A model for the sustainable selection of building envelope assemblies

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Abstract

The aim of this article is to define an evaluation model for the environmental impacts of building envelopes to support planners in the early phases of materials selection. The model is intended to estimate environmental impacts for different combinations of building envelope assemblies based on scientifically recognised sustainability indicators. These indicators will increase the amount of information that existing catalogues show to support planners in the selection of building assemblies.

To define the model, first the environmental indicators were selected based on the specific aims of the intended sustainability assessment. Then, a simplified LCA methodology was developed to estimate the impacts applicable to three types of dwellings considering different envelope assemblies, building orientations and climate zones. This methodology takes into account the manufacturing, installation, maintenance and use phases of the building. Finally, the model was validated and a matrix in Excel was created as implementation of the model.

Keywords

Buildings sustainability. Sustainability indicators. Envelope assemblies.

Introduction

Construction is responsible for an indiscriminate use of non-renewable resources and is an important source of waste and pollution for the air, soil and water. According to UNEP (United Nations Environment Programme) and OECD (Organisation for Economic Cooperation and Development) data, the built-up environment accounts for between 25% and 40% of energy consumption, between 30% and 40% of the solid waste burden, and between 30% and 40% of the greenhouse gas emissions generated worldwide [1].

It is important to stress the importance of studying the potential environmental impacts produced by the use of certain building materials, but it is also important to highlight the impact represented by the combination of these materials when used in a certain constructive assembly [2]. Likewise, it is necessary to be able to establish relationships between these impacts and those produced throughout the lifespan of the building, due to both the actual materials used and the energy consumption linked to the building assemblies employed in the building envelope. As the person responsible for developing the core of the building around which the rest will later be constructed, the designer or planner must be able to control the selection of suitable materials and building assemblies used in their project [3]. In order to make their decisions they therefore need to have access not only to valid technological alternatives but also to relevant objective information about them, as well as instruments that allow them to be evaluated in a comprehensive manner [4].

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Thus, to increase the sustainability of construction it is necessary to consider reducing both the energy consumption and the CO_2 emissions of buildings by improving the building assemblies that make up the building envelope. This envelope has to guarantee the quality of the environment inside the building, since the exchange between the inner and outer environment takes place through it. It is also the point where illumination, ventilation or heat flow act as fundamental design parameters [5].

Obviously the environmental assessment of the building assemblies used for the envelope requires a scientifically rigorous methodology. Among the leading methodologies accepted by the scientific community for environmental impact assessment, the Life Cycle Analysis (LCA) is the most suitable because it is an analytical procedure focused on evaluating the whole life cycle. LCA, however, is an exhaustive, very laborious and complex process that must be carried out by highly skilled professionals and the time needed to apply it is often incompatible with the time available for producing designs. As a result, few life cycle analyses of buildings have been carried out in some countries. In the international context, a wide variety of tools based on the LCA methodology have been developed with the specific aim of aiding the planner in the sustainable selection of building assemblies. These tools allow the components of the building to be evaluated and cover all the different phases of the life cycle [6], [7]. These tools hardly apply outside the countries where they were developed since the environmental impact level caused by building materials and assemblies varies from one territory to another, due to the geographic placement of raw materials extraction and transformation plants in relation to the building location as well as to the possible differences in construction techniques [8].

In Spain, there are environmental assessment tools such as TCQ2000 and its module TCQGMA, which only assess the impacts generated during the manufacturing process and installation of the materials, i.e. the embodied impacts, without taking into account the use phase of the building, i.e. the operating impacts. On the other hand, there are building energy simulation tools such as LIDER and CALENER which offer data about consumption and CO_2 emissions of buildings [7], [9], [10]; they do not, however, take into account the embodied impacts of the manufacturing and installation stages or the impacts generated by the maintenance of the building.

At an international context, there are several studies that propose different methods to evaluate the environmental impact of buildings which consider both embodied and operating energy ([11], [12], [13], [14], [15], [16]). One of them deserves special mention because it synthetises all collected data in the form of indicators to assign scores to each design alternative, considering the different impacts along the whole building life cycle, which is of application to New Zealand houses [11]. The evaluation in this model is made for the whole building, whereas in this paper we focus on the building envelope in order to support the early phases of building envelope materials selection. Our aim is to increase the amount of information that existing catalogues show to support planners in the selection of building assemblies.

Scoring by means of indicators allows to compare data about different buildings using a reference to which the inputs and outputs can be related, the functional unit. It also allows to check the fulfilment of environmental prerequisites, in the initial phases of design, even before the actual design starts.

It would therefore be very interesting to have an evaluation model based on environmental indicators that assigns buildings envelope impact scores in a simple way, considering the whole life cycle. This model that would specifically be developed for building envelopes, would not only evaluate the embodied impacts of the manufacturing, installation and maintenance stages, but would also take into account the impacts generated by the installations due to the contribution of the envelope to energy efficiency during the use phase of the building (operating impacts). The interest in linking both types of impact stems from the fact that certain building assemblies might not substantially improve the energy efficiency of the building or that some high energy efficiency building assemblies include materials with a high impact in their manufacturing process, installation or maintenance. Planners require both embodied and operating energy-related information about building envelope solutions in order to select the building assemblies that ensure good environmental behaviour of the building throughout the whole of its life cycle.

An indicator is an environmental variable or estimation that provides aggregated summarised information about a phenomenon [17]. Its function is therefore to provide information both clearly and efficiently. It is necessary to establish a minimum essential content for presenting indicators, both for processes involving the selection of the indicators themselves and for the analysis and validation of the information they contain, with the aim of having access to specific concise information so as to avoid ambiguities that may arise during their interpretation, as well as to be able to take them as the basis on which to make correct decisions. The system used to obtain the values that allow the development of the formulas for the indicators would be based on a simplified LCA methodology.

1 Aim

The main aim of this article is to define a model for assessing the environmental impact, based on a simplified Life Cycle Analysis (LCA) methodology, produced by different building assemblies used in the envelope of buildings so that they can be assigned a score by means of known sustainability indicators that take into account the manufacturing, installation, use and maintenance phases of building construction.

With this assessment model the intention is to contribute to the development of a tool, to be applied in Spain in the early phases of building materials selection, that allows to obtain estimated live data about the embodied and operating environmental impacts of building envelope assemblies, to aid the design planner in the selection of solutions of low environmental impact before the actual design starts. The main contribution of the model is proposing a method to estimate how to score the envelope impacts at an earlier phase than the existing methods in a simple way.

2 Research methodology

The methodology that was followed to develop this model is summarised in the diagram below (Figure 1).
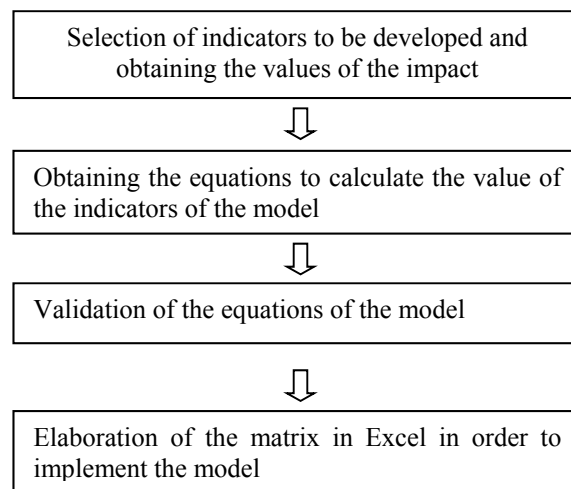
Figure 1 Methodological overview of the research

The adopted methodology is based on the generation of data regarding materials and assemblies of regular use in building construction in Spain, required to develop mathematical equations for a set of sustainability indicators previously selected for each of the building life cycle phases.

2.1 Selection of indicators and impacts rating

From a methodological point of view it must be underlined that the framework of analysis chosen to structure the system of indicators is the so-called "Pressure-State-Response (PSR)", adopted by the OECD [18] and based on a causality model.

According to the general principles established in the norm ISO 15392, when evaluating buildings sustainability, the three dimensions of the sustainable development (environmental, social and economic) should be considered. However, this norm also establishes that the evaluation of sustainability can also be undertaken separately, depending on the scope of the evaluation. This work focuses on the environmental and economic evaluation of buildings envelope.

As the number of indicators that can be proposed is quite large, before going on it is necessary to select certain indicators, to clearly establish the sustainability goals and to determine what selection criteria are to be used. Hence, the grouping proposed by Standard UNE EN 15643-2 was considered, in the following areas:

- Indicators that describe environmental emissions,
- Indicators that describe use of resources,
- Indicators that provide complementary environmental information about waste.

The economic performance assessment according to Norm EN 15643-4 was additionally taken into consideration.

To select the indicators, several studies were analysed ([19], [20], [21], [22], [23]), the conclusions being that:

- As far as emissions are concerned, all the agents involved agree on considering global warming potential or equivalent CO_2 emissions and their direct association with the emissions of other gases (sulphur oxides

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(SOx), nitrogen oxides (NOx), methane (CH4), etc.) as the most representative indicator when it comes to evaluating the environmental quality of buildings, as can be deduced from the EMEP/CORINAIR 2007 methodology drawn up by the EEA [24].

- As regards the indicators that describe consumption of resources, in accordance with the recommendations established in Directive 2012/27/EU, the primary energy consumption indicator was selected to evaluate the energy behaviour of the building. Likewise, a drinking water consumption indicator was selected due to the water stress in Spain.

- With regard to waste, both a hazardous waste indicator and a non-hazardous waste indicator were incorporated that will affect the manufacturing and installation phase, the aim being to give priority to the use of materials that do not generate hazardous waste during their manufacturing process [25], [26].

- Regarding cost appraisal, several economic indicators were selected to provide information about investment costs and energy costs in the manufacturing and installation as well as the maintenance and use phases.

The set of indicators of the impact to be evaluated, for each of the phases of the life cycle, are shown in Table 1, where the units of each indicator are specified.

The value of the selected impacts is obtained by applying a simplified LCA methodology following the diagram set out in Figure 2, the general aim being to quantify the environmental impact of a single home throughout its lifespan [27].

Table 1 Indicators for the impact to be evaluated and the phases of the life cycle

	Indicators that describe environmental impacts	Units	Manufacturing ph.	Maintenance ph.	Use phase
1	Global Warming Potential	$kg.Eq.CO_2/m^2$	x	x	x
	Indicators that describe use of resources	Units	Manufacturing ph.	Maintenance ph.	Use phase
2	Primary energy consumption	$Mj, kWh/m^2$	x	x	x
3	Water consumption	l/m^2	x	x	
	Indicators that describe complementary environmental information	Units	Manufacturing ph.	Maintenance ph.	Use phase
4	Non-hazardous waste	Kg/m^2	x		
	Hazardous waste	Kg/m^2	x		
	Economic indicators	Units	Manufacturing ph.	Maintenance ph.	Use phase
	Investment costs	$€/m^2$	x		
5	Maintenance costs	$€/m^2$		x	
	Energy costs	$€/m^2$	x	x	x

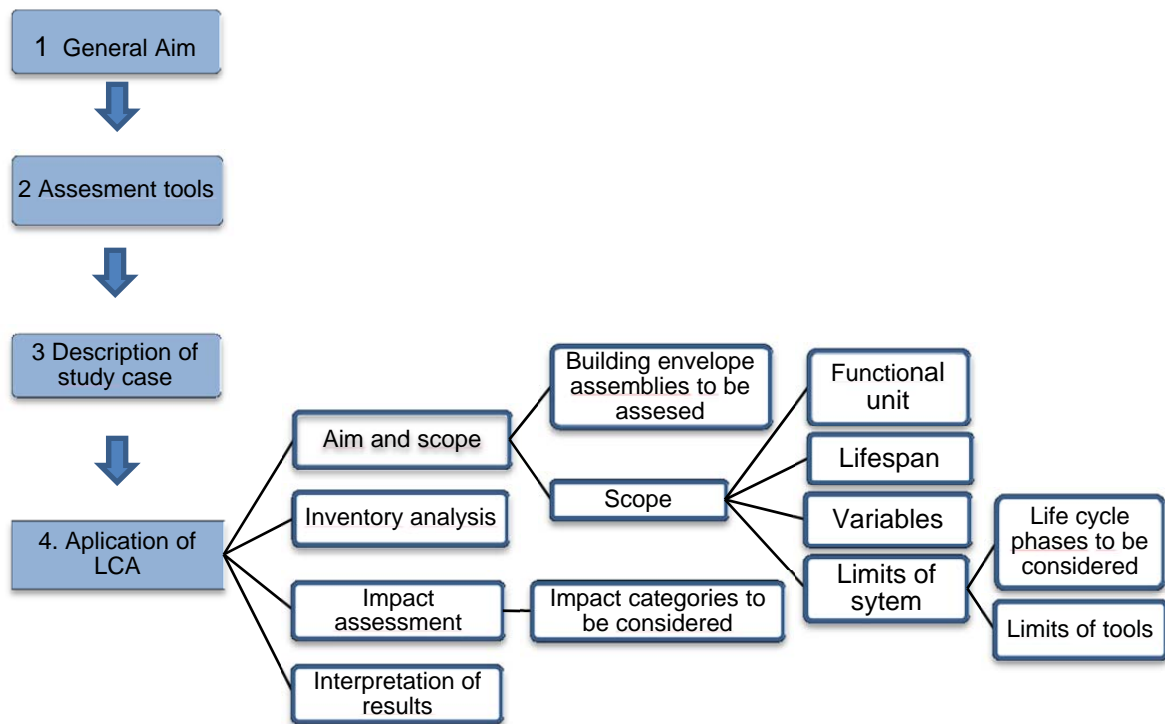## 2.2 The simplified LCA methodology applied to obtain impact values

Figure 2 Diagram showing the simplified LCA methodology applied to obtain impact values

The following steps were observed in the application of the LCA methodology:

- First, the impacts during the manufacturing process and installation of the building materials were calculated using the software application TCQ2000 as well as its environmental management module TCQGMA [28]. This tool defines the type and amount of materials used for each element by associating the input data and the existing values in the BEDEC database [29] referring to the impacts (energy consumption, CO_2 emissions, hazardous and non-hazardous waste generated during the manufacturing and installation phase). Water consumption appears as another item in the breakdown of materials that make up each building assembly.

- Second, the potential impacts produced by the different building assemblies during the building corrective maintenance were estimated. The TCQ2000 software, however, does not incorporate data about maintenance by default, which meant that they had to be obtained by assigning each of the materials that make up the building assembly a reconditioning factor, F_R, to reflect the number of times that material will have to be replaced throughout the lifespan of the building [30]. The impact value is obtained by multiplying the impacts generated by each material by the corresponding F_R. The durability of each element within the building assemblies that were analysed was established by following the recommendations set out in Standard ISO 15686-1.

The durability values used for each of the materials composing each building assembly were defined through the review of relevant sources and databases [31], [32]. These sources provided sufficient information regarding the position of the component in the building assembly. For example, the waterproof sheet durability is different in a conventional and an inverted roof since in the latter the insulating material protects the waterproof sheet from temperature changes. Additionally, to these considerations we also took into account the fact than when certain components need replacement, other components could also be affected. It is the case, for example, of the geotextile and mortar above the waterproof sheet that will have to be substituted if the waterproof is replaced (Table 2).

The assessment of the impacts due to building materials renovation was undertaken using the module TCQGMA of the TCQ2000 software, multiplying the generated impact of each constituting material by the reconditioning factor F_R minus 1 (to deduct the impact of the manufacturing and installation phase).

Table 2 shows, as an example, the data regarding a conventional, non-ventilated, trafficable flat roof and its constituting materials for the maintenance phase inventory. In the first row the code assigned to each construction assembly is shown (C1) as well as the designation of such building assembly. In the first five

columns the constituting materials of each assembly, their thickness, durability and reconditioning factor are given; in the next three columns the impacts during the corrective maintenance phase (considering the whole building lifespan) are shown.

Table 2. Impacts due to the roof materials, during the maintenance phase.

C1	C1 Flat roof, conventional, non-ventilated, trafficable				MAINTENANCE PHASE		
	Material	Thickness m	Durability years	F_R	Emissions * (F_R-1) kg CO_2/m²	Energy consumtion * (F_R-1) kWh/m²	Investment costs * (F_R-1) €/m²
1	P_ Finishing ceramic tiles	0.010	50	1.00	0.00	0.00	0.00
2	MA_ Mortar	0.040	37	3.66	13.83	25.30	18.38
3	Csa_ Geotextile from polypropylene 125 gr/m2	0.00013	30	3.66	4.44	8.41	5.69
4	I_ Waterproof sheet bitumen LO-40/FV	0.007	13.67	3.66	88.13	164.67	88.02
5	Cs_ Geotextile from polypropylene 125 gr/m2	0.00013	30	1.67	1.09	2.10	1.43
6	AT_ Thermal insulation of XPS	0.050	50	1.00	0.00	0.00	0.00
7	B_ Vapour barrier	0.005	61	0.82	0.00	0.00	0.00
8	FP_ Aerated concrete for roof slope	0.048	50	1.00	0.00	0.00	0.00
9	SR_ Reinforced concrete one-way slab, ceramic hollow plot	0.300	50	1.00	0.00	0.00	0.00
10	RI_ Plastering	0.010	46	1.09	0.15	0.46	0.42
	Total	0.470			107.64	200.93	113.94

Finally, consumptions and CO_2 emissions, resulting from heating and air conditioning systems during the use phase, are calculated using the energy simulation tools LIDER [33] and CALENER VYP [34]. The latter is an official tool for energy certification of buildings in Spain, which is only applicable to residential buildings. For this reason the results being showed in this paper are only valid for residential buildings. The CALENER VYP tool is used here to determine the heating and cooling energy demands, the final and primary energy consumptions, and the CO_2 emissions of the building under study during the use phase.

Table 3 shows the building assemblies that are most commonly employed for the building envelope and which were chosen for this study. Each construction assembly is designated with a capital letter that indicates the class (C = roof, F = façade and H = carpentry) and their numerical index that indicates the type of building assembly.

Combining the different building assemblies with one another results in 45 combinations for the envelope that are designated by means of the three letters with their corresponding indices. Calculations for the use phase are carried out for the 45 combinations of the building envelope.

For this study, in order to obtain comparable results, two different climate zones, B3 and E1, were selected. A climate zone is composed by the places of a territory where outdoor conditions are considered to result in common thermal loads for buildings energy demand. In the Spanish Building Code (*Código Técnico de la Edificación*, CTE) in its document DB-HE 1 [35], each climate zone of the Spanish Peninsula is identified by a letter that defines the winter severity (from A to E, being E the most severe), and by a number for the summer severity (from 1 to 4, being 4 the most severe). Climate zone B3 constitutes a temperate humid climate covering approximately the entire Mediterranean basin and climate zone E1 constitutes a cold dry climate which extends inside the Peninsula.

Likewise, calculations were performed in two building orientations (North-easterly orientation – NE – and South-easterly orientation – SE). Altogether 45 combinations were evaluated in two orientations and two climate zones, that is to say a total of 180 options. All the values were obtained for the particular case of a two-storey semi-detached house with a floor area of 93.5 m², the functional unit being taken as 1 m² of net floor area and a service life of 50 years.

Table 3. Identification of the most commonly used building envelope assemblies

C1 — Flat roof, conventional, not-ventilated, trafficable

	Material	Thickness (m)	Section
1	P_ Finishing ceramic tiles	0.01	
2	MA_ Mortar	0.04	
3	Csa_ Polypropylene geotextile (125 gr/m²)	0.000128	
4	I_ Waterproof bitumen sheet LO-40/FV	0.007	
5	Cs_Geotextile, polypropylene geotextile (125 gr/m²)	0.000128	
6	AT_Thermal insulation XPS	0.05	
7	B_ Vapour barrier	0.005	
8	FP_ Aerated concrete for roof slope	0.048	
9	SR_ Reinforced concrete one-way slab, ceramic hollow plot	0.3	
10	RI_ Plastering	0.01	
	Total	0.47	

C2 — Flat roof ventilated, trafficable

	Material	Thickness (m)	Section
1	P_ Finishing ceramic tiles	0.01	
2	MA_ Mortar	0.04	
3	Csa_ Geotextile, polypropylene 125 gr/m²	0.000128	
4	I_ Double waterproof sheet bitumen LO-40/FV	0.007	
5	Cs_ Geotextile, polypropylene 125 gr/m²	0.000128	
6	FP_ Ceramic tiles for roof slope	0.35	
7	C_ Ventilated air chamber	0.003	
8	AT_ Thermal Insulation of mineral wool	0.005	
9	unidirectional fabric forging with ceramic elements	0.3	
10	RI_Plastering	0.01	
	Total	0.725	

C3 — Flat roof with insulation, conventional, non-trafficable.

	Material	Thickness (m)	Section
1	P_Finishing gravel	0.02	
2	Csa_ Polypropylene geotextile (125 gr/m²)	0.000128	
3	AT_ XPS thermal insulation	0.05	
4	Csa_ Geotextile, polypropylene 125 gr/m²	0.002	
5	I_ Double waterproof sheet bitumen LO-40/FV	0.007	
6	FP_ Aerated concrete for roof slope	0.048	
7	SR_ Reinforced concrete one-way slab, ceramic hollow plot	0.3	
8	RI_ Plastering	0.01	
	Total	0.437	

H1 — Aluminium windows with thermal bridge breaking system

	Material	Thickness (m)	Section
1	Double glazing 6/6/6, low E glass	0.012	
2	Aluminium frame with thermal bridge breaking system	0.001	
3	Filler of neutral silicon	0.005	
4	Dry air space 6mm thick	0.006	
5	Ironwork of steel	0.015	
6	Galvanized steel 40x20mm subframe	0.015	
	Total	0.054	

H2 — PVC windows with thermal bridge breakage

	Material	Thickness (m)	Section
1	Double glazing 6/6/6, low E glass	0.012	
2	PVC frame with three chambers	0.001	
3	Filler of neutral silicon	0.005	
4	Dry air space 6mm thick	0.006	
5	Ironwork of steel	0.015	
6	Galvanized steel 40x20mm subframe	0.015	
	Total	0.054	

H3 — Wood windows

	Material	Thickness (m)	Section
1	Double glazing 6/6/6, low E glass	0.012	
2	High density wood frame	0.019	
3	Filler of neutral silicon	0.005	
4	Dry air space 6mm thick	0.006	
5	Ironwork of steel	0.015	
6	Wood frame 40x20mm	0.015	
	Total	0.072	

F1 — Brick cavity walls, with outer wall of facing bricks, 5 cm thick insulation

	Material	Thickness (m)	Section
1	LC_ Exterior masonry wall of ceramic perforated brick of 11.5 cm thick, with cement	0.115	
2	RM_ Intermediate coat. A plaster on the interior face of the principal with cement mortar (1:6)	0.015	
3	C_ Non-ventilated air chamber	0.05	
4	AT_ Thermal Insulation, mineral wool	0.05	
5	LH_ Inner skin of double hollow ceramic brick 7cm thick with cement mortar joints (1:6)	0.07	
6	RI_ Plastering	0.015	
	Total	0.32	

F2 — Brick cavity walls, with coated outer wall of brickwork, 5 cm thick insulation

	Material	Thickness (m)	Section
1	RE_ Continuous outer coating with cement mortar (1:6)	0.015	
2	LC_ Exterior masonry wall of perforated 12 cm thick ceramic brick, with cement mortar joints	0.115	
3	C_ Non-ventilated air chamber	0.05	
4	AT_ Thermal Insulation, mineral wool	0.05	
5	LH_ Inner layer of double hollow ceramic brick 7cm thick with cement mortar joints (1:6)	0.07	
6	RI_ Plastering	0.015	
	Total	0.32	

F3 — Brick cavity walls, with coated outer wall of brickwork, 10 cm thick insulation

	Material	Thickness (m)	Section
1	RE_ Continuous outer coating with cement mortar (1:6)	0.015	
2	ceramic brick 11.5 cm thick with cement mortar joints (1:6)	0.115	
3	C_ Non-ventilated air chamber	0.05	
4	AAT_ Thermal Insulation, mineral wool	0.1	
5	LH_ Inner layer of double hollow ceramic brick 7cm thick with cement mortar joints (1:6)	0.07	
6	RI_ Plastering	0.015	
	Total	0.37	

F4 — Back-ventilated façade of brickwork, 5 cm thick insulation

	Material	Thickness (m)	Section
1	RE_ Outer discontinuous coating of ceramic tiles mechanically fastened with aluminium substructure type T	0.02	
2	C_ Ventilated air chamber	0.05	
3	AT_ Thermal Insulation of mineral wool	0.05	
4	RM_ Continuous outer coating with cement mortar (1:6)	0.015	
5	LC_ Inner layer of double hollow ceramic brick 11.5 cm thick with cement mortar joints (1:6)	0.115	
6	RI_ Plastering	0.015	
	Total	0.265	

F5 — Curtain wall

	Material	Thickness (m)	Section
1	Double glazing 6/8/6, low E glass	0.012	
2	Aluminium substructure of tubular mullions and horizontals transoms		
3	Dry air 8 mm space	0.008	
5	Aluminium Composite Panel	0.0018	
	Total	0.0218	

Finally, the results were used to develop the equations to calculate the indicators, as described next.

Regarding the life cycle phases, even if a LCA should cover the entire life cycle (manufacturing process and installation; use and maintenance; and demolition and final disposal) we decided to focus our research on the manufacturing and installation phase and on the use and maintenance phase, excluding the demolition and final disposal stage, as in other studies of the same nature [7], [10], [12], [13], [14], [15].

The reason is that the impacts due to the demolition phase are significantly low in comparison with the impacts along the whole life cycle.

3   Obtaining the equations for calculating the indicators

3.1   Obtaining the equations for calculating the impacts during the manufacturing, installation and maintenance phases.

The equations for the indicators during the manufacturing, installation and maintenance phases were obtained from the results of the potential impacts obtained by means of the TCQGMA tool, shown in Table 4. The first row indicates the phase of the life cycle under consideration and the second and third rows show the impacts that were evaluated and the corresponding units, all of which are expressed in square metres of constructed element. The column on the left contains the different building assemblies, as variables, for the different building envelope elements (roof, façade, carpentry) whose combinations were studied.

Table 4 Impacts resulting from the building assemblies: manufacturing, installation and maintenance phases

VARIABLES		MANUFACTURING AND INSTALLATION PHASES						Costs	MAINTENANCE PHASE		
		Emissions	Primary energy consumption	Water consumption	Waste		Costs	Costs		Emissions	Primary energy consumption
					Installation plus packaging (kg/m²)		Investment	Maintenance			
		(kg CO_2/m²)	(kWh/m²)	(l/m²)	Hazardous (kg/m²)	Non-hazardous (kg/m²)	(€/m²)	(€/m²)		(kg CO_2/m²)	(kWh/m²)
C1		243.40	543.40	48.00	0.27	12.25	151.52	93.72		92.31	172.68
C2		177.62	472.42	16.00	0.12	16.12	143.09	93.72		92.31	172.68
C3		188.25	418.84	48.00	0.10	10.32	107.32	67.24		66.08	130.51
F1		67.20	218.19	30.00	0.00	22.92	98.24	22.66		7.39	14.09
F2		42.28	134.44	24.00	0.00	10.28	76.38	22.66		7.39	14.09
F3		61.39	215.29	24.00	0.00	10.90	88.15	22.66		7.39	14.09
F4		52.22	192.62	16.00	0.00	11.51	128.07	11.78		4.15	13.00
F5		88.04	414.95	10.00	0.00	0.00	758.72	153.34		63.84	294.91
H1		592.05	1,203.78	0.00	0.06	0.00	231.58	165.24		67.06	300.99
H2		324.42	743.75	0.00	0.06	0.00	218.94	165.24		67.06	300.99
H3		37.46	169.85	0.00	0.06	0.00	247.90	409.43		71.88	326.93

F_S indicates the surface factor that represents the proportion of building assembly per m² of net floor area of the building, as indicated in equation [1]. This datum is obtained by the planner from the building characteristics for which the envelope indicators are to be obtained.

$$F_S = \frac{construction\ element\ area\ (m^2)}{net\ floor\ area\ of\ the\ building\ (m^2)} \quad [1]$$

Table 5. Table of the factors obtained for each impact in the manufacturing and retrofit phases

VARIABLES	F_s Surface factor	MANUFACTURING PHASE						MAINTENANCE PHASE		
		CO$_2$ emissions factor	Energy consumption factor	Water consumption factor	Hazardous waste factor	Non-hazardous waste factor	Investment costs factor	Maintenance costs factor	CO$_2$ emissions factor	Consumption factor
Costructive element	$F_{S,cub}$	F_{cub,CO_2}^{fab}	$F_{cub\,kWh}^{fab}$	$F_{cub\,agua}^{fab}$	$F_{cub\,resp}^{fab}$	$F_{cub\,resnp}^{fab}$	$F_{cub\,€/m^2}^{fab}$	$F_{cub\,€/m^2}^{main}$	F_{cub,CO_2}^{main}	$F_{cub\,kWh}^{main}$
C1	0.72	243.40	543.40	48.00	0.27	12.25	151.52	93.72	92.31	172.68
C2		177.62	472.42	16.00	0.12	16.12	143.09	93.72	92.31	172.68
C3		188.25	418.84	48.00	0.10	10.32	107.32	67.24	66.08	130.51
Types of façade	$F_{S,fac}$	F_{fac,CO_2}^{fab}	$F_{fac\,kWh}^{fab}$	$F_{fac\,agua}^{fab}$	$F_{fac\,resp}^{fab}$	$F_{fac\,resnp}^{fab}$	$F_{fac\,€/m^2}^{fab}$	$F_{fac\,€/m^2}^{main}$	$F_{fac\,€/m^2}^{main}$	$F_{fac\,kWh}^{main}$
F1	0.53	67.20	218.19	30.00	0.00	22.92	98.24	22.66	7.39	14.09
F2		42.28	134.44	24.00	0.00	10.28	76.38	22.66	7.39	14.09
F3		61.39	215.29	24.00	0.00	10.90	88.15	22.66	7.39	14.09
F4		52.22	192.62	16.00	0.00	11.51	128.07	11.78	4.15	13.00
F5		88.04	414.95	10.00	0.00	0.00	758.72	153.34	63.84	294.91
Types of carpentry	$F_{S,car}$	F_{car,CO_2}^{fab}	$F_{car\,kWh}^{fab}$	$F_{car\,agua}^{fab}$	$F_{car\,resp}^{fab}$	$F_{car\,resnp}^{fab}$	$F_{car\,€/m^2}^{fab}$	$F_{car\,€/m^2}^{main}$	F_{car,CO_2}^{main}	$F_{car\,kWh}^{main}$
H1	0.17	592.05	1203.78	0.00	0.06	0.00	231.58	165.24	67.06	300.99
H2		324.42	743.75	0.00	0.06	0.00	218.94	165.24	67.06	300.99
H3		37.46	169.85	0.00	0.06	0.00	247.90	409.43	71.88	326.93

The equations to calculate a given impact 'I$_x$' during the manufacturing phase (I_x^{fab}) are obtained from the simple addition of three elements concerned with this impact 'Ix' produced by the roof assembly under study (I_{xcub}^{fab}), the façade assembly (I_{xfac}^{fab}), and the chosen type of carpentry (I_{xcar}^{fab}). Each of these elements is composed of a surface factor Fs and of a factor depending on the building assembly selected for the impact (Table 5).

$$I_x^{fab} = I_{xcub}^{fab} + I_{xfac}^{fab} + I_{xcar}^{fab} \qquad [2]$$

Where:

$$I_{xcub}^{fab} = (F_{S,cub} \cdot F_{cub,\,I_X}^{fab})$$

$$I_{xfac}^{fab} = (F_{S,fac} \cdot F_{fac,\,I_X}^{fab})$$

$$I_{xcar}^{fab} = (F_{S,car} \cdot F_{car,\,I_X}^{fab})$$

The equations to calculate a given impact 'Ix' in the maintenance phase (I_x^{main}) are also obtained from the simple addition of three lineal elements concerned with this impact 'Ix' produced by the roof assembly under study (I_{xcub}^{main}), the façade assembly (I_{xfac}^{man}), and the chosen type of carpentry (I_{xcar}^{main}). Each of these elements is composed of a factor Fs and of a factor depending on the building assembly selected for the impact (Table 5).

$$I_x^{main} = I_{xcub}^{main} + I_{xfac}^{main} + I_{xcar}^{main} \qquad [3]$$

Where:

$$I_{xcub}^{main} = (F_{S,cub} \cdot F_{cub,\,I_X}^{main})$$

$$I_{xfac}^{main} = (F_{S,fac} \cdot F_{fac,\,I_X}^{main})$$

$$I_{xcar}^{main} = (F_{S,car} \cdot F_{car,\,I_X}^{main})$$

As previously mentioned, the surface factor Fs is a datum that the planner calculates for each project. In Table 5 the Fs of the analysed case study is shown.

For example, to calculate the indicator 'equivalent CO$_2$ emissions' (Em$_{eqCO2}$) during the manufacturing phase of an envelope composed of the combination of building assemblies codified as roof C2, façade F1, and carpentry H1 for a semi-detached house, the impact values for the indicator 'equivalent CO$_2$

emissions' for the different building elements will be summed up, each of which are calculated as the multiplication of two factors whose values are taken from Table 5:

$$Em_{eqCO_2}^{fab} = \left\{ (F_{S,cub} \cdot F_{cub,CO_2}^{fab}) + \left(F_{S,fac} \cdot F_{fac,CO_2}^{fab} \right) + (F_{S,car} \cdot F_{car,CO_2}^{fab}) \right\}$$

$$Em_{eqCO_2}^{fab} = \{(0.72 \cdot 177.62 \quad) + (0.53 \cdot 67.20) + (0.17 \cdot 592.05)\} = 264.16 \text{ Kg eq } CO_2$$

In any environmental evaluation, a great deal of attention should be paid to uncertainty. For the manufacturing and maintenance phases, the uncertainty degree of the values obtained using equations [2] and [3] is associated to the uncertainty of the TCQGMA model. Since this uncertainty is not published, we have not indicated it in our model. This limitation should certainly be a topic of future research. On the other hand, estimating the impacts caused by other building assemblies requires increasing the scope of information within the model, since for the moment it only has the building assemblies described in Table 3.

3.1.1   Obtaining the equations for the use phase impacts.

The equations for the use phase were obtained by producing a multiple linear regression model, using the factors analysed in the case under study, i.e. climate zone, building orientation, three types of roofing, five types of façade and three types of carpentry, as the explanatory variables, and the impacts during the use phase were taken as dependent variables.

Table 6 summarises part of the data used to calculate the regression model. The matrix is divided into two blocks: the block on the left shows the explanatory variables used to obtain the formula for each indicator, while the block on the right shows the dependent variables for the impacts that were evaluated. The first block contains 10 columns: the first lists the combinations of the building assemblies that were evaluated and the other nine columns contain a binary coding for each of the variables used as input data to obtain the equations. The first group of variables is made up of the building assemblies that will form the combinations of the envelope that were used in this research study. Each column is identified by means of letters and numbers that stand for the type of variable.

The orientation of the building envelope is identified by means of two letters (NE: North-easterly Orientation, and SE: South-easterly Orientation) and the climate zone is identified by a letter and a number (B3 and E1). The binary coding allows the building assemblies that make up each combination of the envelope to be identified.

Table 6 showing an extract of the impacts in the use phase

TYPE	VARIABLES										ENVIRONMENTAL IMPACTS IN THE USE PHASE			
SEMI-DETACHED HOUSE	CONSTRUCTIVE SOLUTIONS								Orientation	Climate zone	Heating emissions	Air conditioning emissions	Heating consumption	Air conditioning consumption
		C1	C2	F1	F2	F3	F4	H1	H2	NE	B3	(kg CO_2/m^2)	(kg CO_2/m^2)	(kWh/m^2)	(kWh/m^2)
	C1 F1 H1	1	0	1	0	0	0	1	0	1	1	8.70	4.80	42.90	19.20
	C1 F2 H1	1	0	0	1	0	0	1	0	1	1	8.50	4.80	42.20	19.20
	C1 F3 H1	1	0	0	0	1	0	1	0	1	1	7.70	4.60	38.10	18.60
	C1 F4 H1	1	0	0	0	0	1	1	0	1	1	8.50	5.00	42.10	19.90
	C1 F5 H1	1	0	0	0	0	0	1	0	1	1	5.90	6.80	27.70	27.30
	C2 F1 H1	0	1	1	0	0	0	1	0	1	1	8.90	4.80	44.20	19.30
	C2 F2 H1	0	1	0	1	0	0	1	0	1	1	8.70	4.90	43.40	19.70
	C2 F3 H1	0	1	0	0	1	0	1	0	1	1	7.80	4.80	38.50	19.40
	C2 F4 H1	0	1	0	0	0	1	1	0	1	1	8.80	4.90	43.60	19.60
	C2 F5 H1	0	1	0	0	0	0	1	0	1	1	5.60	6.70	27.70	26.90
	C3 F1 H1	0	0	1	0	0	0	1	0	1	1	8.50	4.70	42.30	18.70

The formula for each indicator was obtained by selecting the data from the column for the corresponding indicator (dependent variable) that is to be calculated and the data corresponding to the columns for all the explanatory variables (types of roofing, façade and carpentry, solar orientation, and climate zone).

As an example, for the indicator 'equivalent CO_2 emissions', the coefficients obtained for the regression model are shown in Table 7.

Table 7 Regression model coefficients for the indicator 'equivalent CO_2 emissions'

Variable	BE	NE	H2	H1	F4	F3	F2	F1	C2	C1	Independent

										term
Regression coefficient	-18.06	0.05	-0.07	0.20	2.31	0.84	2.28	2.62	0.67	0.49	23.7

The regression model is used to obtain the value of the coefficients for each of the dependent variables shown in Table 8. The first column names the variables. The following columns show the numerical values of the four impact factors of the use phase (the independent term and the corrective amounts) and the standard error of the regression model in absolute and relative terms. Such standard error provides a measure of the model uncertainty.

Table 8. Corrective amounts of each impact in the use phase

		Heating emissions	Air conditioning emissions	Heating consumption	Air conditioning consumption
Independent term		23.7	1.58	116.4	6.28
Response standard error		±0.57	±0.31	±2.20	±1.34
Relative response standard error		3%	11%	3%	12%
VARIABLES					
Types of roofing		$F^{uso}_{cub,CO_2 cal}$	$F^{uso}_{cub,CO_2 ref}$	$F^{uso}_{cub,kWhcal}$	$F^{uso}_{cub,kWhref}$
C1		0.49	0.09	1.44	0.48
C2		0.67	0.08	3.21	0.46
C3		0	0	0	0
Types of façade		$F^{uso}_{fac,CO_2 cal}$	$F^{uso}_{car,CO_2 ref}$	$F^{uso}_{fac,kWhcal}$	$F^{uso}_{fac,kWhref}$
F1		2.62	-1.44	14.32	-5.78
F2		2.28	-1.45	12.93	-5.81
F3		0.84	-1.49	5.36	-6.02
F4		2.31	-1.37	12.73	-5.54
F5		0	0	0	0
Types of carpentry		$F^{uso}_{car,CO_2 cal}$	$F^{uso}_{car,CO_2 ref}$	$F^{uso}_{car,kWhcal}$	$F^{uso}_{car,kWhref}$
H1		0.2	-0.08	1.27	-0.3
H2		-0.07	-0.03	0.27	-0.23
H3		0	0	0	0
Climate zone		$F^{uso}_{Z,CO_2 cal}$	$F^{uso}_{Z,CO_2 ref}$	$F^{uso}_{Z,kWh cal}$	$F^{uso}_{Z,kWhref}$
B3		-18.06	4.66	-89.4	18.65
E1		0	0	0	0
Orientation		$F^{uso}_{Or,CO_2 cal}$	$F^{uso}_{Or,CO_2 ref}$	$F^{uso}_{Or,kWhr cal}$	$F^{uso}_{Or,kWhref}$
SE		0	0	0	0
NE		0.05	0.01	0.1	-0.01

The values from Table 8, obtained by applying a linear regression model to the impact values of the use phase, are taken to produce the equations of the regression models that were obtained. The independent term of each equation is established by the regression model, and the corrective amount of each variable is replaced in each case according to the roofing, façade and carpentry option chosen by the planner and depending on the building orientation and the climate zone (Table 8).

The standard error of the estimated impact for the equations is obtained directly from the Excel sheet and is indicated in Table 8. The value of this error indicates the uncertainty interval of the impact estimation. The equation to calculate the impacts in the use phase is defined as follows:

$$I^{uso}_x = \left(\left(TI_x + F^{uso}_{Z,Ix} + F^{uso}_{Or,Ix} + F^{uso}_{cub,Ix} + F^{uso}_{fac,Ix} + F^{uso}_{car,Ix} \right) \pm sey \right) \cdot N^{\text{lifetime}} \qquad [4]$$

Where:

I^{uso}_x = Impact 'Ix' due to the use phase

TI_x = independent term for each impact

$F_{i,Ix}^{uso}$= Corrective amount of variable 'i' for each impact 'x'

Sey = estimation error, measure of the associated uncertainty

N^{lifetime}= lifetime considered

For example, to calculate the indicator 'equivalent CO_2 emissions' during the use phase of the semi-detached house in climate zone B3 and solar orientation NE, with an envelope composed of roof C2, façade F1, and carpentry H1, for a lifetime of 50 years, the values in Table 8 are used in equation [4]:

$$Em_{eq,CO_2cal}^{uso} = \left((23.7 - 18.06 + 0.05 + 0.67 + 2.62 + 0.2) \pm 0.57\right) \cdot 50 = [430.5 , 487.5] \text{ Kg eq CO}_2$$

3.2 Obtaining a corrective factor for the estimation of impacts in other types of buildings

The equations previously proposed to estimate sustainability indicators for the building envelope were obtained from data about semi-detached houses. To extrapolate this model on other types of residential buildings, it would be necessary to undertake all the steps previously followed for the case of the semi-detached houses with the other dwelling types, updating and adapting the previous tables to the type under consideration. However, as a first rough approach to this matter, a corrective factor for different types of residential buildings to be applied to previous equations is calculated next.

For this, eight combinations of building assemblies for the envelope for two types of buildings have been considered: a five-story block of flats with two dwellings per floor and a total of 1,324.7m² of net area, and a single story detached house of 107.4 7m² of net area.

As can be seen in Figure 3 the distance between the values of one type of dwelling and other types is not constant, but it shows certain trends when they are analysed considering the climate zones, i.e. it remains quite similar for the same climate zone (E1 or B3). The followed approach was to calculate a mean value for the difference between the semi-detached house and the other building types to use it as corrective amount, as well as an error that establishes the confidence interval for the spread of data in relation to the calculated mean. This was done for each of the four impact values and for the climate zones E1 and B3. The confidence level for the calculation of the confidence interval was of 95%. The error interval was obtained multiplying by 1.96 the value of the standard deviation divided by the square root of the sample size, consisting of 4 data, as can be seen in Table 9. This way a first corrective factor was obtained, to be used to multiply the impact value for other residential building types (different to semidetached house), applying the error interval corresponding to each impact and climate zone.
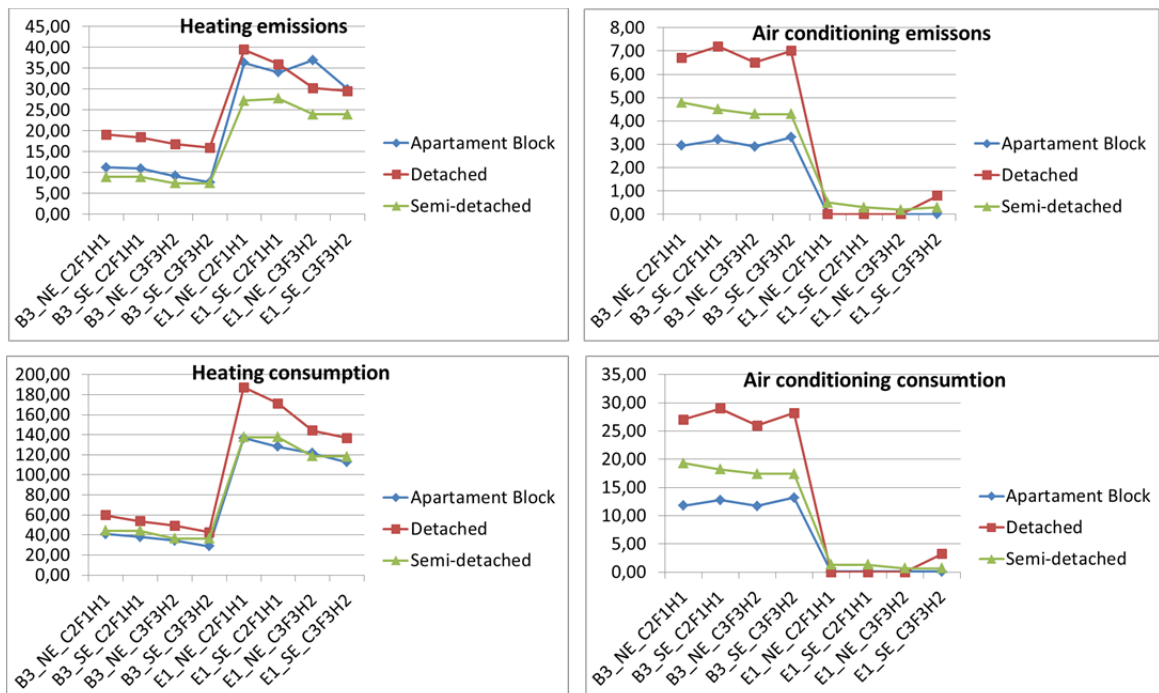
Figure 3 Comparison of impacts in the use phase for different type of dwellings

This corrective factor is obtained by calculating the average distance between each of the impacts produced during the use phase of the apartment block and by the detached house with respect to the impacts produced in this same phase by the semi-detached house used as a study case, each climate zone being considered separately. This value is the factor type of housing F_tviv that can be seen in Table 9.

Table 9 Corrective factor according to the type of dwelling

TYPE	CORRECTIVE FACTOR ACCORDING TO TYPE			
Semi-detached	$F_{tviv,CO_2\,cal}$	$F_{tviv,CO_2\,ref}$	$F_{tviv,kWh\,cal}$	$F_{tviv,kWh\,ref}$
	1±0.00	1±0.00	1±0.00	1±0.00
	1±0.00	1±0.00	1±0.00	1±0.00
Apartment Block	$F_{tviv,CO_2\,cal}$	$F_{tviv,CO_2\,ref}$	$F_{tviv,kWh\,cal}$	$F_{tviv,kWh\,ref}$
	1.18±0.10	0.69±0.06	0.88±0.07	0.69±0.06
	1.34±0.14	0±0.00	0.98±0.04	0.11±0.04
Detached	$F_{tviv,CO_2\,cal}$	$F_{tviv,CO_2\,ref}$	$F_{tviv,kWh\,cal}$	$F_{tviv,kWh\,ref}$
	1.31±0.09	1.53±0.10	1.27±0.09	1.53±0.10
	1.30±0.10	0.67±1.31	1.24±0.08	0.29±0.58

As can be seen in Table 9, the corrective factor of CO_2 emissions to cool the dwellings of the block of flats is of zero value because the calculated impact has exactly the same value that in the semidetached house. It is also worth mentioning that in the single story detached house the error interval is higher than the mean of the corrective factor for both, the emissions and the consumption due to cooling. This is because only one of the combinations of the envelope assemblies presented significant differences between the single story detached house and the semi-detached house, and therefore the standard deviation and consequently the error interval are higher than the mean.

The equation to estimate the impacts in the use phase is obtained multiplying equation [4] by the dwelling type factor Ftviv:

$$I_x^{uso} = \left(\left(TI_x + F_{Z,Ix}^{uso} + F_{Or,Ix}^{uso} + F_{cub,Ix}^{uso} + F_{fac,Ix}^{uso} + F_{car,Ix}^{uso}\right) \pm sey\right) \cdot N^{lifetime} \cdot F_{tviv,I_X} \qquad [5]$$

Where

I_x^{uso} = Impact 'Ix' due to the use phase

TI_x = independent term for each impact

$F_{i,Ix}^{uso}$ = Corrective amount of variable 'i' for each impact 'Ix'

Sey = estimation error, measure of the associated uncertainty

$N^{vida\,util}$ = lifetime considered

F_{tviv,I_X} = Corrective factor depending on the dwelling type and impact type

For example, to calculate the indicator 'equivalent CO_2 emissions' during the use phase due to heating, of an envelope composed of roof C2, façade F1, carpentry H1 of a dwelling in a block of flats in climate zone B3 and orientation NE, for a lifetime of 50 years, equation [5] will be used using the following values:

$$Em_{eq,CO_2cal}^{uso} = [(23,7 - 18,06 + 0,05 + 0,67 + 2,62 + 0,2) \pm 0,57]x\,50\,x\,(1,18 \pm 0,10) =$$

= [503,69; 580,13] Kg eq CO_2

The same applies to obtain equations for the rest of indicators for the use phase.

The value of the equation is multiplied by the lifetime considered and by the corrective factor due to the dwelling type, allowing to roughly estimate the impact with other building types.

The corrective factors and amounts of the evaluation model are only valid for the defined building assemblies and conditions. It will be necessary in the future to broaden the number of building assemblies

solutions to properly aid planners in the decision making process. However, the defined equations will remain the same when more data is added. The equations and the procedure to obtain the factors and amounts constitute the essential elements of the model proposed here and the main contribution of the paper since they represent the method for the easy estimation of impacts of building envelopes considering the whole life cycle.

3.3 Validation of the model

In the first place, it must be pointed out that mathematically speaking, an equation obtained through lineal regression fits the data when the R-squared (r^2) is close to value 1. In this case, the regression model obtained is considered to be sufficiently reliable, since the r^2 values of the regressions that were performed and obtained by means of an Excel sheet, are very close to 1, the lowest r^2 being 0.9819; all the regression models therefore fit the real data quite well (Table 10).

Additionally, we have checked the appropriateness of the model by means of the F-statistic, which makes it possible to check whether the variables used for the regression model really explain the value of the impacts that are analysed. When there is no relation between the independent variables, xi and the dependent one y, the value of the F-statistic is below the critical F value, which is obtained from F distribution tables. This distribution depends on the degrees of freedom n and N, n being equal to the number of degrees of freedom and N equal to the size of the sample minus the number of degrees of freedom (df). Hence, for the regression models that were produced:

N= 180
df= 169
n= N-df= 180-169 = 11
The critical F (Fcrit) value for an error α= 0.05 is 1.88.

Table 10 shows the r^2 value and the F distribution for each of the regression models. The value of F in each equation is much higher than the Fcrit (1.88), thereby indicating that the variables used explain the final impact value well. As a result, the model equation developed to evaluate the impact of CO_2 emissions and energy consumptions in the use phase is considered to be valid.

Table 10 Values of r^2 and the F distribution for each of the regression models.

Impacts use phase	$Em^{uso}_{eq,CO_2 cal}$	$Em^{uso}_{eq,CO_2 ref}$	$Con^{uso}_{kWh\ cal}$	$Con^{uso}_{epkWh\ ref}$
r^2	0.9963	0.9841	0.9978	0.9819
F	4,551.9	1,048.84	7,530.38	917.003

Ideally, evidence of validation of these model data against real performance of the types of buildings under consideration should be provided. In fact, within the building industry, there is an increasing concern about the mismatch between the predicted performance of buildings environmental behaviour and the actual measured performance. However, studying that gap is beyond the scope of the present paper because this represents by itself a vast topic of research. For the moment this work studies the level of uncertainty associated to the process of obtaining of equations by means of checking how close the values obtained with the equations for the use phase (i.e., the equations obtained through lineal regression) are to the values obtained with the official simulation software (i.e. LIDER and CALENER VYP). In the future, it will be interesting to compare them also with real building data, when they exist.

For the comparison between the simplified method here proposed and the simulation software, the percentage value of the deviation for 180 combinations was studied. In the following the results of testing the level of error of the model are discussed:

With regard to the manufacturing and installation phase, the relative error did not exceed 0.46%, the average relative error being 0.31%.
As regards the maintenance phase, the relative error reached 11.20% for some values, although it can be seen that the average is 7.15% and that the error always has a negative sign. This confirms the idea that the error is always produced in the same sense, that is to say, the model would always be below the real value and the error is therefore within acceptable values.
As far as the use phase is concerned, the relative error in the indicator Equivalent CO_2 Emissions ranges between values of 0.15 and 10.5% in most cases. Likewise, it can be seen that the average of the relative

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errors is 1.96% and that the relative error of a particular building assembly holds the same sign and is similar in all the different types. The estimated values given by the indicator can therefore be considered acceptable.

In this same use phase the relative error in the indicator Equivalent CO_2 Emissions due to emissions from air conditioning cannot be tested in several of the results because they are real values that are insignificant (close to 0), which raises the relative value of the indicator sharply in percentage terms.

Taking all the above into account, the model developed here is considered to be valid.

3.4 Creation of the matrix in Excel to implement the model

Once the equations had been obtained and their validity tested, they were implemented in a number of matrices in Excel. This allows different alternative designs to be chosen for the building envelope in different climate zones and orientations in three types of buildings, so that the estimated values of the impacts generated in each of the phases of the life cycle of the building can be shown automatically.

The first step is to develop a calculation matrix, which is divided into two parts: the left-hand side of the matrix contains the columns of data in which the user can select the different variables corresponding to the construction assemblies, orientation and climate zone. There is a column to incorporate the Fs (Surface factor) value corresponding to the proportional share of the surface area of each element in the envelope per square metre of net floor area of the building.

The right-hand part of the matrix contains the columns of the results and is divided into three blocks, one for each of the phases of the life cycle of the building evaluated: the manufacturing and installation phase subdivided into six columns, the maintenance phase subdivided into four columns and the use phase subdivided into six columns. Each column contains an impact in its corresponding phase and shows the name of the indicator and the corresponding units according to the type of impact per square metre of usable floor area in the dwelling.

The planner can use this calculation matrix by selecting the type of dwelling in the first column and using the second column to indicate the surface factor, Fs. Furthermore, the user can also select the climate zone and the building orientation.

The estimated value of the impacts is obtained because the equations developed for each indicator are linked to the corresponding cell of the calculation matrix (Figure 3.3). Columns belonging to the same indicator are identified with the same colour in the different phases of the life cycle. The user can estimate the value of the impacts in real time and can compare different design options easily. Thus, table 11 and table 12 show the calculation matrix with the results obtained for the options that were selected. The estimated values for the impacts are the mean of the extreme values of the uncertainty interval presented in section 3.1.1.

Table 11 Calculation matrix: Result of the estimated values of each impact in the manufacturing phase and maintenance phase of the life cycle

BUILD TYPE	Fs	MANUFACTURING PHASE							MAINTENANCE PHASE			
		Eq. CO₂ emissions $Em^{fab}_{eqCO_2}$ kg CO₂/m²	Energy consump Con^{fab}_{kWh} kWh/m²	Water consump Con^{fab}_{agua} m³/m²	Non Hazardous waste Gen^{fab}_{resno} kg/m²	Hazardous waste Gen^{fab}_{resp} kg/m²	Energy costs $Cost^{fab}_{ep/m^2}$ €/m²	Investment costs $Cost^{fab}_{€/m^2}$ €/m²	Eq. CO₂ emissions $Em^{man}_{eqCO_2}$ kg CO₂/m²	Energy consump Con^{man}_{kWh} kWh/m²	Energy costs $Cost^{man}_{ep/m^2}$ €/m²	Retrofit costs $Cost^{man}_{€/m^2}$ €/m²
SEMIDET 0.72 / BLOCK 0.23 / DETACHED 1.00		264.16	0.17	0.03	23.74	0.10	119.71	197.05	85.88	182.10	32.98	107.37
SEMIDET 0.72 / BLOCK 0.23 / DETACHED 1.00		222.75	0.17	0.05	13.21	0.08	98.18	161.04	66.57	152.03	27.54	88.49
SEMIDET 0.53 / BLOCK 0.63 / DETACHED 1.44		165.53	0.14	0.02	18.15	0.04	75.11	129.54	39.22	89.95	75.11	58.88
SEMIDET 0.53 / BLOCK 0.63 / DETACHED 1.44		126.81	0.14	0.03	9.24	0.03	60.86	110.67	33.06	80.35	14.55	52.85
SEMIDET 1.00 / BLOCK 1.44 / DETACHED 0.25		421.17	0.25	0.06	49.11	0.13	197.06	346.47	129.56	266.24	48.22	167.34
SEMIDET 1.00 / BLOCK 1.44 / DETACHED 0.25		356.44	0.25	0.08	26.01	0.11	165.65	288.54	102.73	224.48	40.66	141.12

Table 12 Calculation matrix: Result of the estimated values of each impact in the use phase of the life cycle

BUILD TYPE			VARIABLES				USE PHASE										
		Surface factor	Constructive elements	ORIENTATION	CLIMATE ZONE		Eq. CO₂ heating emissions $Em^{uso}_{eqCO_2cal}$		Eq. CO₂ conditioning emissions $Em^{uso}_{eqCO_2ref}$		Energy heating consump Con^{uso}_{kWhcal}		Energy conditioning consump Con^{uso}_{kWhref}		Energy heating costs $Cost^{uso}_{ep€/m²cal}$		Energy conditioning costs $Cost^{uso}_{ep€/m²ref}$	
Type	Fs		C1 C2 C3 F1 F2 F3 F4 F5 H1 H2 H3	NE SE	B3 E1		max (kg CO₂/m²)	min (kg CO₂/m²)	max (kg CO₂/m²)	min (kg CO₂/m²)	max (kWh/m²)	min (kWh/m²)	max (kWh/m²)	min (kWh/m²)	max (€/m²)	min (€/m²)	max (€/m²)	min (€/m²)
SEMIDET / BLOCK / DETACHED	0,72 / 0,23 / 1,00						487,50	430,50	256,00	225,00	2.405,00	2.185,00	1.032,00	1.062,00	415,68	415,68	174,79	174,79
SEMIDET / BLOCK / DETACHED	0,72 / 0,23 / 1,00						349,00	292,00	252,00	221,00	1.719,50	1.499,50	933,50	1.023,50	291,52	291,52	169,08	169,08
SEMIDET / BLOCK / DETACHED	0,53 / 0,63 / 1,44						580,13	503,69	192,00	141,75	2.284,75	1.769,85	723,75	669,06	394,90	336,70	131,09	110,12
SEMIDET / BLOCK / DETACHED	0,53 / 0,63 / 1,44						415,31	341,64	189,00	139,23	1.628,78	1.210,55	700,13	644,81	276,95	236,13	126,81	106,52
SEMIDET / BLOCK / DETACHED	1,00 / 1,44 / 0,25						682,50	525,21	417,28	321,75	3.270,80	2.578,30	1.572,95	1.518,66	565,33	490,51	284,90	249,94
SEMIDET / BLOCK / DETACHED	1,00 / 1,44 / 0,25						488,60	356,24	410,76	316,03	2.338,52	1.769,41	1.521,61	1.463,61	396,47	344,00	275,60	241,92

The environmental impact scores of life cycle assessments are often presented in units that are difficult to grasp, such as equivalent CO2 emissions. One way to make their interpretation easier is to normalise them, that is to say, to divide the scores by a reference score. Normalising the data linearly in such a way that the minimum and maximum values of the indicators shift to the values 0 and 1, respectively, and all the other indicators take on relative values within the dimensionless range (0, 1), allows to easily compare all the values estimated with the model. The normalisation functions were defined based on the idea that the higher the value of the indicator is, the lower the impact will be, that is to say, they are inversely related. Table 13 and table 14 show the normalisation matrix with the results obtained following the normalisation of all the impacts in Figure 3.3. This matrix has the same structure of rows and columns as the calculation matrix and the columns have the same colour as in the calculation matrix. This way, tables 13-14 show the normalised values of the impact in a 0 to 1 scale.

Table 13 Normalisation matrix: Result of the normalised values of each impact in the manufacturing phase and retrofit phase of the life cycle

BUILD TYPE			VARIABLES				MANUFACTURING PHASE							RETROFIT PHASE			
		Surface factor	Constructive elements	ORIENTATION	CLIMATE ZONE		Eq. CO₂ emissions $Em^{fab}_{eqCO_2}$	Energy consump $Con^{fab}_{ep.kWh}$	Water consump Con^{fab}_{agua}	Non Hazardous waste Gen^{fab}_{resnp}	Hazardous waste Gen^{fab}_{rpso}	Energy costs $Cost^{fab}_{ep€/m²}$	Investment costs $Cost^{fab}_{€/m²}$	Eq. CO₂ emissions $Em^{man}_{eqCO_2}$	Energy consump $Con^{man}_{ep.kWh}$	Energy costs $Cost^{man}_{ep€/m²}$	Retrofit costs $Cost^{man}_{€/m²}$
Type	Fs		C1 C2 C3 F1 F2 F3 F4 F5 H1 H2 H3	NE SE	B3 E1												
SEMIDET / BLOCK / DETACHED	0,72 / 0,23 / 1,00						0,87	1,00	0,92	0,52	1,00	0,92	0,63	0,95	0,98	0,98	0,52
SEMIDET / BLOCK / DETACHED	0,72 / 0,23 / 1,00						0,89	1,00	0,59	0,73	1,00	0,94	0,79	0,96	0,98	0,98	0,69
SEMIDET / BLOCK / DETACHED	0,53 / 0,63 / 1,44						0,91	1,00	1,00	0,63	1,00	0,95	0,92	0,98	0,99	0,99	0,95
SEMIDET / BLOCK / DETACHED	0,53 / 0,63 / 1,44						0,93	1,00	0,94	0,81	1,00	0,96	1,00	0,98	0,99	0,99	1,00
SEMIDET / BLOCK / DETACHED	1,00 / 1,44 / 0,25						0,79	1,00	0,39	0,00	1,00	0,88	0,00	0,93	0,97	0,97	0,00
SEMIDET / BLOCK / DETACHED	1,00 / 1,44 / 0,25						0,82	1,00	0,00	0,47	1,00	0,90	0,25	0,94	0,97	0,97	0,23

Table 14 Normalisation matrix: Result of the normalised values of each impact in the use phase of the life cycle

BUILD TYPE	Surface factor	Constructive elements	ORIENTATION	CLIMATE ZONE	Eq. CO₂ heating emissions $Em^{uso}_{eq.CO_2cal}$		Eq. CO₂ conditioning emissions $Em^{uso}_{eq.CO_2ref}$		Energy heating consump $Con^{uso}_{kWh cal}$		Energy conditioning consump $Con^{uso}_{kWh ref}$		Energy heating costs $Cost^{uso}_{ep€/m²cal}$		Energy conditioning costs $Cost^{uso}_{ep€/m²ref}$	
Type / Fs	C1 C2 C3 F1 F2 F3 F4 F5 H1 H2 H3	NE SE	B3 E1	maximum value	minimum value	maximum value	minimum value	maximum value	minimum value	maximum value	minimum value	maximum value	minimum value	maximum value	minimum value
SEMIDET 0.72 / BLOCK 0.23 / DETACHED 1.00				0.76	0.78	0.87	0.88	0.73	0.76	0.88	0.88	0.74	0.74	0.89	0.89
SEMIDET 0.72 / BLOCK 0.23 / DETACHED 1.00				0.83	0.85	0.87	0.88	0.81	0.83	0.89	0.88	0.82	0.82	0.89	0.89
SEMIDET 0.53 / BLOCK 0.63 / DETACHED 1.44				0.71	0.75	0.90	0.92	0.75	0.80	0.92	0.92	0.76	0.79	0.92	0.93
SEMIDET 0.53 / BLOCK 0.63 / DETACHED 1.44				0.79	0.83	0.90	0.93	0.82	0.86	0.92	0.93	0.83	0.85	0.92	0.93
SEMIDET 1.00 / BLOCK 1.44 / DETACHED 0.25				0.67	0.73	0.79	0.84	0.64	0.71	0.82	0.83	0.65	0.70	0.82	0.84
SEMIDET 1.00 / BLOCK 1.44 / DETACHED 0.25				0.76	0.82	0.80	0.84	0.74	0.80	0.83	0.84	0.75	0.79	0.83	0.85

The last step of the model consists of providing a single overall score for each impact that has into account all the life cycle phases studied. The aggregation method requires a weighting process based on trade-offs between different environmental impacts, and hence it is considered the most subjective part of a LCA. Different weighting methods can give different and sometimes contradictory results [36]. Any aggregation method is considered subjective according to the ISO standards. In this model, the simple addition is selected because even if it as subjective as any other method, it offers as advantage in comparison to others the fact that it gives more freedom to the decision maker to do his own trade-offs, without biasing his/her choices towards a type of impact.

With the simple addition the score will go from 0 to 4, where 0 is the worst possible value within the proposed scale and 4 is the maximum value that can be attained by an indicator. To obtain this overall score of the combination of building envelope assemblies that allows to compare each of the impact categories with each other, the values of each impact category are scaled up to a range of 0 to 4. These values are obtained from the matrix of normalised values (Tables 3-14). This requires to consider the number of times that the impact appears in the normalised matrix. For example, CO₂ emissions show up four times: the first one for the manufacturing phase, the second one for the maintenance phase, and the third and fourth times for the heating and cooling during the use phase respectively. Since each of these impacts has a value from 0 to 1, to scale them up to the range of 0 to 4, they are summed up (equation [6]). For the energy consumption indicator the same calculation is taken (equation [7]). Water consumption is obtained exclusively for the manufacturing phase. For this reason to scale it up to a range of 0 to 4, the impact is multiplied by four (equation [8]). Regarding waste generation, there are two normalised input, non-hazardous and hazardous waste, both of which are produced in the manufacturing phase. For this reason, they are summed up and the result is multiplied by two (equation [9]). Lastly, there are six different normalized values for the cost of the different phases. For this reason to scale this indicator value up to a 0 to 4 range, it is necessary to sum these six normalized values up and the result is divided by six and multiplied by four (equation [10]).

$$Em_{eq\,CO_2} = Em^{fab}_{eq\,CO_2} + Em^{man}_{eq\,CO_2} + Em^{uso}_{eq\,CO_2cal} + Em^{uso}_{eq\,CO_2ref} \qquad [6]$$

$$Con_{ep\,kwh} = Con^{fab}_{epkwh} + Con^{man}_{epkwh} + Con^{uso}_{kwh\,cal} + Con^{uso}_{kwh\,ref} \qquad [7]$$

$$Con_{agua} = Con^{fab}_{agua} \cdot 4 \qquad [8]$$

$$Gen_{res} = \left(Gen^{fab}_{resnp} + Gen^{fab}_{resp}\right) \cdot 2 \qquad [9]$$

$$Cost_{€/m²} = \left(Cost^{fab}_{ep€/m²} + Cost^{fab}_{€/m²} + Cost^{man}_{ep€/m²} + Cost^{man}_{€/m²} + Cost^{uso}_{ep€/m²cal} + Cost^{uso}_{ep€/m²ref}\right) \cdot \frac{4}{6} \qquad [10]$$

Weighting the indicators makes it possible to obtain a single value, ranging from 0 to 4, for each of the five indicators considered globally in the whole life cycle. These results are represented on a new matrix that has been called the decision matrix because it allows different design options to be compared, thereby facilitating decision-making (Table 13).

The indicators on the decision matrix refer to the whole life cycle of the building; the right-hand side of the decision matrix will therefore have only five columns of results, each column being identified by the name of the corresponding indicator.

Table 13 Decision matrix. Weighted value of indicators

BUILD TYPE	Type	Fs	Constructive elements / Orientation / Climate zone	Eq. CO_2 emissions (interval value)		Energy consump (interval value)		Water consump (value)	Waste Hazardous and non hazardous (value)	Energy investment costs (interval value)	
SEMIDET		0.72		3.45	3.48	3.59	3.61	3.68	3.03	3.13	3.13
BLOCK		0.23									
DETACHED		1.00									
SEMIDET		0.72		3.55	2.62	3.68	3.69	2.35	3.46	2.32	2.32
BLOCK		0.23									
DETACHED		1.00									
SEMIDET		0.53		3.51	2.58	3.64	3.71	4.00	3.26	2.39	2.42
BLOCK		0.63									
DETACHED		1.44									
SEMIDET		0.53		3.61	3.66	3.72	3.77	3.76	3.62	2.49	2.52
BLOCK		0.63									
DETACHED		1.44									
SEMIDET		1.00		2.25	2.36	3.42	3.50	1.56	2.00	1.63	1.67
BLOCK		1.44									
DETACHED		0.25									
SEMIDET		1.00		2.38	2.48	3.54	3.60	0.00	2.94	1.87	1.90
BLOCK		1.44									
DETACHED		0.25									

In order to assess the importance of the obtained results with respect to other reference data, they are compared to the emissions associated to an average dwelling in Spain, estimated in 2.992 kg CO_2 [36]. For example, the difference in CO2 emissions between the combination C2F1H1 (ventilated flat roof, brick cavity wall with external wall coating and 5 cm insulation, and aluminium carpentry) and the combination C3F3H2 (inverted flat roof, brick cavity wall with external wall coating and 10 cm insulation, and PVC carpentry), in a lifetime of 50 years for the semi-detached house is of 179.91 kg CO_2/m^2. This represents 23.94% less emissions for the first option per square meter of net floor. The difference between choosing one combination over another one is in total 16,761.63 kg CO_2 in 50 years; that is to say, the selection of one combination over another one may represent emissions savings equivalent to the overall emissions of an average dwelling in Spain during 5.6 years.

4. Conclusions

A model has been developed to calculate the environmental impacts related to the materials used during the manufacturing, installation and maintenance phases of the envelope of residential buildings (embodied impacts), as well as the impacts generated by the heating and cooling installations due to the contribution of the envelope to energy efficiency during the use phase of the building (operating impacts). It also makes it possible to evaluate the economic cost of the impacts associated to its life cycle in terms of both investment and energy saving.

The developed model allows to obtain and compare live estimated data about the environmental embodied and operational impacts of different building envelope assemblies at the early phases of materials selection. The calculation matrix allows the planner to know the value of the estimated impacts of each of the possible combinations by selecting different options on the matrix.

The normalisation matrix provides the planner with a normalised value for each impact in the different phases of the life cycle. The results obtained in this matrix are dimensionless values between 0 and 1 that are easily comparable. The colour coding makes it easier to identify the indicators. Simplifying the homogenised values allows the planner to compare the weight of a particular impact in the different phases of the life cycle or to compare the weight of a specific impact in different building assemblies. Likewise, the planner can compare the investment costs with the costs of the energy consumed at the end of the life cycle and also obtain the saving that can be obtained by choosing one particular combination rather than another, in terms of both investment and energy saving.

The decision matrix makes it possible to estimate an overall score per indicator and even an overall score for the environmental behaviour of each combination of building envelope assemblies that is evaluated; this value can be used in the catalogues of building assemblies covering a range from 0 to 4. The score obtained can be used, if a limit is established, to require that a minimum value is reached in order to be able to use a particular combination in a climate zone or in an orientation.

It has been found that the model developed here can be applied to three types of residential use: a semi-detached house, a block of apartments and a standalone detached house. Hence, the designer planner can know the estimated value of the impacts of different alternative envelopes in these three different types of building in the different phases of the life cycle.

As a final conclusion, it could be said that the model developed here can make the planner's job easier by characterising, comparing and selecting alternatives not only in terms of materials but also at an intermediate level between the material and the building, by combining different materials that go to make up the building assembly. It provides a scale of comparison that allows the impacts of all the phases of the life cycle of the building to be related, as well as allowing easy detection of the most critical phase or the most critical impact.

It offers a system of scoring based on indicators that can be integrated within construction databases and catalogues of building assemblies, including economic-environmental criteria.

This work has limitations regarding the uncertainty of the estimations that the model can produce because it relies on data from energy simulation tools, instead of from real building data. Within the building industry, there is an increasing concern about the mismatch between the predicted performance of buildings energy behaviour and the actual measured performance. Studying this gap was beyond the scope of the present paper. However, it is a line of research currently being studied by the scientific community. In this paper, for the moment we have just provided a level of uncertainty associated to the process of obtaining the equations by means of simulation models. In the future, when the gap between predicted performance of buildings energy and real building energy behaviour is better diagnosed, the level of uncertainty will require to be updated with regard to real data.

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