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A macro-component approach for the assessment of building sustainability in early stages of design

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ABSTRACT

In the framework of the European research project *SB_Steel*, a new life cycle methodology was developed aiming at the evaluation of life cycle impacts of buildings in the early stages of design. The proposed approach includes the estimation of the energy needs of the building during the operation stage. The early stages of design have the higher influence on the life cycle performance of the building; however, in these stages the availability of design data is often limited. Moreover, the estimation of energy needs is usually based on a performed-based approach, requiring a full definition of the building design.

In the proposed methodology both problems are addressed by the macro-component approach, which provides a range of pre-defined construction solutions for the main components of a building, integrating life cycle embodied data. The approach enables a simplified estimation of the life cycle environmental performance of a building based on limited design data and provides aid for decision making in relation to the use of different materials and construction solutions aiming to lower life cycle impacts and lower energy consumption.

The proposed approach is illustrated by a case-study, in which a residential building is assessed in the early stages. Finally, based in complete data, an advanced analysis of the building is performed in order to discuss the limitations of the developed approach.

It is shown that the limitations introduced by the simplified approach are not relevant and that, even with lower availability of data, the guidance provided by the methodology is adequate.

1. Introduction

The construction industry is a major contributor to the global economy, but it is also one of the most important contributors in resource consumption and waste production [7], playing a fundamental role in the global sustainable development. Measures to make buildings more sustainable rely mostly in life cycle approaches, covering the three main aspects of sustainability: environmental, economical and social/cultural. Life cycle analysis (LCA) is a systematic approach enabling the quantification of potential environmental impacts of a building over its life cycle – from structure's conception to the end of its service life, and from raw material extraction to the management of building's demolition waste. The use of such an approach at the beginning of a design process is very important in the pursuit of sustainable construction, as illustrated in Fig. 1 [33].

The assessment of building efficiency in terms of the minimization of life cycle environmental impacts and energy consumption is of paramount importance in the context of building's sustainability. Most fundamental decisions influencing the life cycle performance of a building are taken in the very beginning of the design process. As shown in Fig. 1, the earlier the assessment, the higher is the potential to effectively influence the life cycle performance of the building.

However, the assessment of building sustainability in the early stages of building design faces several barriers.

One major problem is the availability of data in the initial stages of design. Life cycle analysis requires a huge amount of data and a certain degree of expertise in the field. Moreover, in case of buildings, it usually requires a good definition of the building plans, including details of external walls, partitions, slabs, roof, cladding system, etc. Often, in the early stages of design, architects and engineers have only a rough idea of the building design and building plans and details are not available at this stage. In addition, most architects and engineers do not have the expertise to perform life cycle analysis and most design decisions at these stages are taken based solely on the designer experience rather than quantitative indicators.

On the other hand, the assessment of energy requirements for the building operation usually requires a performance-based

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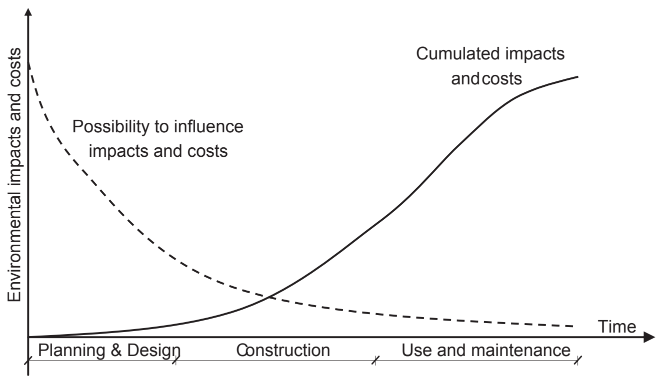


Fig. 1. Influence of design decisions on life cycle impacts and costs [33].

approach, which is usually carried out at the end of the design process to demonstrate code compliance.

The aim of this paper is to present a new approach that enables a simplified assessment of the building sustainability, considering two distinct early stages of design: the concept stage and the preliminary stage. The lack of building details is overcome by the use of the macro-component approach, while the energy required for building operation is estimated by a numerical tool developed with this purpose. Macro-components are pre-defined construction solutions, integrating materials and the respective life cycle environmental information, thus avoiding the need to carry out independent life cycle analysis.

The proposed approach is illustrated by a case-study: the life cycle assessment and energy analysis of a residential building are performed in the concept stage and in the preliminary stage of design. An advanced analysis, taking into account complete data for the building, is performed in the end to identify and discuss the main limitations of the simplified approach.

The approach presented in this paper has been developed in the framework of the European Research project SB_Steel: Sustainable Building Project in Steel. The methodology is currently being implemented into a free-access web-based tool. Although the methodology was developed in the scope of steel buildings, it can be used for any type of buildings.

2. Early stages of building Design

2.1. Design stages

The design process of a building comprises several stages. The first stage in a project is the **Project Start-Up** whereby the project brief is developed by identifying the requirements of the building through consultation with stakeholders. This initial stage basically states the wishes of the Client and will not be addressed in this paper.

The second stage in a project is the **Concept Design** that develops an initial building concept for the project. This design stage defines the overall system configuration and produces schematic drawings and layouts that provide an early project configuration.

The following stage is the **Preliminary Design** whereby schematic diagrams are refined enabling to estimate the main quantities for the building project.

Finally, the **Developed Design** contains all the information required to execute the building and all data necessary for a sustainability assessment is available.

In the concept stage of design the availability of data is poor and any assessment has to be based mainly on assumptions. The preliminary design stage fills the gap between the concept stage and the developed design stage of a building. In this stage, the level of data is higher than in the previous stage, which enables a more accurate evaluation of the solution. The methodology presented in this paper addresses the **concept stage** and the **preliminary stage**.

2.2. Available methodologies for the assessment of buildings in early stages of design

The assessment of the sustainability of buildings needs to address multiple dimensions such as environment, economy, society, cultural, etc, by following a life cycle analysis (LCA).

In normative terms, the international standards [21,22] lay down general guidelines for life-cycle environmental assessment of products. In relation to the construction sector, CEN TC 350 has been developing a series of standards for the assessment of building sustainability [10] addressing environmental aspects [11,14], social aspects [12] and economic aspects [13].

However, all these standards assume that the building bill of materials, construction processes, material sourcing and type of occupancy are known. This is not the case in early stages of design. Another barrier for the use of LCA in early stages is that it relies on inventory data of building materials, which is usually time consuming and requires some level of expertise by building professionals.

Simplified approaches for early design avoiding the need of LCA modelling were proposed by Luttropp and Lagerstedt [26,28] based on basic rules and decision boxes for Ecodesign, respectively.

Focussing only on the calculation of the energy demand of buildings in early stages, simplified tools were proposed by Nielsen [1], Petersen and Svendsen [27], Attia et al. [29] and Carlos and Nepomuceno [5].

On the other hand, the integration of building information modelling (BIM) with other tools has a major potential for sustainability assessment of buildings and it's a subject addressed by numerous authors. This integration faces however several barriers such as the lack of interoperability between the different approaches and the need for a common data format [15].

In terms of the assessment of energy needs in early stages of design [32], proposed a performance-based approach based in BIM that takes into account the quality of the energy sources by an exergy analysis.

With respect to the assessment of life cycle embodied impacts in early stages [2], proposed a method integrating BIM software with a LCA tool and energy analysis. The proposed approach excludes end-of-life stages and it's limited to the accounting of carbon dioxide equivalents. A similar framework to evaluate the impacts of buildings was proposed by Gu et al. [18] but it was concluded that for a comprehensive analysis a full life cycle assessment via LCA software was necessary.

In terms of costs estimation, a BIM model that incorporates cost estimation was proposed by Cheung et al. [6].

Most of the reviewed approaches require the use of BIM software together with other tools, either for energy calculation and LCA. This naturally depends on the availability of such tools and requires, from the point of view of the user, some expertise in modelling and management of the different approaches. A model of the building is required and the interoperability of the different tools must be ensured. This is particularly difficult at early design stages because essential data will be missing for the operation of some of the specific tools. In summary, current available approaches present the following drawbacks:

- they are time-consuming, particularly LCA;
- they require specific expertise to operate the different tools;
- they provide poor results with low availability of data, which very often lead to wrong ranking of alternatives.

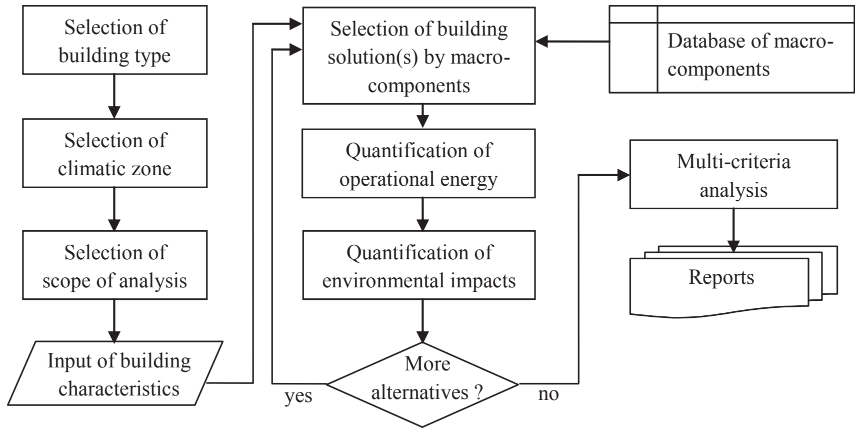


Fig. 2. Flowchart of the algorithm.

The approach proposed in this paper avoids the need to use such tools by providing an integrated approach that includes the features of building modelling, the features of LCA for the quantification of the building environmental profile and the quantification of the building energy demand.

Therefore, the aim of the proposed approach is to perform simple and fast but efficient analyses in early stages of design enabling more informative decisions to be made, while improving the potential of achieving improved performances.

3. Assessment of buildings in early stages of design

In the early stages of design the building designer faces different questions in relation to: (i) building location (which is usually not really a decision of the building designer but of the owner of the building); (ii) building orientation; (iii) building shape; (iv) structural system to be adopted; (v) building envelope and (vi) interior finishes.

Naturally, this is a challenging procedure as each question has a wide range of different alternatives that globally will lead to an even wider range of different solutions. In addition, from the point of view of the environmental assessment, the problem is more complex as one solution may be beneficial in some environmental categories and simultaneously harmful in others.

The methodology herein proposed aims to guide the building designer in the resolution of the above questions, in the pursuit of a more efficient building design.

The proposed methodology aims to quantify cycle embodied impacts and energy consumption, and it is intended to be used in the two stages of design described before: the concept stage and the preliminary stage. The algorithms for input of data and calculation procedure are similar in both stages; however, due to the lower availability of data in the former, simplifications are considered for both the energy calculation in the operation stage and life cycle environmental impacts.

The lack of detailed project data in early stages of design is addressed by the macro-components, which are a set of predefined construction solutions incorporating life cycle embodied impacts. For the calculation of the energy needs of the building, an algorithm was developed based on [20].

The general flowchart of the methodology is illustrated in Fig. 2 and it comprehends three main parts: (i) the input data; (ii) the evaluation of life cycle embodied impacts and energy consumption; and (iii) the comparison between alternative solutions (if the building designer specifies more than one solution).

A detailed description of each step of the methodology is provided in the following sub-sections.

3.1. Classification of building typology

Buildings can be clustered into different classifications according to different criteria. Given the wide variability of building solutions and the need to calibrate and validate each sub-set, the classification scheme presented in this paper focuses on steel-intensive buildings. However, it is emphasized that the approach is completely general and may be expanded to cover all building possibilities.

In the proposed approach buildings are classified according to its functionality and to respective steel content.

In terms of functionality, buildings are broadly classified as residential buildings and non-residential buildings. Residential buildings are further classified according to their size in: (i) single family houses; (ii) multi-family houses; and (iii) apartment blocks. Non-residential buildings can be classified into: (i) office buildings; (ii) commercial buildings; and (iii) industrial buildings.

Steel is a common material used in the construction of buildings. The application of steel in a building varies from simple service ducting to the main frame of the building.

Therefore, in relation to the parameter "steel content", three main categories are defined: (i) category 1, representing steel-intensive buildings, in which the main structure (frame and metal floor decking) and/or sub-structure (foundations and sheet piling) are made of steel components; (ii) category 2, representing buildings in which the main structure is not made of steel but the envelope (roofing and wall cladding), is made of steel; and (iii) category 3, representing buildings in which only secondary components such as service ducting, furnishings, fittings and finishes are made of steel.

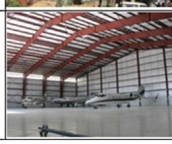
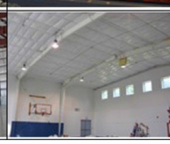
Taking these aspects into account, the classification matrix of Table 1 is considered in which the columns represent the building categories in terms of "steel content" and the rows the building typologies in terms of building functionality.

3.2. Climatic zoning

Climate is a key-factor for the energy consumption of buildings [31]. Besides the direct influence of the climate (e.g. air temperature) on the energy needs for heating and cooling the building environment, the specific location of the building is also responsible for other types of energy consumption. An example is the increased energy needs for building illumination when the number of daylight hours decrease.

In the proposed approach the Köppen-Geiger climate classification [25] was adopted. Focussing on Europe (see Fig. 3), the climatic classification within Europe depends on the latitude, the altitude and coast vicinity [31].

Table 1
Matrix for classification of steel buildings.

	Category 1	Category 2	Category 3
Single & multi-family building			
Apartment blocks			
Office buildings			
Commercial/Industrial buildings			

Given that in the early design stages the location of the building is known, the influence of the appropriate climate is properly taken into account.

3.3. Scope of the analysis

The life-cycle analysis is carried out in accordance with European standards [11,14]. The modular concept of the aforementioned standards, which is represented in Table 2, is adopted in the methodology. Therefore, the life cycle environmental analysis of the building comprehends the stage of material production (modules A1 to A3), the construction stage (module A4), the use stage (modules B1 to B5), the end-of-life stage (modules C1 to C4) and the benefits and loads due to recycling processes (module D).

Nevertheless, the designer is able to select between a cradle-to-gate analysis (modules A1 to A3), a cradle-to-gate analysis plus recycling (modules A1 to A3 and module D) or a cradle-to-grave analysis plus recycling (modules A to D).

Modules A5, B1 and B7 are not covered. The importance of the impacts due to the construction process (module A5) (including the use of equipment, the operation of the construction site and the production of waste) are discussed in the case study.

Module B1 covers the emissions due to the use of installed materials in the building that are not considered in the remaining modules of the use stage. Considering that nowadays due to strict material legislation construction materials are low-emission, this module has little importance. Finally, the quantification of water use (module B7) is not considered as it does not depend on the construction options.

3.4. Input of building characteristics

The geometric characteristics of the building are defined, enabling the quantification of the environmental impacts and of the energy needs of the building. The introduction of data distinguishes between the concept stage and the preliminary stage. In the former, the building is assumed to be of a rectangular shape. Therefore only the length, the width and the height of each floor are needed. The glazing areas of each façade are computed automatically according to the building orientation and the climatic zone, based on predefined parameters for each building typology.

For the preliminary stage, the input of the building geometric characteristics is more detailed since building plans already exist. In this case, either a few pre-defined solutions are provided, as indicated in Fig. 4, or the designer may consider a generic building by the input of the areas of each façade.

In addition, for the quantification of the energy needs of the building for cooling and heating, data is needed in relation to the use of mechanical equipment, shading devices, etc. Again, the input distinguishes between the concept stage and the preliminary stage. In the former, a representative value for each parameter is provided for each building typology (Table 8); in the latter, the designer may select the parameters according to the availability of information.

3.5. Definition of building solution by the use of macro-components

The definition of the building envelope and other building components is made by the use of macro-components. Building components are herein classified according to the UniFormat classification scheme [34]. The following categories are considered in the proposed approach: (A) Substructure, (B) Shell and (C) Interiors. Each main category is further sub-divided. The detailed classification scheme adopted in this approach is represented in Table 3.

On the other hand, macro-components are a set of pre-assembled solutions for the different components of the building, which include the results of life cycle analysis per functional unit.

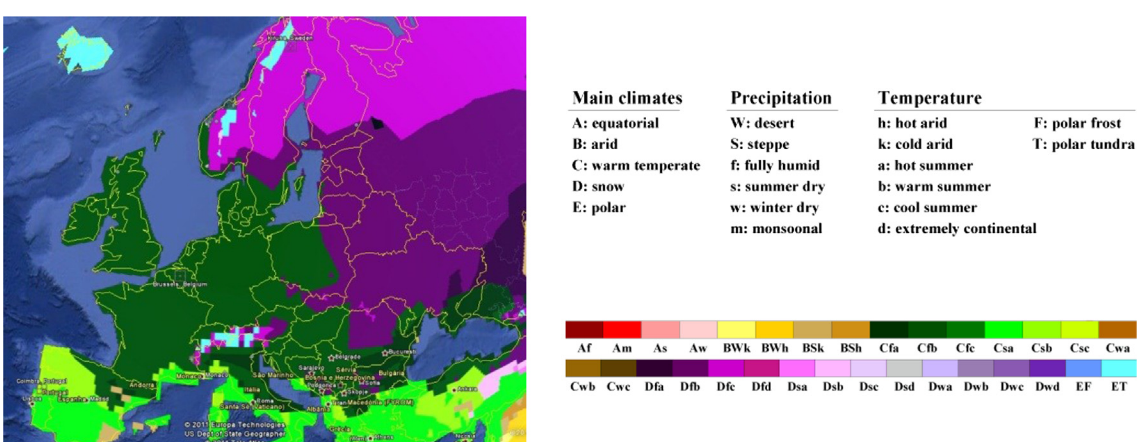


Fig. 3. Europe map of Köppen-Geiger climate classification [25].

Table 2
Building life-cycle information modules (according to EN 15643-2 [11]).

Product stage			Construc. stage		Use stage							End-of-life stage				Reuse/Recycling potential
Raw material supply	Transport	Manufacturing	Transport	Construction process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
x	x	x	x	–	–	x	x	x	x	x	–	x	x	x	x	x

The functional unit of each macro-component is 1 m^2 of a building component with similar characteristics, to fulfil a service life of 50 years. To cope with the lack of design data, the load bearing structure (for a hot-rolled structure, a light-weight steel structure or a concrete structure) is considered per m^2.

The information provided by each macro-component is illustrated by the example in Table 4. In this case, a macro-components assemblage for an interior slab of a building is defined by the following macro-components: (i) a macro-component for flooring (C2030), (ii) a macro-component for a floor structural system (B1010.10), and (iii) a macro-component for ceiling finishes (C2050).

Apart from the characteristics of the different layers of materials, the coefficient of thermal transmittance (U) (taking into account thermal bridges if applicable) and the thermal inertia (κ_m) are also provided to enable for the quantification of the operational energy of the building (at the building level).

It is noted that in the particular case illustrated in Table 4, the value of thermal transmittance (U) is not provided as the macro-component corresponds to an interior slab and therefore, it does not influence the calculation of energy needs.

In addition, macro-components are parameterized so that they can be adapted to the designer's requirements. Hence, the thickness of different layers and transportation distances (modules A4 and C2 in Table 2) may be changed according to the needs. In case the thickness of layers are changed, the values the thermal transmittance and thermal inertia are automatically updated.

The life cycle environmental profile of each macro-component comprehends a cradle-to-grave analysis plus recycling (modules A to D). For the quantification of maintenance and end-of-life stages, appropriate scenarios are defined for each macro-component according to the characteristics of the involved materials.

Finally, a database of macro-components was created for each building component, in order to enable the assessment of alternative building solutions.

3.6. Quantification of the operational energy and environmental impacts of the building

The quantification of the operational energy of the building is based on a monthly quasi-steady-state approach, following the guidance provided by the international standard [20] for the quantification of the building energy need for space heating and cooling. In addition, the energy need for the production of domestic hot water is estimated according to [9]. The simplified approach was calibrated for different types of buildings by the use of the simulation program DesignBuilder [8] (see Ref. [30] for further details).

On the other hand, life cycle environmental impacts are simply compiled for the entire building from the information provided from the macro-components and from the areas of each building component.

The environmental categories selected to describe the environmental impacts of the building are indicated in Table 5 and correspond to the environmental categories recommended in the European standards for the assessment of environmental performance of buildings [11,14].

As already mentioned, the modular concept of the aforementioned standards was adopted in the approach. Therefore, the output of the life cycle environmental analysis of the building is provided per module or by the aggregate value of each stage.

3.7. Multi-criteria analysis

Once different solutions are defined for the building, the final step of the approach is the comparison between different building

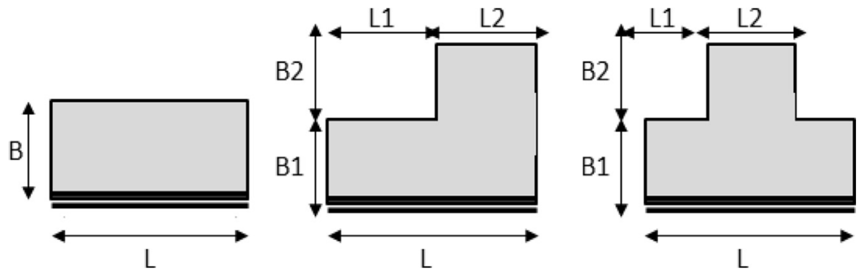


Fig. 4. Pre-defined building solutions in the preliminary stage of design.

Table 3
Building component classification scheme (adapted from Ref. [34]).

(A) Substructure	(A40) Slabs-on-grade	(A4010) Standard slabs-on-grade	
(B) Shell	(B10) Superstructure	(B1010) Floor construction	(B1010.10) Floor structural frame
			(B1010.20) Floor decks, slabs and toppings
		(B1020) Roof construction	(B1020.10) Roof structural frame
			(B1020.20) Roof decks, slabs and sheathing
	(B20) Exterior vertical enclosures	(B2010) Exterior walls	(B2010.10) Ext. wall veneer
			(B2010.20) Ext. wall construction
		(B2020) Exterior windows	
		(B2050) Exterior doors	
	(B30) Exterior horizontal enclosures	(B3010) Roofing	
		(B3060) Horizontal openings	
(C) Interiors	(C10) Interior construction	(C1010) Interior partitions	
	(C20) Interior finishes	(C2010) Wall finishes	
		(C2030) Flooring	
		(C2050) Ceiling finishes	

solutions. The comparison is based on the environmental criteria indicated in Table 3 and in the operational energy of the building. Different methods are available in the literature for multi-criteria analysis in the context of sustainability [17]. In order to avoid trade-offs between criteria, outranking based methods are preferred to aggregating methods (or single criterion methods) because they involve weaker trade-offs [17].

Therefore, the method adopted for the combination of criteria is the *Preference Ranking Organization Methodology of Enrichment Evaluation* (PROMETHEE) [3]. According to this method, the information within each criterion is based on pair wise comparisons. A complete ranking of the alternatives is provided by PROMETHEE II [4], thus enabling a quicker identification of the most efficient solution.

4. Case study: assessment of a residential building

A case study is herein presented to illustrate the way the approach deals with the lack of data in early stages of design. In addition, in order to discuss the limitations of the developed approach, a full life cycle analysis and an advanced energy analysis are performed for the same building, taking into account complete data and by the use of appropriate software.

To enable this discussion, first the building is assessed in the concept stage of design, when data is scarce, and in the preliminary stage of design, for which some detailed information is already available.

4.1. General data

The building assessed in this case study is a two-storey residential house, for a single family. The building is located in Coimbra (Portugal), belonging to the climatic region Csb (according to the Köppen-Geiger climate classification). The respective monthly values of the air temperature and global solar radiation are shown in Fig. 5.

4.2. Macro-components selection

In this case study, three different construction systems are considered. The first and second construction solutions are assumed to be steel intensive and correspond to a light weight steel framing solution and a steel structure with hot-rolled profiles, respectively. The third solution is assumed to be a traditional reinforced concrete and brickwork building. Therefore, the first two solutions belong to Category 1 and the last one belongs to Category 3 (see Table 1).

Hence, from the database of macro-components, different sets are selected taking into account the category of the building and the climatic region. In order to comply with the latter, a maximum value for the thermal transmittance (U) is considered, narrowing the number of appropriate macro-components and enabling an easier selection.

Macro-components are selected for the main components of the building, namely, the superstructure, the exterior vertical enclosure

Table 4
Macro-components assemblage for an interior slab.

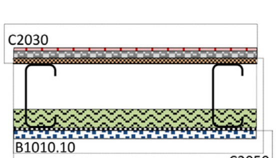
Macro-components assemblage	Macro-components	Material	Thickness (mm)/density (kg/m^2)	U-value (W/m^2 K)	κ_m (J/m^2 K)
	C2030 Flooring	Ceramic tiles	31 kg/m^2		
		Concrete screed	13 mm		
	B1010.10 Floor structural frame	OSB	18 mm		
		Air cavity	160 mm		
		Rock wool	40 mm	–	61,062
		Light weight steel	14 kg/m^2		
		Gypsum board	15 mm		
	C2050 Ceiling finishes	Painting	0.125 kg/m^2		

Table 5
Parameters describing environmental impacts.

Impact category	Characterization factor	Unit
Global Warming	Global warming potential (GWP)	kg CO_2 eq.
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg R11 Eq.
Acidification for soil and water	Acidification potential of soil and water (AP)	Kg SO_2 eq.
Eutrophication	Eutrophication potential (EP)	kg $(PO_4)^{-3}$ eq.
Photochemical ozone creation	Formation potential of tropospheric ozone (POPC)	kg C_2H_4 eq.
Depletion of abiotic resource – elements	Abiotic depletion potential (ADP – E) for non-fossil resources	kg Sb eq.
Depletion of abiotic resources – fossil fuels	Abiotic depletion potential (ADP – F) for fossil resources	MJ

and the interiors. Moreover, the definition of the properties of the glazed envelope is crucial for the thermal balance of the building. In this case study, the characteristics of the glazed envelope of the building are the same for the three construction solutions. The macro-components selected for the three different construction solutions are provided in the Appendix.

4.3. *Assessment of the building in the concept stage of design*

In the concept stage of design it is considered that no plans of the building are available and therefore the assessment is made on a simplified rectangular area of construction. In this case study, it is considered that the total construction area is 240 m^2 and the building has two floors. Hence, the area of each floor is about 120 m^2 and the height of the building is assumed to be 6.0 m, equivalent to a two-storey building. Moreover, it is considered that the main façade of the building is facing west.

All remaining data is estimated according to the procedure described in the following sub-sections.

4.3.1. *Geometry and envelope*

For the rectangular area of the building a width-to-length ratio of 1:2 is considered and the glazing areas in each façade are obtained as a percentage of the respective façade. Hence, walls and glazing areas in each façade are summarized in Table 6.

4.3.2. *Data needed for the quantification of the operational energy*

In this stage it is assumed that no precise information is available about the use of equipment for space heating and cooling. Therefore, all the parameters necessary for the quantification of the energy needs of the building are estimated, as described in the following sub-sections.

4.3.2.1. Additional data for the building envelope. As previously mentioned, the building envelope has a dominant role in the building operational energy consumption. Some of the main relevant parameters related with the building envelope are: (i) the total conditioned floor area; (ii) areas and orientation of external opaque and glazed envelope; and (iii) thermal properties of the materials.

The values of the thermal transmittance for each building component are obtained from the values provided by the macro-components, indicated in the Appendix. In case of the construction solution 1, the *U*-values were obtained taking into account the thermal bridges due to the light-weight steel frame.

Shading devices for the windows are taken into account in order to avoid overheating during the summer season, as well as to provide extra insulation of the glazing components during the night (winter season). If no data is available (which is usually the case in this stage), the thermal and optical properties of the shading devices are taken as the recommended values by ISO 10077-1 [19]; as indicated in Table 7.

4.3.2.2. Building services. The buildings services include: space heating/cooling (air conditioning), mechanical ventilation, exhaust air heat recover and domestic hot water production. Since, in this stage no data is available, the adopted equipment data is presented in Table 8, based in recommended default values provided by international standards [20,9]. However, the designer is able to change any of the recommended parameters. The values related with building services are independent of the constructive solution adopted for the building envelope. Therefore, these values are kept constant for the three alternative solutions.

4.3.2.3. Human factor. The human factor plays a key-role in the energy performance of buildings, since buildings are used and controlled by people. The internal heat gains due to the number of occupants inside the building and the use of equipment are of particular importance. Following guidance in Ref. [20] the occupancy schedule and respective internal gains presented in Table 9 are considered. The use of HVAC equipment is considered only in the period from 17:00 to 23:00, since this is usually the period when occupants are at home and the HVAC system is turned on.

Likewise, these values are kept constant in the assessment of the three construction solutions.

4.3.3. *Environmental life cycle analysis*

According to the assumed building geometry and from data of the selected macro-components, the environmental calculations are undertaken for the complete building and for a life span of 50 years.

The results for the first solution are indicated in Fig. 6, considering the modules defined in European standards [11,14]. This

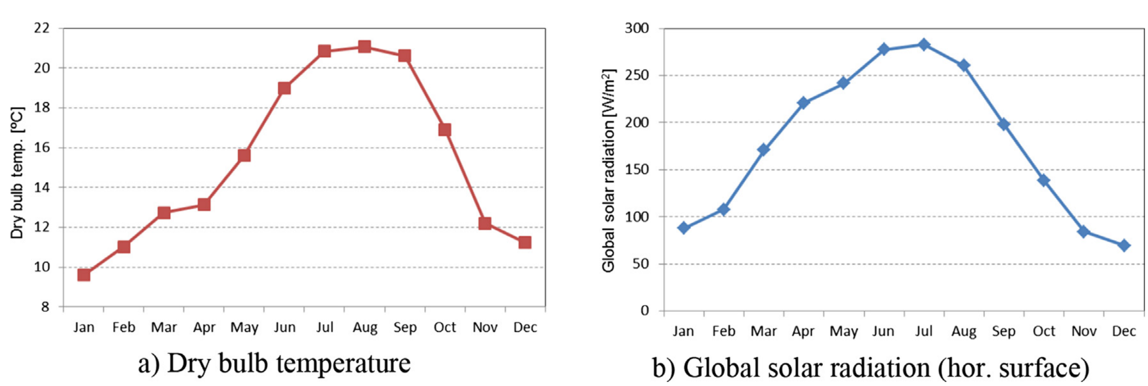


Fig. 5. Weather data for Coimbra, PT: monthly values [23].

Table 6
Building envelope areas in the conceptual stage.

Building envelope	North [m^2]	East [m^2]	South [m^2]	West [m^2]	Sum [m^2]
Opaque area	33.5	75.3	31.4	77.0	217.2
Glazed area	8.4	8.4	10.5	6.7	34.0

Table 7
Thermal and optical properties of the shading devices.

Element	Solar transmittance	Solar reflectance	R [m^2 K/W]
Shutters	0.04	0.35	0.220[a]

[a] Shutter and air space included [19].

graph represents the contribution of each module per impact category. The stage of material production (modules A1-A3) dominates all impact categories (with contributions higher than 60%).

The stage of operation (module B4) and the recycling and recover of materials (module D) have a significant contribution to most impacts categories, followed by the demolition stage (modules C2 – C4). Similar results were obtained for the other solutions. It is noted in Fig. 6 that negative values are obtained for module D indicating that for this particular solution credits are obtained due to the recycling and/or recovering of materials after building demolition.

Hence, the results for the three solutions are summarized in Table 10. Solution 1 has a better performance (lower impact) for environmental categories of ADP_{fossil}, EP and GWP. On the other hand, Solution 3 has a better performance for environmental categories of AP, ODP and POCP. Solution 2 has a better performance only for environmental categories of $ADP_{elements}$.

4.3.4. Operational energy quantification

In the concept stage, the energy needs for space heating and cooling, for the three solutions, are indicated in Table 11.

Solution 2 and solution 3 are clearly more efficient than solution 1. Although the macro-components were selected in order to have similar thermal transmittance coefficients, the thermal inertia of the solutions is quite different as observed in the macro-components tables provided in the Appendix.

The energy need for domestic hot water (DHW) production is the same for all solutions, since it's only dependent on climate, building function and conditioned area. It takes the value of 2605.6 kWh/year.

4.3.5. Comparison between the three constructive solutions in the concept stage

From the results of the life cycle assessment (seven impact categories) plus the indicator of energy needs, it is hard to select the most beneficial solution. Therefore, multi-criteria analysis is performed in order to rank the alternative solutions against the eight criteria referred above.

Table 8
Building services/equipment default input data.

Building services	Values
Air conditioning (Set-point 20 °C–25 °C)[a]	COP Heating = 4.0 COP Cooling = 3.0
Energy need for hot water production[b]	Efficiency: 0.9
Ventilation and infiltration rate[c] (Constant values)	0.6 ACH (Heating mode) 1.2 ACH (Cooling mode)

[a] From Ref. [20] – Table G.12.
[b] Calculated according with [9].
[c] Depends on air tightness of the building envelope and passive cooling strategies.

Table 9
Occupancy schedule and internal heat gains (from Ref. [20]).

Days	Occupancy period	Living room and kitchen [W/m^2]	Other conditioned areas [W/m^2]
Monday to Friday	07:00 to 17:00	8.0	1.0
	17:00 to 23:00	20.0	1.0
	23:00 to 07:00	2.0	6.0
	Average	9.0	2.67
Saturday and Sunday	07:00 to 17:00	8.0	2.0
	17:00 to 23:00	20.0	4.0
	23:00 to 07:00	2.0	6.0
	Average	9.0	3.83

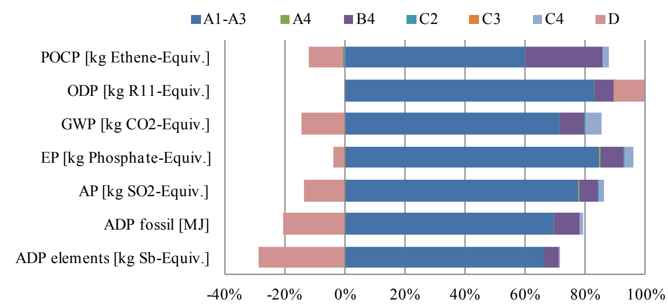


Fig. 6. Solution 1: contribution of each module per environmental category (concept stage).

In order to use PROMETHEE II, two main steps are needed: (i) the selection of weighting factors for different criteria, and (ii) the selection of the preference function and respective threshold for each criterion [17].

In this case study, the Gaussian criterion is selected, in which the preference function is monotonically increasing for all deviations and has no discontinuities (preference function type VI). Hence, considering the same importance (equal weighting factors) and preference function type VI for all criteria, the ranking of alternatives, given by the balance between the positive and negative outranking flows [17], leads to the results indicated in Fig. 7. The higher rank, meaning the most beneficial solution among the alternatives, is obtained by solution 1, followed by solution 3 and solution 2 in decreasing order.

4.4. Assessment of the building in the stage of preliminary design

The availability of data in the preliminary stage of design is usually higher than in the previous stage. In this case study, it is assumed that in this stage the main sketches of the building are already known, as described in the following sub-sections.

4.4.1. Geometry and envelope

The façades and the horizontal plans of the building are provided in Figs. 8 and 9, respectively.

Table 10
Life cycle environmental analysis results, in the concept stage.

Concept stage	Solution 1	Solution 2	Solution 3
ADP elements [kg Sb-Equiv.]	1.68E-01	8.00E-02	2.44E-01
ADP fossil [MJ]	5.37E+05	8.89E+05	7.48E+05
AP [kg SO_2-Equiv.]	1.63E+02	1.86E+02	1.56E+02
EP [kg Phosphate-Equiv.]	1.87E+01	2.49E+01	2.41E+01
GWP [kg CO_2-Equiv.]	4.36E+04	9.05E+04	8.96E+04
ODP [kg R11-Equiv.]	1.24E-03	1.46E-03	6.53E-04
POCP [kg Ethene-Equiv.]	4.26E+01	5.13E+01	2.87E+01

Table 11
—Energy need for space heating and cooling in the concept design stage.

	Solution 1	Solution 2	Solution 3
TOTAL (kWh/year)	2734.7	1853.8	1862.4

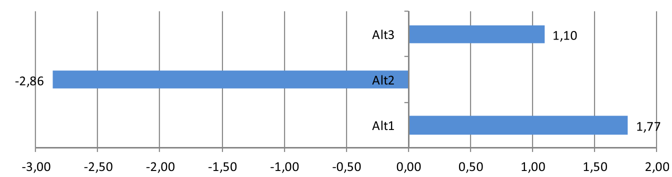


Fig. 7. Ranking of solutions considering the same importance for all criteria (concept stage).

The total area of construction is about 202.00 m^2, with 100.8 m^2 on the ground floor and 100.8 m^2 on the first floor (20.2 m^2 in terrace). The total height of the building is 6 m. The main façade of the building, indicated in Figs. 8 and 9, is considered to face west.

The glazing areas of each façade are also provided in the plans of the building. Table 12 summarizes the areas of the building envelope.

4.4.2. Data needed for the quantification of the operational energy

Although in this stage further project details may be already available in relation to the use of equipment for heating and cooling, for the purpose of this case study, the same parameters considered for the concept stage are taken this stage. Therefore, no further details are herein provided.

4.4.3. Environmental life cycle analysis

According to the building geometry previously presented in Figs. 8 and 9, and by the use of selected macro-components, the environmental calculations are undertaken for the complete building and for a life span of 50 years.

The results for the three solutions are summarized in Table 13. As already observed in the concept stage, Solution 1 has a better performance for environmental categories of ADP_{fossil}, EP and GWP; Solution 3 has a better performance for environmental categories of AP, ODP and POCP; and Solution 2 has a better performance only for environmental categories of $ADP_{elements}$.

In terms of relative importance of each stage, the results obtained for the preliminary analysis are similar to those obtained for the previous analysis. The stage of material production is dominating all impact categories, followed by the stage of operation and the recycling of materials, and finally the demolition stage with lower importance.

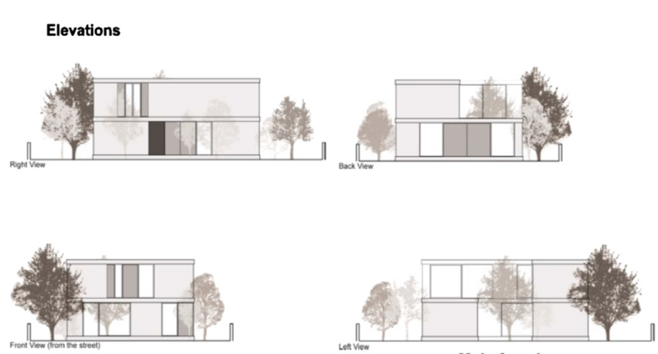


Fig. 8. Building's façades.

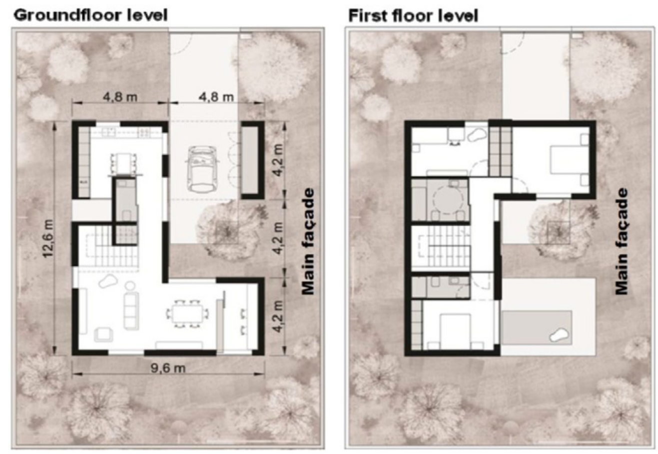


Fig. 9. Building's floors.

Table 12
Walls and glazing areas in the preliminary stage.

	North [m^2]	East [m^2]	South [m^2]	West [m^2]	Sum [m^2]
Walls	41.3	49.9	38.3	60.4	189.9
Glazing	13.0	17.3	15.6	4.3	50.2

4.4.4. Operational energy quantification

The energy need for space heating and cooling in the preliminary stage, for the three different solutions, is presented in Table 14.

In this case, solution 3 has a slightly advantage in relation to solution 2, while solution 1 remains the worst solution. Likewise, the energy need for domestic hot water (DHW) takes the value of 2642.6 kWh/year, for the three solutions.

4.4.5. Comparison between the three constructive solutions in the preliminary stage

Following the same approach as for the concept stage, a multi-criteria analysis is performed in order to rank the three solutions. Considering preference function type VI for all criteria, the ranking of solutions is indicated in Fig. 10, assuming the same importance to all criteria.

Similar trends are obtained for the preliminary stage. It may be concluded from the two analyses that the developed methodology provides a good agreement between the concept stage and the preliminary stage of design, despite the different levels of data availability. Moreover, it is shown that even in the case of the lower level of data (the concept stage), the methodology provides an adequate guidance towards an efficient building design.

4.5. Full LCA and advanced numerical analysis of the building

In this section, the single family house, previously presented as construction solution 1 (the light-weight steel framed building), is

Table 13
Life cycle environmental analysis of the three alternative building solutions, in the preliminary stage.

Concept stage	Solution 1	Solution 2	Solution 3
ADP elements [kg Sb-Equiv.]	1.11E-01	5.00E-02	1.72E-01
ADP fossil [MJ]	4.38E+05	7.12E+05	6.06E+05
AP [kg SO_2-Equiv.]	1.35E+02	1.48E+02	1.26E+02
EP [kg Phosphate-Equiv.]	1.53E+01	1.98E+01	1.94E+01
GWP [kg CO2-Equiv.]	3.54E+04	7.21E+04	7.24E+04
ODP [kg R11-Equiv.]	1.00E-03	1.14E-03	5.05E-04
POCP [kg Ethene-Equiv.]	3.71E+01	4.35E+01	2.44E+01

Table 14
–Energy need for space heating and cooling in the preliminary design stage.

	Solution 1	Solution 2	Solution 3
Total (kWh/year)	2868.4	1942.6	1881.3

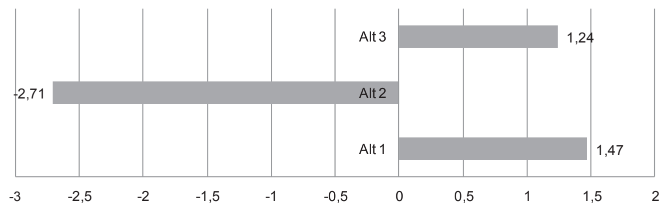


Fig. 10. Ranking of solutions considering the same importance for all criteria (preliminary stage).

analysed taking into account full building details and life cycle stages. The plans and building details used in this section are the ones presented for the preliminary stage.

The main goal of this analysis is to compare and verify the accuracy of the simplified approach described before and to quantify the importance of the aspects that are not covered in the macro-components approach.

4.5.1. Full life cycle analysis

The life-cycle analysis herein presented fills the gaps in the macro-component approach described previously, namely the foundations of the building and the construction stage (module A5). The full life cycle analysis was performed by GaBi 6 [16].

The foundations of the building are in reinforced concrete and the first level of the building is elevated about 50 cm from the ground. At the end-of-life, reinforced concrete is recycled assuming the same recycling rates as in the preliminary stage for concrete and steel reinforcement.

The construction stage (module A5) takes into account the following processes: (i) the preparation of the terrain (excavation of soil and transport to deposit) and (ii) the construction process (use of construction equipment for the assemblage of the structure and a forklift for the lifting of the structural panels). The construction of the building was considered to take 1.5 months.

The results of the life cycle analysis, taken into account all the life cycle stages, are represented in Fig. 11.

The stage of material production (modules A1-A3) dominates all impact categories (with contributions higher than 60%). The construction stage (modules A4-A5) has a negligible importance, varying from 0%, for the categories of ODP, POCP and $ADP_{elements}$ to

Table 15
Error (%) in each impact category by the use of the macro-components approach.

ADP elements	ADP fossil	AP	EP	GWP	ODP	POCP
0.0%	−2.4%	−1.3%	−1.3%	−1.3%	−0.1%	−0.5%

about 2.1% for the environmental category of ADP_{fossil}. The stage of operation (module B4) and the recycling and recover of materials (module D) have a significant contribution to most impacts categories, followed by the demolition stage (modules C2 – C4). It is noted that these conclusion were already achieved in the macro-components approach, despite its limitations.

Finally, the relative error in each impact category, of the macro-components approach in relation to the full analysis is indicated in Table 15.

For most environmental categories the error is negligible. Naturally, the consideration of other construction systems may lead to a higher relevance of the construction stage. However, according to [24]; the construction stage may usually be neglected in simplified approaches.

Therefore, despite the limitations of the macro-component approach, the results obtained by the proposed methodology are consistent with the results obtained from the full life cycle analysis.

4.5.2. Energy calculation

The advanced dynamic simulation of the thermal behaviour of the building was performed using the DesignBuilder [8] software.

The building model was assembled using ten different thermal zones, corresponding to the internal partitions of the building, as indicated in Fig. 12.

The construction elements considered in the model are the same as described previously for the macro-components approach for constructive solution 1. Likewise, the same strategy for windows shading control was considered. In addition, the occupancy schedule, the ventilation and infiltration rates, the efficiency and the schedule of the air-conditioning equipment are taken from the previous analysis.

The main difference between the numerical analysis and the simplified approach is related with the internal heat gains. Instead of default values per area (in W/m^2), as indicated in Table 9, in the advanced approach the internal heat gains were computed taking into account the number of estimated persons in each compartment (occupancy density) and their metabolic activity.

The heating and cooling set point temperatures are the same (20 °C and 25 °C, respectively). However, in the numerical analysis set-back temperatures are defined in order to avoid extreme temperatures inside the building. In this case, the set-back

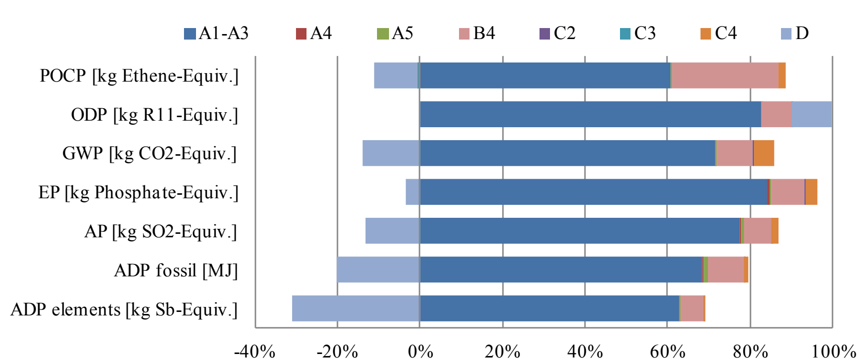


Fig. 11. Life cycle analysis of the full building.

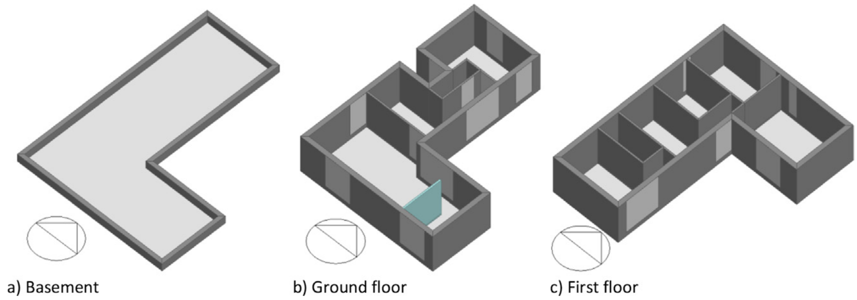


Fig. 12. Layout of the floors.

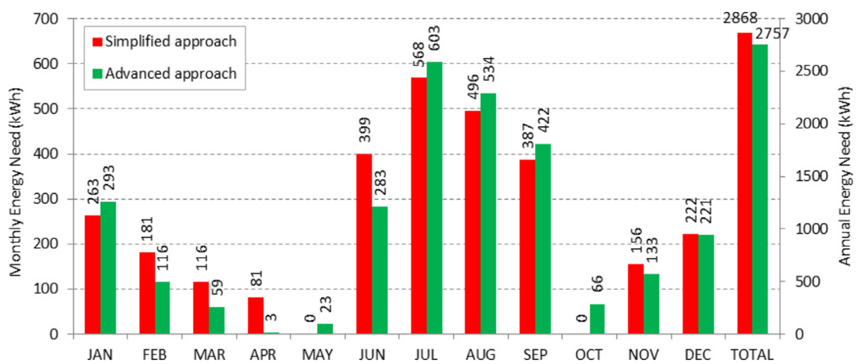


Fig. 13. Comparison of energy needs for space heating and cooling.

temperatures for heating and cooling modes are 16 °C and 31 °C, respectively.

A graphical comparison between the monthly and annual energy needs, for heating and cooling, computed by both approaches for construction solution 1, is displayed in Fig. 13.

It is observed that there is a fair agreement between the simplified approaches and the advance approach herein presented. Taking as reference the values of the advanced approach, the value of the energy need for space heating in the simplified approach has an error of +23%. On the other hand, the value of the energy need for space cooling in the simplified approach has an error of −4%. Taking into account the balance per year, the annual average error provided by the simplified approach is about +4%.

It is noted that the results obtained from this analysis for energy heating and cooling of the building are not necessarily optimized as this was not the aim of the case study.

5. Conclusions

Decisions taken in early stages of design have a huge potential to influence the life cycle performance of a building in terms of environmental impacts and energy consumption. Due to the lack of data and simplified tools to perform early stage analysis, the design process of a building is usually guided by the rationality and expertise of the professionals involved in the process.

In this paper, a methodology for the assessment of building in early stages of the design process was introduced. The method addresses the lack of data in early design stages by a macro-component approach that enables to make accurate estimations of the building performance over its life cycle based on simplified shapes and assumptions. Furthermore, the methodology avoids the use of complex tools such as LCA that usually requires some expertise in the field and provides substantial reduction in the time usually needed to perform such analysis. By enabling to make comparative analysis in relation to the most important factors in the lifetime performance of buildings, the proposed approach is a useful tool for designers in the pursuit of a construction solution with lower embodied life cycle impacts and lower energy consumption.

A case study was presented to illustrate the use of the approach, considering two distinctive design stages: the concept stage and the preliminary stage. Based on different building shapes, according to data available in each design stage, the analyses led to similar conclusions, showing a good agreement between design stages.

A full life cycle analysis and an advanced numerical analysis for the quantification of energy consumption were performed for the same building, to determine the relevance of missing data in the simplified approach. It was concluded that the absolute errors are not very relevant. Nevertheless, it is highlighted that the assessment made by the proposed approach is of a comparative nature. Therefore, the absolute error is not important but only the accuracy of the relative assessment in each design stage.

In order to further improve the guidance provided by the macro-components approach in the early design of buildings and to foster the sustainability of the entire process, the cost of different options is an important issue to be considered in the decision making process. Therefore, the next step is the integration of costs in the functional unit of each macro-component.

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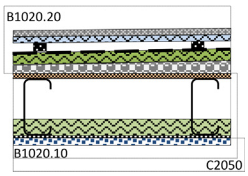
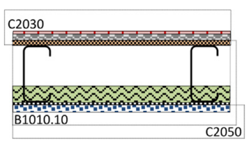
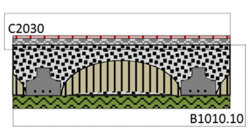
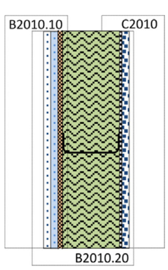
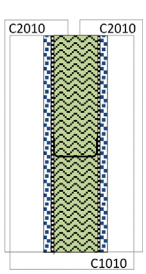
This paper reflects only the author's views and the Community is not liable for any use that may be made of the information contained therein.

Appendix. Macro-components selected for the case study

Table I
Macro-components for the first solution.

	Macro-component reference	Material layers	Thickness [mm] Density [kg/m^2]	*U*-value [W/m^2 K]	κ_m [J/m^2 K]
Roof floor					
	B1020.20 Roof deck Deck, slabs and Sheathing	Cement slab	30 mm	0.373[a]	13,435
		XPS slab	30 mm		
		Air cavity	30 mm		
		Waterproof film	1.63 kg/m^2		
		XPS	0 mm		
		Concrete screed	40 mm		
	B1020.10 Roof Structural frame	OSB	18 mm		
		Air cavity	80 mm		
		Rock wool	120 mm		
		Light weight steel	17 kg/m^2		
		Gypsum board	15 mm		
	C2050 Ceiling finishes	Painting	0.125 kg/m^2		
Interior floor					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	–	61,062
		Concrete screed	13 mm		
	B1010.10 Floor Structural frame	OSB	18 mm		
		Air cavity	160 mm		
		Rock wool	40 mm		
		Light weight steel	14 kg/m^2		
		Gypsum board	15 mm		
	C2050 Ceiling finishes	Painting	0.125 kg/m^2		
Ground floor					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	0.599	65,957
		Concrete screed	13 mm		
	B1010.10 Floor Structural frame	Precast concrete Slab	180 mm		
		XPS	40 mm		
Exterior wall					
	B2010.10 Exterior wall veneer	ETICS	13.8 kg/m^2	0.296[a]	13,391
	B2010.20 Exterior wall construction	OSB	13 mm		
		Rock wool	120 mm		
		Light weight steel	15 kg/m^2		
		Gypsum board	15 mm		
	C2010 Interior wall finishes	Painting	0.125 kg/m^2		
Interior wall					
	C2010 Interior wall finishes	Painting	0.125 kg/m^2	–	26,782
	C1010 Interior Partitions	Gypsum board	15 mm		
		Rock wool	60 mm		
		Light weight steel	10 kg/m^2		
		Gypsum board	15 mm		
	C2010 Interior wall finishes	Painting	0.125 kg/m^2		

[a] Corrected values for thermal bridging.

Table II
Macro-components for the second solution.

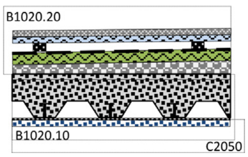
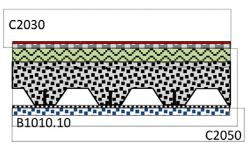
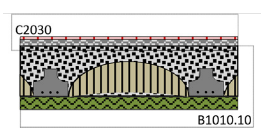
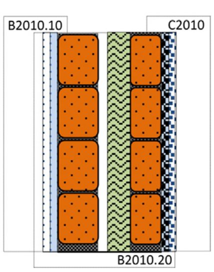
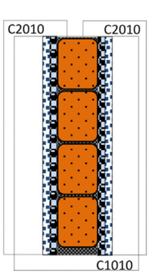
	Macro-component reference	Material layers	Thickness [mm] Density [kg/m^2]	*U*-value [W/m^2 K]	κ_m [J/m^2 K]
Roof floor					
	B1020.20 Roof deck Deck, slabs and Sheathing	Cement slab	30 mm	0.3398	108,756
		XPS slab	30 mm		
		Air cavity	30 mm		
		Waterproof film	1.63 kg/m^2		
		XPS	50 mm		
		Concrete screed	40 mm		
	B1020.10 Roof Structural frame	Composite steel-Concrete deck	200 mm		
		Gypsum board	15 mm		
		Steel structure	40 kg/m^2		
	C2050 Ceiling finishes	Painting	0.125 kg/m^2		
Interior floor					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	–	138,885
		Concrete screed	13 mm		
	B1010.10 Floor Structural frame	Polyethylene foam	10 mm		
		Composite steel-concrete deck	200 mm		
		Gypsum board	15 mm		
		Steel structure	40 kg/m^2		
	C2050 Ceiling finishes	Painting	0.125 kg/m^2		
		Steel structure			
Ground floor					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	0.599	65,957
		Concrete screed	13 mm		
	B1010.10 Floor Structural frame	Precast concrete Slab	180 mm		
		XPS	40 mm		
Exterior wall					
	B2010.10 Exterior wall veneer	ETICS	13.8 kg/m^2	0.305	62,047
	B2010.20 Exterior wall construction	Brick wall	110 mm		
		Air cavity	0		
		XPS	60 mm		
		Brick wall	110		
	C2010 Interior wall finishes	Mortar	15 mm		
		Painting	0.125 kg/m^2		
Interior wall					
	C2010 Interior wall finishes	Painting	0.125 kg/m^2	–	50,117
		Mortar	15		
	C1010 Interior Partitions	Brick wall	110		
	C2010 Interior wall finishes	Mortar	15		
		Painting	0.125 kg/m^2		

Table III
Macro-components for the third solution.

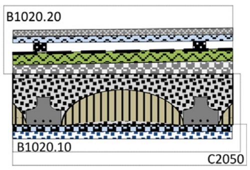
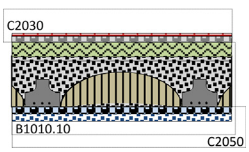
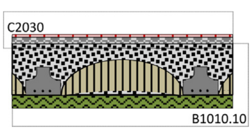
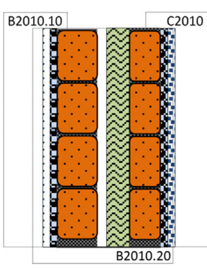
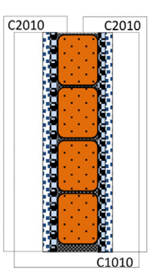
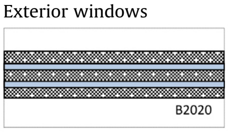
	Macro-component reference	Material layers	Thickness [mm]	U-value [W/m^2 K]	κ_m [J/m^2 K]
Roof floor					
	B1020.20 Roof deck	Cement slab	30	0.342	85,042
		XPS slab	30		
		Air cavity	30		
		Waterproof film	1.63 kg/m^2		
		XPS	50		
		Concrete screed	40		
	B1020.10 Roof Structural frame	Precast concrete Slab	180		
		Concrete structure	235 kg/m^2		
	C2050 Ceiling Finishes	Mortar	15 mm		
		Painting	0.125 kg/m^2		
Interior floor					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	–	115,171
		Concrete screed	13		
	B1010.10 Floor Structural frame	Polyethylene foam	10		
		Precast conc. slab	180		
		Concrete structure	235 kg/m^2		
	C2050 Ceiling Finishes	Mortar	15 mm		
		Painting	0.125 kg/m^2		
Ground floor					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	0.599	65,957
		Concrete screed	13 mm		
	B1010.10 Floor Structural frame	Precast concrete Slab	180 mm		
		XPS	40 mm		
Exterior wall					
	B2010.10 Exterior wall veneer	Painting	0.125 kg/m^2	0.300	64,193
		Mortar	15 mm		
	B2010.20 Exterior wall construction	Brick wall	150 mm		
		Air cavity	25 mm		
		XPS	80 mm		
		Brick wall	150 mm		
	C2010 Interior wall finishes	Mortar	15 mm		
		Painting	0.125 kg/m^2		
Interior wall					
	C2010 Interior wall finishes	Painting	0.125 kg/m^2	–	50,117
		Mortar	15 mm		
	C1010 Interior Partitions	Brick wall	110 mm		
	C2010 Interior wall finishes	Mortar	15 mm		
		Painting	0.125 kg/m^2		

Table IV
Macro-component for exterior windows: thermal and optical properties.

	Macro-component reference	Materials	U-value [W/m^2 K]	SHGC
Exterior windows				
	B2020 Exterior windows	PVC frame Double glass panes (8 + 6 mm, with an air gap of 14 mm)	2.60	0.780

SHGC – solar heat gain coefficient.

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