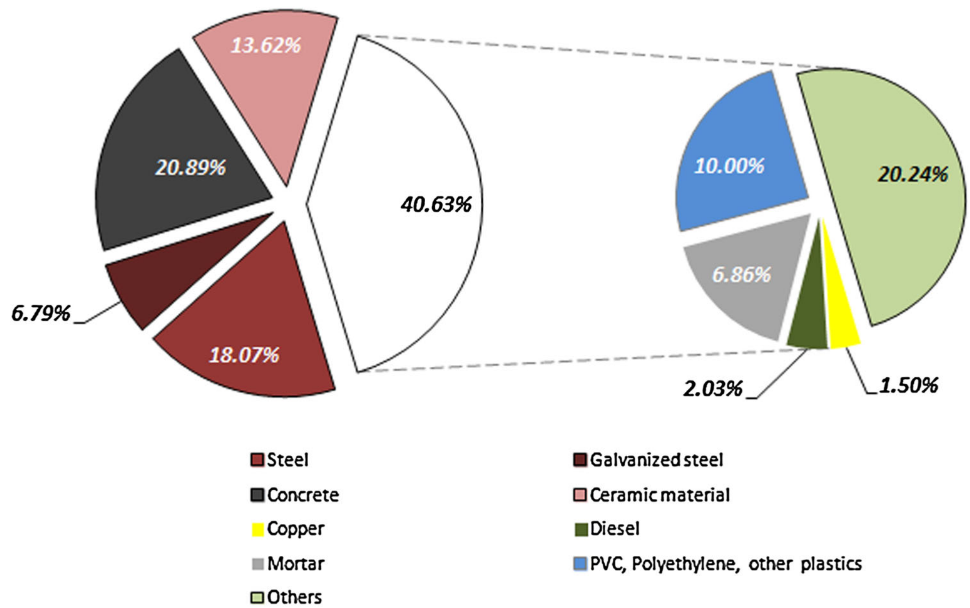


Fig. 6 Distribution of CO_2 emissions ($kgCO_2/m^2$) generated by the construction materials needed for a 5-floor apartment building

network, electricity grid, telephone system, landscaped areas, and watering system.

Water supply The design of the water supply system was based on a consumption of 350 l/day·cap, a point coefficient of 2.4, and four inhabitants per dwelling. In reference to social, school, and commercial areas, the water consumption was quantified at 10/liters/m^2/day. The water supply system also included water hydrants for street cleaning (8.3 l/s) as well as water hydrants for fire protection (16.63 l/s).

The material used in the design of the drainage system was cast-iron pipe fittings for diameters greater than or equal to 150 mm and high-density polyethylene pipes for diameters smaller than 150 mm. The pipes were located at a depth of 1.5 m. Each pipe was placed on 10 cm of bedding material, and the trench filled with material from the excavation.

The system was calculated with a maximum flow speed of 2.5 m/s and a minimum flow speed of 0.5 m/s. The minimum pressure was 15 m of water column above the level of the last frame element of the buildings, and the maximum pressure was 60 m of water column. Based on these constraints, we designed the network using the Hardy–Cross method and the formulas of Darcy–Weisbach, Hagen–Poiseuille and Colebrook–White to calculate the head losses because of the friction in the pipeline (see appendix A).

Sewage network The sewage system was designed with a maximum slope of 5.0 % and a minimum slope of 0.5 %. The maximum slope was 3 m/s for wastewater and 5 m/s for rainwater. The minimum flow speed was 0.5 m/s. The pipeline was buried with at least 50 cm of soil between the top of the pipe and the ground level. The material for the sewage network was the following: concrete piping for diameters greater than or equal to 0.5 m, and PVC piping for smaller diameters.

The system was designed to drain both wastewater and rainwater. The drainage of wastewater was based on 350 L/day·cap, a point coefficient of 2.4, and four inhabitants per dwelling.

The calculation of the rainwater flow volume was performed with the rational method, according to the formula (1) (Témez 1991).

$$Q = C \times I_t \times A/3.6 \quad (1)$$

where C is runoff coefficient in m^3/s; I_t is rain intensity for a ten-year return period, in mm/h, and A is area of the water shed.

The hydraulic calculation of the pipelines was performed with the Manning–Strickler formula (2):

$$V = R \times h^{\frac{2}{3}} \times I^{\frac{1}{2}}/n \quad (2)$$

where V is mean (m/s); Rh is hydraulic radius (m); I is hydraulic slope (m/m) and n is the Manning coefficient.

Electricity grid The electricity grid was calculated with the following design parameters[3]:

[3] In each case, the nominal power is specified by the electricity distribution company in the area. As a reference, the values adopted were the ones specified by the Spanish electricity company, Endesa S. A. (Resolution 23-03-2006 of the Directorate General of Industry, Energy, and Mining of Spain *D.G.*).

- Highest line voltage: 20 kV.
- Highest voltage for equipment: 36 kV.
- Rated lightning impulse withstand voltage: 170 kV peak.
- Rated power frequency withstand voltage: 70 kV.

Generally speaking, a rated short-time current of 1 s in kA was established for the medium-voltage grid. Similarly, the peak value of the maximal short-circuit current was 40 kA. The maximum value of the earth fault current was 300 A or 1000 A per transformer.

In medium-voltage lines, the voltage was quantified by calculating the number of transformation centers, taking into account the simultaneity of operation and the structure of the grid. A simultaneity coefficient of 0.8 was applied to the sum of the voltage in the transformation centers.[4] The material for the cables was aluminum with standard sections of 150 and 240 mm^2 (XLPE and EPR dry insulation). In power lines with a nominal voltage of 20 kV, the conductor to be installed was 18/30 kV.

In the electricity grid, a nominal power in the low-voltage grid of 230/400 V corresponds to a building electrification of 9200 W. The total power of the houses was obtained by multiplying the mean value of the maximum power in each dwelling by the simultaneity coefficient, *Cs*.[5]

Table 3 shows the space allotted for different uses in the urban planning regulations. The electrical power projected for each use is the following: school equipment, 5 kW/100 m^2; sports equipment, 3 kW/100 m^2; social equipment, 4 kW/100 m^2; commercial use, 10 kW/100 m^2; and road network, parking areas, and leisure spaces, 0.002 kW/m^2.

Street lighting The streets were lit with metal halide lamps of 150 W. The mean illuminance was 15 lux and the height of each luminaire was 8 m. The number of luminaires was calculated by the following formula:

$$N = (E_m \times S)/(n \times \mu \times F \times f_c) \quad (3)$$

where N is the number of projectors; E_m is recommended mean illuminance; S is the mean illuminated surface in m^2 (l $\times$ a); n is number of lamps; F is the lumens per lamp (lm) or projector; μ is the utilization factor or coefficient of beam utilization, C.B.U. (defined as the ratio of the lumens that reach the illuminated surface and the beam lumens), with a value ranging from 0.6 to 0.9.; and fc is the maintenance factor (value ranging from 0.65–0.80).

Telephone and gas networks The telecommunications network was designed to comply with Spanish legislation.[6] The cable conduits were polyvinyl chloride (PVC) pipes having diameters of 110, 63, and 40 mm.

The design parameters for the gas network were the following:

- Fuel in the network: natural gas.
- Maximum supply pressure: 0.4 bar. M
- Material for the pipeline: HDPE SDR17 1.3/2.
- Space allotted per dwelling: 1.4 m^3/h.

Emissions generated by the construction of the housing development

The same procedure used for building construction was applied to the civil engineering work. Similarly as done for buildings in the previous section, Table 8 summarizes the profile of quantity materials involved in the urbanization work in each case study. Columns 1 and 2 contains the materials that are most commonly used in abundance (based on total mass), grouped by task. Those major materials are: aggregates, concrete, cast iron, brick, mortar, galvanized steel, PVC, precast, aluminum, polyethylene, cement, bitumen, stone, ceramic paver, wood. Column 3 includes some clarifications on the specific element assessed. The embodied energy of each material by unit (in MJ/kg) is shown in column 4, and its equivalent in CO_2 emissions (in kgCO_2/kg) is included in column 5. The following columns include the total quantity of each material (in tonnes) derived in each case study.

Clearly, the most common material is aggregates, followed by concrete, stone and mortar. Cast iron and PVC must be highlighted due to their high embodied energy and carbon emissions rates.

The total number of construction work units, 459, was divided into the following categories: (1) land preparation; (2) earth-moving; (3) water supply network; (4) sewage network; (5) medium-voltage grid; (6) low-voltage grid; (7) public lighting; (8) telecommunications network; (9) gas network; (10) pavement; (11) landscaping; (12) green areas; (13) watering network; (14) street furniture; (15) signs.

After calculating the CO_2 emissions generated by the work units in each of the previously mentioned categories,

[4] According to the Circular of 14 October 2004 of the Directorate General of Industry, Energy, and Mining of Spain regarding the estimated electrical power loads and simultaneity coefficients in residential and industrial areas. BOJA 216.

[5] The Cs coefficient is specified in official regulations. In Spain, this coefficient can be found in the ITC-BT-10 Technical Guidelines.

[6] The regulations applied were the Norma Técnica de Planificación Tecnológica de Telefónica de España, S.A., NT.f1.003 and those in Construction Method n 434.012 of Canalizaciones Subterráneas (Underground Conduits).

Table 8 Amount of major construction materials required for the urbanization of each case studied

Task	Material	Specific element	Embodied energy by unit (MJ/kg)	CO_2 emissions ($kgCO_2/kg$)	Quantity (tonnes)					
					URB-1	URB-2	URB-3	URB-4	URB-5	URB-6
Water supply	Aggregates		0.1178	0.0066	7910.76	7845.83	1888.88	1884.76	1850.88	1732.14
	Concrete	Manhole	1.0578	0.0991	625.72	555.48	182.24	177.78	152.32	151.21
	Cast iron	Pipe	33.4560	2.6731	179.97	165.02	34.60	33.65	29.63	27.64
	Cast iron	Valve	32.8000	2.6195	49.92	46.79	6.45	10.67	9.44	8.91
	Brick	Manhole	4.5444	0.3408	56.04	42.57	3.64	2.78	2.35	2.14
	Mortar		1.2144	0.1133	33.45	25.41	2.17	1.66	1.40	1.28
	Galvanised steel	Valve	41.7000	3.1500	13.54	10.29	0.88	0.68	0.57	0.52
Sewage network	Aggregates		0.1178	0.0066	27,276.52	35,218.18	12,198.61	11,575.12	10,446.92	9815.59
	Concrete	Precast	1.0578	0.0991	1197.84	2002.91	379.08	425.53	411.59	362.27
	PVC	Pipe	80.3374	12.0331	104.56	120.05	33.02	30.11	27.62	26.55
	Precast	Pipe	1.3674	0.1218	85.61	85.61	54.24	54.24	54.24	54.24
	Cast iron	Valve	32.8000	2.6207	2.15	52.83	10.05	10.37	10.50	8.70
	Steel	Manhole	34.8766	2.7895	6.77	11.41	2.14	2.41	2.32	2.05
Medium-voltage grid	Aggregates		0.1178	0.0066	2292.91	2292.91	2291.54	2291.54	2291.54	2291.54
	Precast	Manhole	2.3000	0.2200	14.28	14.28	23.53	23.53	23.53	23.53
	PVC	Pipe	80.3374	12.0331	5.65	5.65	5.49	5.49	5.49	5.49
Low-voltage grid	Aggregates	Trenches	0.1178	0.0066	4221.69	4153.65	1809.23	901.86	309.20	285.38
	Precast	Manhole	2.3000	0.2200	230.92	215.28	14.72	10.12	5.52	5.52
	Cast iron	valve	32.8000	2.6195	26.10	24.34	1.66	1.14	0.62	0.62
	PVC	Pipe	80.3374	12.0331	24.24	24.12	10.68	6.37	2.16	2.03
	Aluminum	Cable	43.4391	3.2144	11.27	11.21	4.96	1.47	1.00	0.94
Public lighting	Aggregates	Trenches	0.1178	0.0066	2526.65	2526.65	1810.15	1810.15	1728.32	1676.76
	Polyethylene	Pipe	77.3372	11.4209	10.13	10.13	6.91	6.91	6.68	6.48
Telecommunications network	Aggregates	Trenches	0.1178	0.0066	3234.84	4934.77	1116.50	1140.94	1139.06	755.07
	Steel	Manhole	35.3374	2.8250	55.90	76.42	37.21	33.57	29.01	19.89
	Cement	Trenches	3.7788	0.8327	55.65	65.06	25.28	25.14	24.96	19.83
Gas network	Aggregates	Trenches	0.1178	0.0066	3468.77	3468.77	783.01	823.89	652.99	651.74
	Concrete	Manhole	1.0578	0.0991	197.84	197.84	19.62	13.08	3.44	1.72
	Polyethylene	Pipe	77.3372	11.4209	5.49	5.49	1.48	1.39	0.85	0.94
Pavement	Aggregates	Pavement	0.1178	0.0066	25,463.32	25,477.37	18,646.92	18,646.92	17,136.84	16,383.99
	Concrete	Sidewalk	1.0578	0.0991	8563.35	8563.35	5186.00	5186.00	4931.50	4650.16
	Stone	Sidewalk	0.1800	0.0200	791.52	791.52	747.54	747.54	707.56	670.83
	Mortar	Sidewalk	1.2144	0.1133	726.76	726.76	355.90	355.90	324.96	305.67
	Precast	Sidewalk	2.3000	0.2200	700.61	700.61	318.00	318.00	283.69	266.53

Table 8 continued

Task	Material	Specific element	Embodied energy by unit (MJ/kg)	CO_2 emissions ($kgCO_2$/kg)	Quantity (tonnes) URB-1	URB-2	URB-3	URB-4	URB-5	URB-6
	Bitumen	Pavement	0.1178	0.0066	164.66	149.74	112.53	112.53	104.21	100.05
	Cement		3.7788	0.8327	10.70	10.70	4.86	4.86	4.33	4.07
Green areas	Aggregates	Pavement	0.1178	0.0066	4255.32	4255.32	12,144.97	12,144.97	12,144.97	12,144.97
	Concrete	Pavement	1.0578	0.0991	2342.43	2342.43	5058.47	5058.47	5058.47	5058.47
	Ceramic paver	Pavement	7.1300	2.6600	296.90	296.90	567.55	567.55	567.55	567.55
	Precast	Pavement	2.3000	0.2200	82.79	82.79	184.41	184.41	184.41	184.41
	Steel	Pavement	35.3374	2.8250	2.54	2.54	8.57	8.57	8.57	8.57
	Wood	Pavement	3.0712	0.0922	0.83	0.83	1.63	1.63	1.63	1.63
Watering network	Aggregates	Trenches	0.1178	0.0066	159.43	159.43	654.50	649.34	649.34	649.34
	Concrete	Manhole	1.0578	0.0991	44.28	44.28	88.56	82.99	82.99	82.99
	Cast iron	Valve	32.8000	2.6195	2.69	2.69	10.54	9.11	9.11	9.11
Total					97,533.35	107,816.20	66,848.91	65,385.12	61,424.29	59,029.04

Sources: Inventory of Carbon and Energy (Hammond and Jones 2011), database of the Instituto de Tecnología de la Construcción (ITEC 2012), Environmental Product Declaration (EPD)

the total emissions were then measured for each of the six housing profiles (see Fig. 1). Graph 4 shows the following results,[7,8]: URB-1 (Single-family detached houses), 73.45 $kgCO_2/m^2$; URB-2 (Single-family semi-detached houses), 86.42 $kgCO_2/m^2$; URB-3 (eight 5-floor high-rise apartment buildings), 42.10 $kgCO_2/m^2$; URB-4 (four 10-floor high-rise apartment buildings), 40.18 $kgCO_2/m^2$; URB-5 (two 20-floor high-rise apartment buildings), 37.30 $kgCO_2/m^2$; and URB-6 (one 40-floor high-rise apartment building), 35.82 $kgCO_2/m^2$.

Figure 7 shows the CO_2 emissions ($kgCO_2/m^2$) for the construction work unit categories of the housing development profiles.

For example, in the case of URB-3, the profile with eight 5-floor apartment buildings, it was found that the sewage network, paving, and landscaping and treatment of green areas were responsible for 71.5 % of the emissions. Paving accounted for the largest percentage of emissions (42.2 %).[9]

Regarding the impact of the construction materials, the following materials were the source of 66.05 % of the emissions: asphalt (17.32 %); concrete (22.86 %); PVC pipes in the sewage network (13.17 %); and the cast-iron pipe fittings in the water supply system (12.7 %).

Moreover, 12.5 % of emissions were due to the fuel consumed by the machinery used in the urbanization process. As in the building construction, concrete was the source of most of the emissions. For this reason, policies conducive to reducing environmental impact should consider this important factor in the construction phase of urban planning (see Fig. 8).

This section summarizes the design of supply networks and services of each of the six housing development alternatives in our sample. Table 8 lists the major materials involved in each case study. The carbon emission levels (by work unit) were compared. The following section presents the results for the profiles, putting forth possible measures for reducing these emissions.

Results

After calculating the emissions of each of the housing profiles and of the urbanization process, we proceeded to obtain the total emissions as the sum of the emissions from

[7] The values per m^2 were obtained by dividing the total emissions into 100,000 m^2, the total surface area of the housing development.

[8] These values do not include the emissions from the development of the inner section of the land plot.

[9] In the case of the detached and semi-detached housing profiles where the road surface is greater, the sources of most emissions are the water supply network (13.56%), the sewage network (22.01%), and the pavement (36.45%). These values are for the detached housing profile.

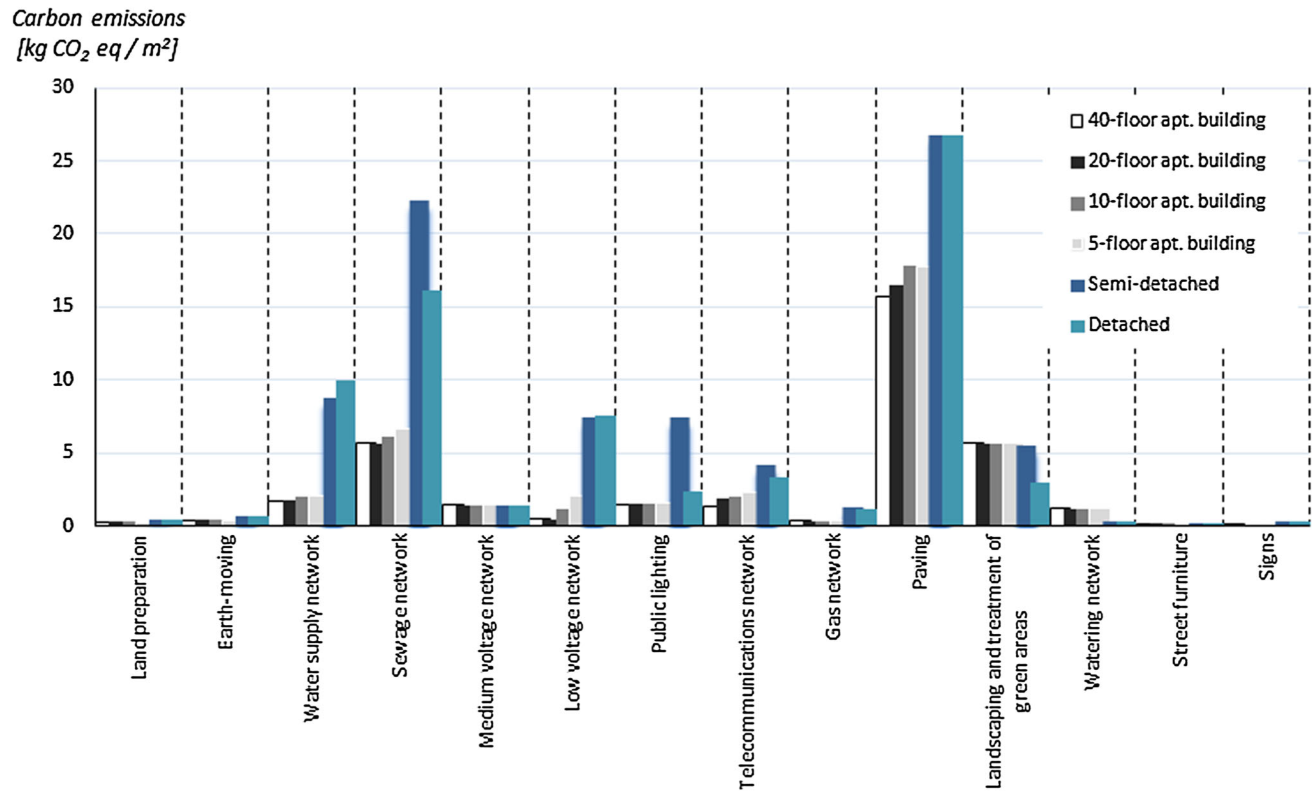
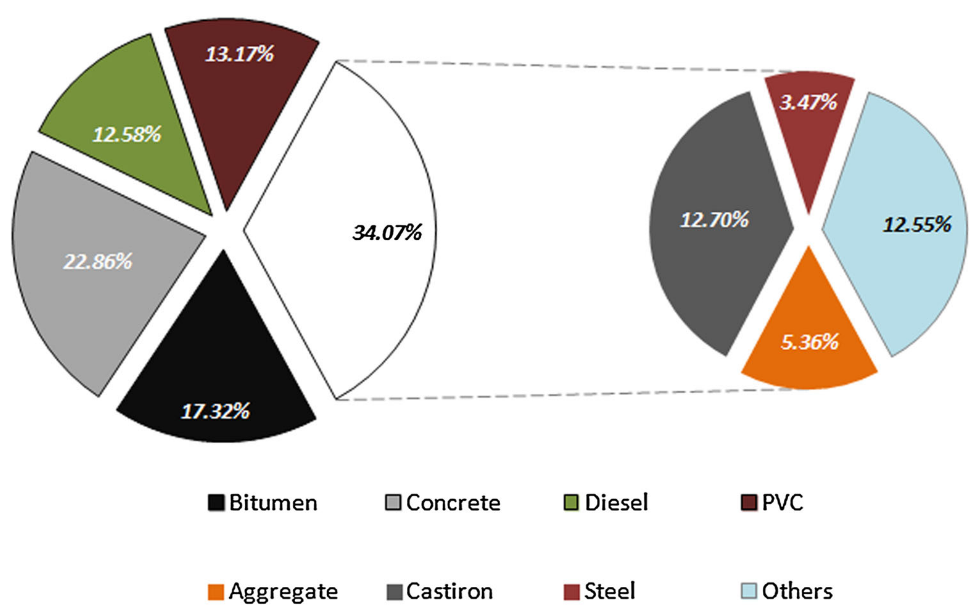


Fig. 7 CO_2 emissions in $kgCO_2/m^2$ for the housing development profiles

Fig. 8 Distribution of CO_2 emissions ($kgCO_2/m^2$) in the URB-3 profile



the buildings in each housing profile, as well as the emissions from the urbanization process for each of the profiles. These data are given in Table 9. The profile that generated the smallest environmental impact is URB-3 with nearly the same value as URB-4. In view of these results, the 5-floor apartment building (URB-3) became the reference value, to be used as a basis of comparison for the other options. The last row of Table 9 shows the percentages of the other housing profiles in relation to URB-3, which as the reference, took on a value of 0.

As shown in Fig. 3, the structure and foundation were responsible for the highest levels of CO_2 emissions. Within

Table 9 Total emissions for the housing development profiles in tCO_2

	URB-1	URB-2	URB-3	URB-4	URB-5	URB-6
Housing profile	Detached	Semi-detached	Block 5	Block 10	Block 20	Block 40
Number of buildings	225	65.00	8	4	2	1
Building surface (m^2)	307.00	1144.00	7592.00	15,185.00	30,369.00	60,739.00
(CO_2 kg/m^2)	402.70	365.80	363.60	376.10	394.50	461.40
Building construction emissions (tCO_2)	27,849.60	27,208.90	22,083.1	22,838.9	23,956.8	28,020.30
Civil engineering works (tCO_2)	7345.10	8642.40	4210.30	4017.70	3730.30	3582.40
Total emissions (tCO_2)	35,194.70	35,851.20	26,293.40	26,856.60	27,687.10	31,602.70
% in regards to the optimum	33.85 %	36.35 %	0.00 %	2.14 %	5.30 %	20.19 %

the same housing type, the 40-floor apartment building generated considerably more emissions than the 5-floor apartment building. In our case study, this difference was approximately 20 % greater (see Table 9).

As can be observed, URB-3 with its 5-floor apartment buildings was the profile with the least impact. In fact, the profiles with apartment buildings were found to be more environmentally friendly than the detached and semi-detached profiles. More specifically, the URB-3 profile had 33.85 % fewer emissions than the detached profile (URB-1) and had 36.35 % fewer emissions than the URB-2 profile.

There were no significant differences among apartment building profiles URB-3, URB-4, and URB-5. Only in the case of the 40-floor building did the emissions increase almost 20 %. With a view to proposing actions to reduce the environmental actions of building construction, Fig. 9 shows the emissions percentages generated by the materials used in the building construction and urbanization processes for the URB-3 housing profile.

When the building construction and urbanization processes were both considered, it was found that concrete was responsible for approximately 21 % of all emissions. When the 21 % from the steel was added to this percentage, then concrete and steel were found to generate more than one-third of all CO_2 emissions.

As previously mentioned, these results indicate that efforts to reduce the environmental impact of construction materials should encourage the use of cement, steel, and asphalt mixes with low levels of CO_2 emissions. This research analyzed a low-density urban area typical of the context in Spain. The building potential of the case study was set at 0.5 m^2/m^2 since this is a representative value, as reflected in urban development plans in Spain. Higher-density urban areas could logically require higher apartment buildings with more floors and with more resistant foundations and structure. This would involve a greater consumption of steel and concrete, and would thus produce a higher environmental impact.

Although this research is a case study, the relevant variables are urban density and the construction materials and systems characteristic of the zone. If the combination of these assumptions were modified, the results in Table 9

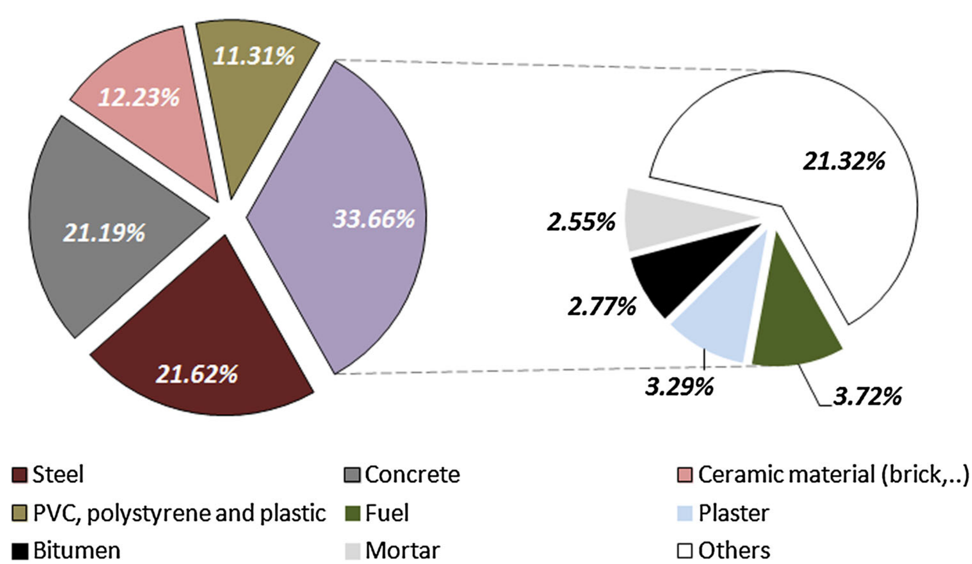


Fig. 9 Emissions from materials used in building construction and urbanization in the URB-3 profile

would also be different. Nevertheless, it is highly probable that certain tendencies would also be reflected in the new results, such as the weight derived from the use of significant amounts of materials with a high environmental impact (e.g., cement, steel, asphalt, etc.) as opposed to other environmentally friendly materials such as wood and stone.

Conclusions

Building type and urban layout have an effect on the material consumption at construction stage and therefore in the amount of embodied energy and the environmental impact of buildings. This study has evaluated the environmental impact of urban planning models resulting from different building construction profiles. The impact of materials involved in supply networks and services was also considered. The methodology of LCA was used, and the level of CO_2 emissions was specified for the construction stage of each alternative.

The study features the following highlights:

– The design of different case studies that, while meeting the urban normative, reflect different urban layout alternatives.
– Estimation of building materials involved in each solution. Foundations and structure were calculated with specific software.
– Use of LCA for the estimation of embodied energy and carbon emissions of building materials. This assessment was done in the construction stage.

The results showed that the materials that are the source of most emissions were related to the activities carried out to construct the foundations, frame elements, and siding of the buildings on the one hand, and the sewage network, paving, and landscape work in the housing development.

The work units that include cement were found to be responsible for a high level of embodied energy and of the environmental impact generated by the construction process. In this study, the percentages of emissions were 20 % for concrete and 7 % for mortar. The material with the second highest percentage of emissions was steel (18.2 %).

The results obtained confirm that urban layout and building type bear an impact on total embodied energy and carbon emissions at the construction stage. Generally speaking, the 5-floor and 10-floor housing profiles were found to have a lower impact than developments with detached houses. The detached housing profile produced an increase in emissions due to a major consumption of materials involved in walls and sidings. In this profile, there are more m^2 of façade as well as greater volumes of earth and mastic as the result of road surfaces. The effect of high environmental impact materials involved in foundations and structures is underlined in the results obtained.

Because the materials derived from urbanization tasks have a considerable effect on the total emissions involved, this should be taken into account when assessing environmental impact of buildings. The process followed in this research study can be used as a methodology that allows a project designer to obtain the housing development profile with the least environmental impact in terms of CO_2 emissions produced during the project design stage and construction stage of buildings.

In regards to future research, the authors are currently working to apply this methodology in another country, where the most commonly used construction materials are different and the urban planning regulations are conducive to other solutions. Also, future research should extend this work and include emissions due to the operation phase of the building.

The results presented here clearly indicate that future work should take into account the benefits derived from construction materials with a low environmental impact.

Acknowledgments This project was financed by a research contract N C-3513 with Construcciones Otero S.A. and the Fundación General UGR-Empresa [University Business Foundation] of the University of Granada.

Appendix A

The networks were calculated with Cype Instalaciones Urbanas (CYPE Ingenieros S.A., 2012), the CYPE computer application for architecture, engineering, and construction. his computer program obtains the head loss between two nodes of the same branch with the Darcy–Weisbach formula (A.1.):

$$h_p = f \cdot \frac{8 \cdot L \cdot Q^2}{\pi^2 \cdot G \cdot D^5} \quad \text{(A.1.)}$$

where,

h_p: head loss (m.w.c[10]).
L: length of pipe or duct (m).
Q: volume flow (m3/s).
g: acceleration of gravity (m/s^2).
D: hydraulic diameter of the pipe or duct (m).

The factor f is the function of the Reynolds number (Re) and the relative roughness (*e*/*D*). In the case of water, the transition values between the laminar and turbulent flow regimes for the Reynolds number range from 2000 to 4000. They can be calculated as follows (A.2.):

[10] m.w.c: meter water column.

$$R_e = \frac{v \times D}{\upsilon} \quad (A.2.)$$

where,

v: flow rate in the pipe or duct (m/s).

D: hydraulic diameter of the pipe or duct (m).

υ: kinematic viscosity of the fluid in the pipe or duct.

For values of Re lower than the turbulence threshold, the program uses the Hagen–Poiseuille equation to obtain the friction factor for the laminar flow (A.3.):

$$f = \frac{64}{\mathrm{Re}} \quad (A.3.)$$

The Colebrook–White equation is used for the turbulent regime (A.4.):

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \quad (A.4.)$$

which is iterated in order to reach a value of f because of its implicit nature, and where:

f: friction factor.

ε: absolute roughness of the material (m).

D: diameter of the pipe or duct (m).

Re: Reynolds number.

The following parameters are assumed:

- Kinematic viscosity of the fluid: 1.15e-6 m^2/s.
- Reynolds number for the laminar-turbulent transition: 2500

However, there is no guarantee that for the selected threshold value of the Reynolds number for the laminar-turbulent transition (Re = 2500), the friction factor obtained with the Hagen–Poiseuille equation will be equal to that obtained with the Colebrook–White equation.

Consequently, the head loss is calculated in a first iteration with the Colebrook–White equation. If this iteration provides a flow value in the laminar zone, it is subsequently calculated with the Hagen–Poiseuille equation. If the Hagen–Poiseuille equation gives a result in the turbulent zone, the result of the Colebrook–White equation is then regarded as the definitive value.

References

Asif M, Muneer T, Kelley R (2007) Life cycle assessment: a case study of a dwelling home in Scotland. Build Environ 42:1391–1394. doi:10.1016/j.buildenv.2005.11.023

Bardhan S (2011) Embodied energy analysis of multi-storied residential buildings in urban India. Energy Sustain 143:411–421. doi:10.2495/ESUS110351

Cabeza LF, Barreneche C, Miró L et al (2013) Low carbon and low embodied energy materials in buildings: a review. Renew Sustain Energy Rev 23:536–542. doi:10.1016/j.rser.2013.03.017

Cuéllar-Franca RM, Azapagic A (2012) Environmental impacts of the UK residential sector: life cycle assessment of houses. Build Environ 54:86–99. doi:10.1016/j.buildenv.2012.02.005

CYPE Ingenieros SA (2012) CYPECAD

Davila CC, Reinhart C (2013) Urban energy lifecycle: an analytical framework to evaluate the embodied energy use of urban developments. In: Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26–28. pp 1280–1287

Ding GKC (2004) The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities. University of Technology, Sydney

European Committee for Standardization (2006a) EN ISO 10040. Environmental management—life cycle assessment—principles and framework

European Committee for Standardization (2006b) EN ISO 14044. Environmental management life cycle assessment requirements and guidelines

European Committee for Standardization (2008) CEN/TC 350. Sustainability of construction works—assessment of buildings—part 2: framework for the assessment of environmental performance

European Parliament (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings

European Parliament (2012) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency

González MJ, García Navarro J (2006) Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact. Build Environ 41:902–909. doi:10.1016/j.buildenv.2005.04.006

Guinée J, Hiejungs R, Huppes G (2011) Life Cycle Assessment: past, Present, and Future. Environ Sci 45:90–96

Hammond G, Jones C (2011) Inventory of carbon and energy (ICE) version 2.0

ITEC (2012) ITEC. http://www.itec.es/home/index.asp

Jeong Y-S, Lee S-E, Huh J-H (2012) Estimation of CO2 emission of apartment buildings due to major construction materials in the Republic of Korea. Energy Build 49:437–442. doi:10.1016/j.enbuild.2012.02.041

Mercader MP, de Arellano Ramírez, Olivares M (2012) Modelo de cuantificación de las emisiones de CO_2 producidas en edificación derivadas de los recursos materiales consumidos en su ejecución. Inf la Construcción 64:401–414. doi:10.3989/ic.10.082

Ministerio de Fomento (2003) Código Técnico de la Edificación Código Técnico de la Edificación

Ministerio de Obras Públicas y Urbanismo (1978) Real Decreto 2159/1978, de 23 de junio, por el que se aprueba el Reglamento de Planeamiento para el Desarrollo y Aplicación de la Ley sobre Régimen del Suelo y Ordenación Urbana

Ministerio de Vivienda. (2008) Real Decreto Legislativo 2/2008, de 20 de junio, por el que se aprueba el Texto Refundido de la Ley de Suelo

Mithraratne N, Vale B (2004) Life cycle analysis model for New Zealand houses. Build Environ 39:483–492. doi:10.1016/j.buildenv.2003.09.008

Ordóñez J, Modi V (2011) Optimizing CO2 emissions from heating and cooling and from the materials used in residential buildings, depending on their geometric characteristics. Build Environ 46:2161–2169. doi:10.1016/j.buildenv.2011.04.030

Paulsen JS, Sposto RM (2013) A life cycle energy analysis of social housing in Brazil: case study for the program "MY HOUSE MY LIFE". Energy Build 57:95–102. doi:10.1016/j.enbuild.2012.11.014

Perkins A, Hamnett S, Pullen S et al (2009) Transport, housing and urban form: the life cycle energy consumption and emissions of city centre apartments compared with suburban dwellings. Urban Policy Res 27:377–396. doi:10.1080/08111140903308859

Peuportier B, Thiers S, Guiavarch A (2013) Eco-design of buildings using thermal simulation and life cycle assessment. J Clean Prod 39:73–78. doi:10.1016/j.jclepro.2012.08.041

Porhin M, Adriana E (2013) Comparative analysis of environmental performance of building materials towards sustainable construction.Chemical Engineering Transactions. 35:1291–1296. doi: 10.3303/CET1335215

Rickwood P, Glazebrook G, Searle G (2008) Urban structure and energy—a review. Urban Policy Res 26:57–81. doi:10.1080/08111140701629886

Singh A, Berghorn G, Joshi S, Syal M (2011) Review of life-cycle assessment applications in building construction. J Arch Eng 17:15–23

Society of Environmental Toxicology and Chemistry (1993) Guidelines for life-cycle assessment: a "code of practice"

Solís-Guzmán J, Marrero M, Ramírez-de-Arellano A (2013) Methodology for determining the ecological footprint of the construction of residential buildings in Andalusia (Spain). Ecol Indic 25:239–249. doi:10.1016/j.ecolind.2012.10.008

Témez J (1991) Extended and Improved Rational Method.Highways Administration of Spain. In: XXIV Conference. Madrid

Varun Sharma A, Shree V, Nautiyal H (2012) Life cycle environmental assessment of an educational building in Northern India: a case study. Sustain Cities Soc 4:22–28. doi:10.1016/j.scs.2012.03.002

Waldron D, Jones P, Lannon S, et al (2013) Embodied energy and operational energy: case studies comparing different urban layouts. In: Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26–28. pp 1264–1271

Wang W, Rivard H, Zmeureanu R (2006) Floor shape optimization for green building design. Adv Eng Informatics 20:363–378. doi:10.1016/j.aei.2006.07.001

Wen TJ, Siong HC, Noor ZZ (2014) Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: case studies of residential buildings in Iskandar Malaysia. Energy Build 93:295–302. doi:10.1016/j.enbuild.2014.12.002

World Commission on Environment and Development (1987) Our common future. Oxford University Press, Oxford

Zabalza Bribián I, Aranda Usón A, Scarpellini S (2009) Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build Environ 44:2510–2520. doi:10.1016/j.buildenv.2009.05.001