FCTUC DEPARTAMENTO DE ENGENHARIA CIVIL
FACULDADE DE CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

SUSTAINABLE STEEL CONSTRUCTION

Sustainability of steel structure buildings

Submitted in partial fulfillment of requirements for the degree of Master of Science in Construction of Steel and Composite Structures

Author

Rodolfo Jorge Patrício Bacelar Rocha Martins

Supervisors

Professor Helena Maria dos Santos Gervásio

Faculdade de Ciências e Tecnologia da Universidade de Coimbra

Professor Paulo Fernando Antunes dos Santos

Faculdade de Ciências e Tecnologia da Universidade de Coimbra

Coimbra, July, 2013

ACKNOWLEDGEMENTS

I am grateful to my supervisors, Professor Helena Gervásio and Professor Paulo Santos, whose guidance, expertise and constant availability was of paramount importance for the development of this dissertation.

I would also like to take this opportunity to thank Prof. Luís Simões da Silva for his clear insights, critical analysis and seriousness.

A word of appreciation to my colleagues which made easier some tough moments, characteristic of this kind of research work.

I would like to express my gratitude for the patience of my friends in all of the moments that I couldn’t be present.

Finally, a special thanks to my mother, father, brother and other relatives for all the support and advices. It would have been impossible without your support and affection.

RESUMO

Nesta dissertação estudou-se o ciclo de vida de edifícios com estrutura metálica desde a fase conceptual até ao final do projecto. Calcularam-se os impactos ambientais associados a todas as fases de vida do edifício, bem como, a energia operacional durante a fase de uso. Os primeiros foram calculados de acordo com as mais recentes normas europeias: EN 15978 (2011) e EN 15804 (2011). A quantificação da energia operacional foi realizada numa base mensal, de acordo com a ISO 13790 (2008), tendo-se desenvolvido uma ferramenta de cálculo para o efeito.

Efectuou-se a calibração do algoritmo e, posteriormente, testou-se a aplicabilidade da metodologia desenvolvida para o estudo do ciclo de vida de edifícios através de casos de estudo. Todos os cálculos de energia efectuados pela ferramenta foram comparados com um *software* de cálculo dinâmico.

ABSTRACT

In this research work, the life cycle of steel structure buildings was analyzed since their early stages of design until the final stage. The embodied impacts generated throughout the buildings' life cycle are quantified, as well as the operational energy. The environmental impacts are calculated in accordance with the most recent European standards: EN 15978 (2011) and EN 15804 (2011). The quantification of the operational energy was undertaken in a monthly basis, under the guidance of ISO 13790 (2008). A tool was especially developed to calculated both environmental impacts and operational energy.

The precision of the operational energy calculations is calibrated and the applicability of the methodology are finally tested with the development of case studies. All the energy calculations are verified with software that undertakes dynamic calculations.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Global warming

We are now aware of the importance in reducing the burdens created by the evolution of our society and the life style we take. Even though the increase of the greenhouse gas (GHG) emissions and its effect in the global climate is widely known, it is worth showing its figures. It was recognized in the Copenhagen Accord that, in order to limit the global warming in 2°C by 2020, global emission should not exceed 44 Gigatonnes of carbon dioxide equivalent ($GtCO_2e$). However, despite the environmental policies of the countries it is expected that the global emissions increase to between 49 and 53 $GtCo_2e$ (UNEP, 2011). The likely probability (i.e. higher than 66%) of global temperature increase suggests that by 2020, it is expected an increase of 2 to 3°C in the global mean temperature.

1.2 GHG emissions by economic sector: past, present and future perspective

The commitment of the European Union (EU) in addressing the environmental issues is evident through the numerous policies it has been issuing, as it discussed in more detail in section 2.1. The monitoring of the GHG emission evolution showed that the electricity consumption is one the major polluters as it is presented through the curve of energy use in Figure 1-1. It is noteworthy that energy supply refers to direct fuel combustion only and electricity is not included (EEA Report, 2012).

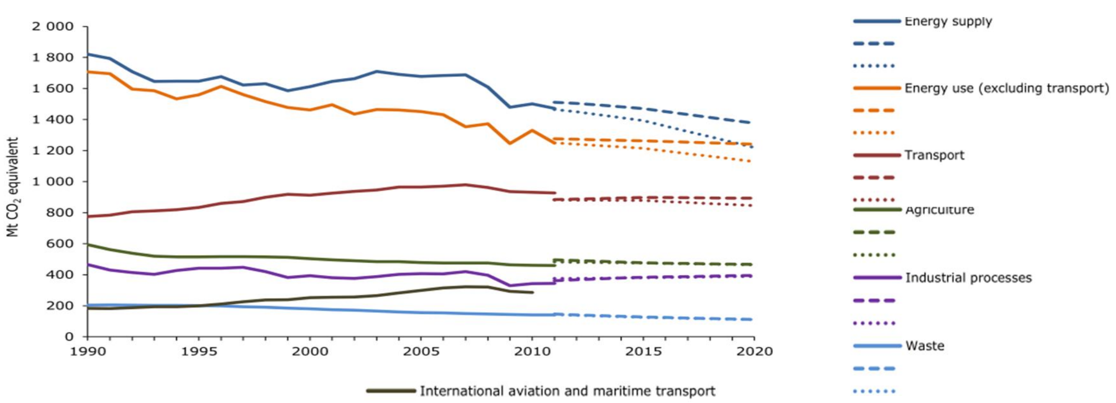


Figure 1-1 –GHG emissions in the EU by sector: trends and projections

1.3 Breaking down the environmental burdens of the construction sector

Focusing the discussion in the construction industry, it is known that this is one of the major sectors in the economy of the EU. In fact it generates about 10% of the GDP of the 27 Member States, employing 13.2 million persons. Furthermore, the sector is responsible for more than 50% of all materials extracted from Earth and also for the generation of over than 450 million tonnes of construction and demolition waste (COM, 2007).

Additionally, it was identified that the energy consumption in buildings represented 40% of the total energy consumption in the member states (Directive 2010/31/EU), motivating the efforts and the commitment of all EU countries to reduce up to 20% its value, in order to comply with the Kyoto Protocol. However, the sustainability of the construction sector is not assured by energy efficiency policies alone. In fact, when reducing the burdens of the use phase, the materials/products and end-of-life stages become more important as illustrated in Figure 1-2.

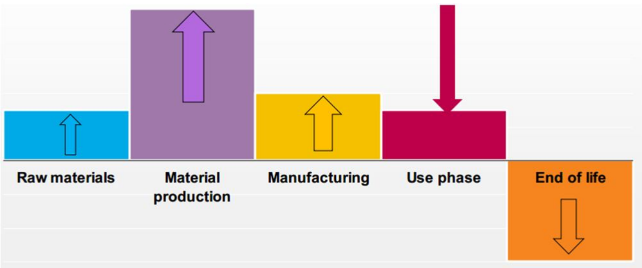


Figure 1-2 – Importance of the other stages of the building, when reducing only the burdens of the use stage

To address the issue of the construction and demolition waste, the EU set another target regarding the sustainable development of construction works: increase up to 70% the rates of re-use, recycling and material recovery of construction and demolition waste. Although a great part of the construction waste is used as embankment, it could also be used as aggregates, thus, substituting the need for new extractions (COM, 2007). These facts also demonstrate the interest within the Member States to develop policies and regulation to minimize the environmental burdens of the construction sector.

Even though the production of steel generates, per kg, more CO_2 than the production of concrete, this is only valid when the comparison is done only at this level: the production. However, if the whole life cycle of the steel products is analysed the advantages of this material in the construction sector are evident. Regarding the end-of-life, steel presents, in some countries, a recycling rate higher than 94%, a re-use rate of 5%, being send to landfill only 1% of the total weight of the steel used. Besides, it is infinitely recyclable maintaining its key properties (Worldsteel, 2012). Whereas, concrete, for example, is limited to be used only as secondary material (as aggregate), still needing the cement to produce concrete, and even steel, in the case of reinforced steel (Tata Steel Report, 2012). Given the goals set to reduce emissions, energy and waste in the construction, it is clear that steel plays an important part in meeting these challenges.

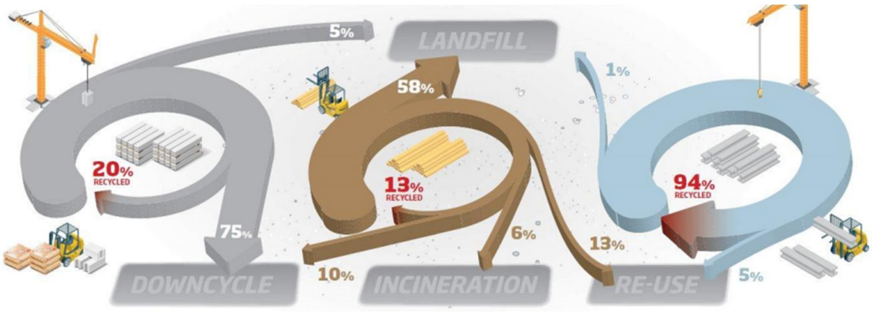


Figure 1-3 – Overview of the end-of-life of concrete, timber and steel (Tata Steel Report, 2012)

This dissertation covers the development of a tool to swiftly assess the sustainability of the buildings since the early stages of design, destined to be used by any player in the construction sector. A general overview is given on the work done in the EU to mitigate the impacts of the construction works in terms of European regulation and voluntary initiatives, and the main reasons that motivate the study of the buildings' sustainability assessment since the early stages of design are also addressed. The existing tools to assess the environmental sustainability of buildings are also focused and discussed. The stages of design addressed in the tool and the available data in each one of these are presented. In the following sections the tool is described, the relevance of the input data needed to undertake the calculations is highlighted, the engine of the tool is dissected and the provided outputs are presented. Follows the verification of the energy algorithm precision under EN 15265 (2007) test rooms and the applicability of the tool is also put to test through a case study. Finally, the results are discussed and the conclusion are produced.

2 CONTEXT AND BACKGROUND

2.1 Sustainability in the Construction sector: EU concerns

The burdens that the Construction sector presents in the environment motivated the strategic interest of the European Union (EU) to potentiate its contribution into a more sustainable development. To address this concern, the EU issued a series of directives developed to:

i. improve the energy performance of buildings;
ii. regulate the waste stream;
iii. harmonize the requirements for construction products.

In terms of mandatory requirements, the EU put into force the directive that rules the Energy Performance of Buildings (EPBD) and defines two stages to meet the goals proposed. In a first stage (already into force) existing and new buildings, as well as major renovations, shall achieve a mini mum energy performance, which is determined at national level. In a second stage, the so called "nearly zero-energy buildings" will be mandatory: in 2020 for all new building and in 2018 for all occupied or new public infrastructures (Directive 2010/31/EU). The effect of these measures is already felt and is supported by the fact that nearly two-thirds of the world's new solar panels were installed in Europe in 2011 (Jager-waldau, 2012).

Given the importance of the waste generated by the construction sector, the EU issued the Directive 2008/98/EC that regulates the waste stream in the EU. The directive entered into force in 12 December 2008, laying down rules on how to handle waste, as well as encouraging to apply the waste hierarchy (Figure 2-1).

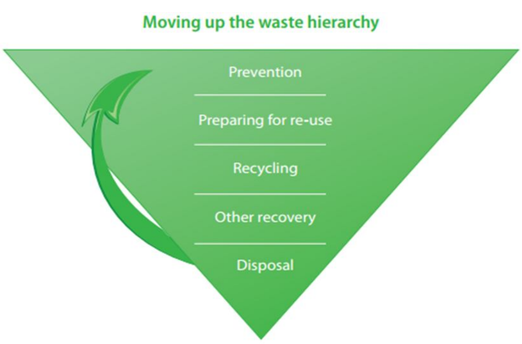


Figure 2-1 – Waste hierarchy (Waste and the Environment, 2010)

This is supported by another important EU directive (2000/532/EC) that categorizes the types of waste by attributing them a code. This procedure harmonizes the nomenclature of waste, improving the efficiency of waste management activities. In order to be up to date with the construction industry, the list of waste shall be revised regularly, with the last revision dated from 2008 (LoW, Okopol, 2008). The harmonization of the products characteristics and properties is also backed up by the CRP (Construction Products Regulation 305/2011), which will supersede the existing CPD (Construction Products Declaration 89/106/EEC) in 1 July 2013.

A series of voluntary tools were launched to assess the environmental performance of products, materials and construction works in general: from the work of TC 350 on the sustainability of construction works to the Environmental Product Declarations (EPD's). However, in order to increase the construction of greener buildings with high levels of sustainability performance it is necessary to produce more efficient and coherent government policies, towards the transparency of building operating costs and other sustainability metrics (ECORYS, 2011). Another key aspect is the decisions based in the economic aspects rather than in quality, safety and environmental criteria and life-cycle costs (COM, 2007). In a much broader spectrum than limiting the environmental concerns to technical solutions, it is the philosophy of the building design that should also be revised and improved, in order to meet the responsible targets set by the EU. Measures to make buildings more sustainable rely mostly in life cycle approaches, covering the three main aspects of sustainability: environmental, economical and social/cultural. The concept of the Kyoto pyramid is also noteworthy in the design of low energy buildings (see Figure 2-2). The left side of the pyramid shows that a responsible selection of construction materials leads to both, reducing the energy demand and applying renewable energy sources.

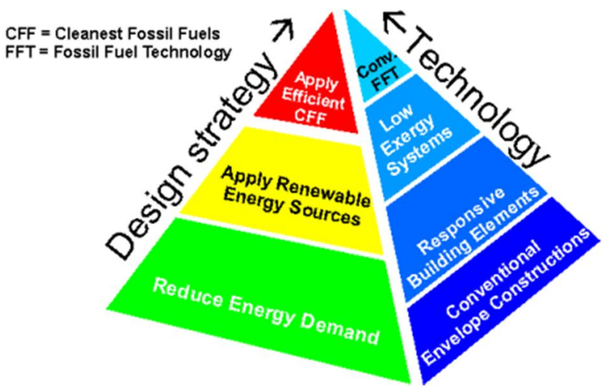


Figure 2-2 – Strategy for designing low energy buildings (IEA ECBSS Annex 44, 2009)

The EU also issued other types of policies to promote the reduction of environmental impacts of products, such as, the Eco-design Directive (2009/125/EC) destined to energy related products, Eco-label (66/2010/EC) certifies products with reduced impacts throughout their life cycle or EMAS regulation (1221/2009/EC) for the improvement of the environmental performance of companies and other organizations (BIO Intelligence Service, 2012).

2.2 Sustainability assessment of buildings in European standards

The increase in EU efforts to achieve high sustainability levels in the construction sector, culminated with the production of several standards aimed to assess the environmental performance of buildings. The international standards ISO 14040 (2006) and 14044 (2006) lay down general guidelines for life-cycle environmental assessment, which were the ground rules to produce the European standards, developed by the CEN TC 350. This technical committee has been developing a series of standards for the assessment of building sustainability (EN15643-1, 2010) addressing environmental aspects (EN15643-2, 2011 and EN15978, 2011), social aspects (EN15643-3, 2012) and economic aspects (EN15643-4, 2012). (EN15643-1, 2010) establishes that the life-cycle of a building comprises the following stages: (i) before use (materials and products); (ii) use; (iii) after use.

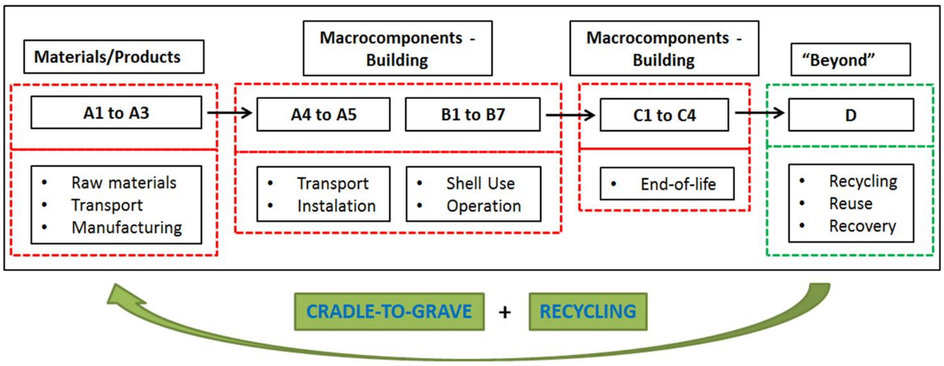


Figure 2-3 – Life-cycle of a building (modules of information) according with (EN15643-1, 2010)

The assessment of the whole building is undertaken with the guidance given in EN15978 (2011). This standard provides information on the calculation methods to undertake the Life Cycle Assessments (LCA), as well as, indicating which potential environmental impacts to use in the quantification of the burdens produced by the building's life cycle. It covers all the stages already presented in Figure 2-3 and it is based in the data gathered from the modular information of the materials/products (obtained through ISO15804 (2011)) and other information related and relevant to the building's life cycle. Another important aspect of the analysis is the definition of scenarios, for example: use of the buildings envelope elements, their disposal, and others. According with the modular system of EN15978 (2011), Module B6 corresponds to the operational energy, i.e., building energy consumption, namely, energy for:

- Space heating and cooling;
- Domestic hot water (DHW) production;
- Auxiliary systems (lighting, fans, pumps, controls).

Ironically, according with EN15978 (2011) the activities of recycling, re-use and recovery are not mandatory in the life-cycle analysis, in spite of the EU stress in respecting the waste hierarchy (Figure 2-1).

It is noteworthy that 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 the early stages of design.

2.3 Environmental performance assessment since the early stages of design

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 Figure 2-4 (UNEP, 2003). Moreover, an holistic approach in the environmental performance of a building is of higher effectiveness if applied in early stages of design (Balcomb & Curtner, 2000).

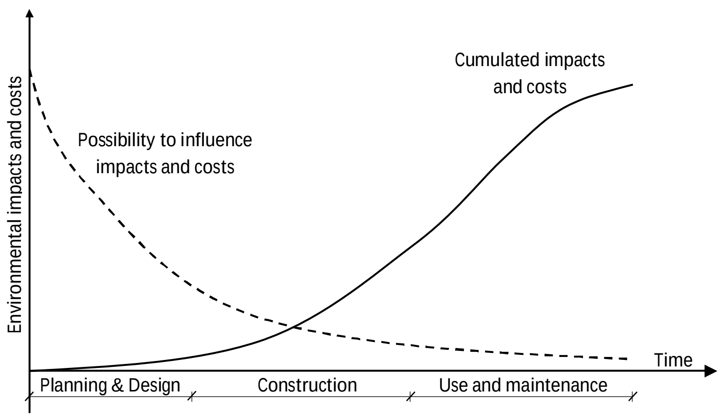


Figure 2-4 – Influence of design decisions on life cycle impacts and costs (UNEP, 2003)

The aforementioned demonstrates the importance of estimation, optimization through comparison of several solutions and monitoring building energy need at early stages of design. Most fundamental decisions influencing the life cycle performance of a building are taken in the very beginning of the design process. As shown in Figure 2-4, the earlier the assessment, the higher is the potential to effectively influence the life cycle performance of the building.

2.4 Available methodologies

The assessment of the environmental performance of a building includes the quantification of the energy consumption and the embodied impacts throughout its life-cycle.

There are two major types of methods to predict the thermal behaviour of a building in terms of its energy needs: dynamic calculations and quasi-steady-state methods.

Most of the advanced software available for energy quantification relies on the first method, enabling to accurately determine energy related information on an hourly basis, through complex algorithms that predict building energy needs through series of iterations taking in account a large amount of heat transfer mechanisms and phenomenon, e.g. EnergyPlus (Crawley et al., 1994).

Simplified methods, however, are based in the simplification of the general case, which in the case of ISO13790 (2008), is a “quasi-steady-state approach”.

There are several tools available to quantify the building energy need. However, most of them have some drawbacks (Attia, Gratia, De Herde, & Hensen, 2012):

- Time consuming;
- Require deep knowledge of thermal efficiency and the subjects involved;
- Not user friendly;
- Do not take into account the early stages of design;
- The calculations are not in compliance with international standards, such as ISO13790 (2008).

There are also other types of tools developed to assess the building in the early stages of design, such as the work of Carlos and Nepomuceno (2012), Nielsen (2005), Schlueter and Thesseling (2009) and Petersen and Svendsen (2010). These tools present some negative aspects, such as:

- do not deal with embodied impacts;
- only calculate heating loads (Carlos and Nepomuceno, 2012);

- require hourly data;
- Do not allow for a swift estimation of envelope areas;
- Lack of a data-base of solutions for the envelope elements;
- The user must provide the properties of the envelope (e.g. U-values, thermal inertia of the envelope, SHGC, reduction factors due to shading provisions):
- Need expertize in energy efficiency and the subjects it comprises;
- Do not calculate the energy use for DHW production.

Besides the aforementioned tools there are schemes specially designed to assess the sustainability of several types of buildings (non-residential and residential) with a holistic approach, namely, BREEAM, DGNB, HQE and LEED. The first three are European and the last is a North America certification scheme. All these schemes evaluate the main issues of the building's environmental performance: (i) environmental; (ii) economical; (iii) social/cultural. These aspects are verified by specialized practitioners in the respective classification scheme.

BREEAM (Building Research Establishment Environmental Assessment Method) is a scheme developed in the UK, where it was launched in 1990 and updated on a regular basis, the last dated from 2011 (Bevan, 2011). In this assessment, the key issues of sustainability are evaluated at design, construction and post-construction stages, not only in a qualitative, but also a quantitative way. The latter is performed through Key Performance Indicators (KPI) which include, among others, Greenhouse Gas Emissions (GHG) and energy use in the several stages of the building, in accordance with the guidelines of ISO15804 (2011), but not following it thoroughly. The evaluated sustainability issues are graded through a scheme of credits and weights, leading to a score, which will provide the rating of "Unclassified", "Pass", "Good", "Very good", Excellent" or "Outstanding".

The German DGNB (German Sustainable Building Certification) system was launched in 2009 in its home country and later internationalized, to assess the environmental performance since the planning stage of a building. It also relies in a scoring attributed to the sustainability aspects of a building, which are weighted to thereafter calculate the performance index of the building. This is defined as "Bronze", "Silver" and "Gold". All environmental information is aligned with the requirements of EN 15804 (2011) and EN 15978 (2011). Furthermore, it possesses a data-base of construction materials with the respective LCA information calculated (Eurima, 2012) and requires the calculation of the energy consumption and proportion of renewable energy. Thus, this is a scheme that also bases its rating on qualitative and quantitative information.

France also developed a certification scheme: HQE (High Environmental Quality). It has been applied since 1996 (last version dated from September 2011) and it is destined to be applied during the conception of the project, throughout the construction of the building. This system relies in several environmental categories that are scored with “Basic”, “Performing” and “High performing” and thereafter weighted to produce an overall rating of the building, which also relies in the same rating. The LCA is undertaken in quantitative terms by gathering information given in EPD’s developed in accordance with French regulations and, although it is similar to EN 15804 (2011), there are several differences (Eurima, 2012). In order to improve the rating of the building, it is necessary to define scenarios in accordance with the French norms.

LEED classifies the building with a rating based in a check list of issues that grants points, assuring the sustainability level according with the grade of the building. This means that this is a prescriptive method, rather than a quantitative one.

These systems assess thoroughly the sustainability performance of a building in all its stages, but with that come some drawbacks:

- Time consuming;
- Require practitioners trained by the team of the respective classification scheme;
- High amount of input data to produce the evaluation;
- Not in full agreement with European standards.

3 SUSTAINABILITY ASSESSMENT TOOL

The increased initiatives into greener buildings by, either EU directives or voluntary programs, and the awareness of the environmental burdens of the construction sector, urged the development a tool capable of steering the design process since the early stages of design in a swift way. This tool was developed bearing in mind the drawbacks and positive aspects of the available methodologies. It is designed to be used by all players in the construction sector, enabling to produce an assessment of the the life-cycle of the building in terms of its sustainability performance. The tool possesses two main modules to undertake the calculations that will provide the quantitative evaluation of energy and embodied impacts: (i) Energy module – estimates the energy needs of the building according with the international standard ISO 13790 (2008); (ii) Embodied impacts module – quantifies the potential impacts of the building throughout its life-cycle in accordance with EN 15978 (2011) and EN 15804 (2011). In addition, the user can select pre-assembled elements of the envelope suited to the type of building under study, denominated macro-components.

3.1 General description

In the early stages of design the building designer faces different questions in relation to: (i) the building location (which is usually not really a decision of the building designer but of the owner of the building); (ii) the building orientation; (iii) the building shape; (iv) the structural system to be adopted; (v) the building envelope and (vi) the 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 constructional solution may be beneficial in some environmental categories and simultaneously be very harmful in others.

The proposed approach aims to provide the building designer guidance to the above questions.

Focussing on the concept stage and on the preliminary stage of design, the algorithm for input of data and calculation method are similar in both stages; however, due to the lower availability of data in the former, simplifications are needed for both the energy calculation in and the environmental impacts. These simplifications grow inversely with the availability of the input data.

The general flowchart of the methodology is illustrated in Figure 5 and a detailed description of each step is provided in the following sub-sections.

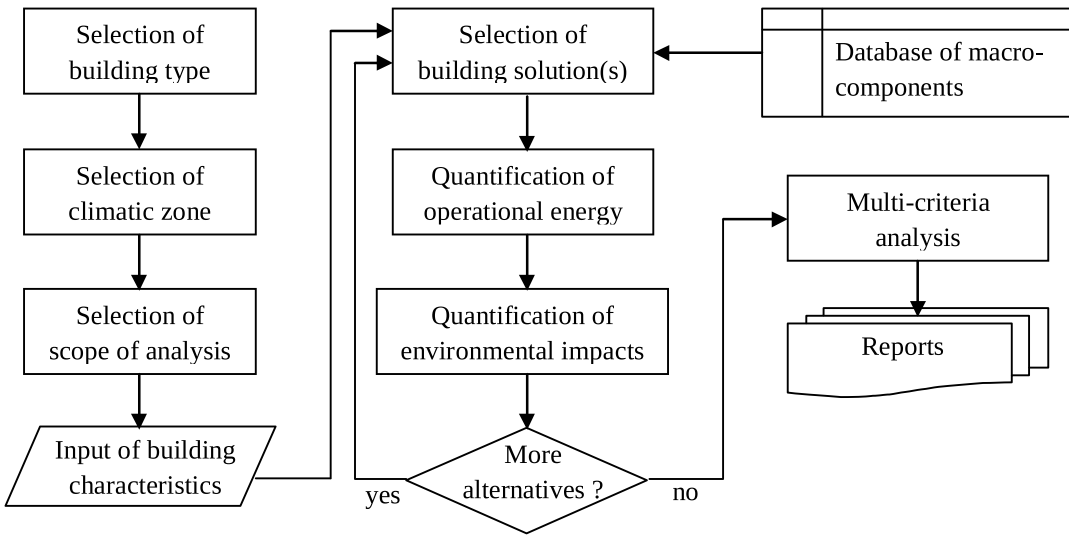


Figure 5 – Flowchart of the algorithm

3.2 Concepts and assumptions

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 or concepts for the project. The following aspects are defined and assessed in this stage (Ministry for the Environment, 2008): (i) objectives; (ii) assumptions and givens; (iii) opportunities and constraints; (iv) risks; (v) timeline; (vi) budget; (vii) spatial requirements and interrelationships; (viii) sustainability objectives and measures; (ix) specialist, consultants required and their time of introduction to the project; (x) site development, and urban design and landscaping approaches; (xi) orientation, massing and building form; (xii) initial services distribution strategies and plant space requirements; (xiii) initial structural systems and (xiv) initial costing.

The following stage is the **Preliminary Design** whereby approximate quantities become available. The following aspects are addressed in detail (Ministry for the Environment, 2008): (i) internal space planning and circulation; (ii) building envelope (day lighting, thermal and energy performance); (iii) structural systems; (iv) lighting, acoustics and thermal comfort design; (v) HVAC options; (vi) water and wastewater systems; (vii) fire safety strategy; (vii) materials selection; (viii) preliminary thermal, day lighting and energy modelling.

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

Figure 3-1 illustrates the level of detail available for the various design stages. The concept design stage of a building defines the overall system configuration and produces schematic drawings and layouts that provide an early project configuration. Therefore, at this stage, 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.

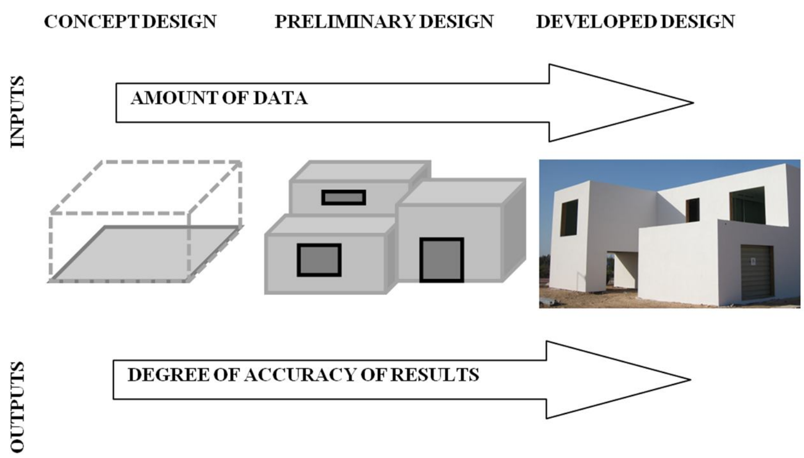


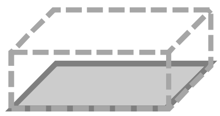
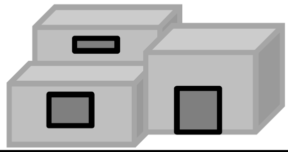
Figure 3-1 – Design stages of a building

The early stages of building design addressed by the methodology presented in this study are the **concept stage** and the **preliminary stage**.

3.3 Availability of input data in early stages of design

It is extremely important to be aware of the data available at each stage of design, in order to identify the key gaps where a regular sustainability assessment would fail, allowing to develop methods to overcome these hurdles. Thus, a series of enquiries was addressed to several players in the construction sector, under the European Research Investigation Project: SB_Steel: Sustainable Building Project in Steel, focused in identifying the available data in each stage of the building design (see Table 3-1).

Table 3-1 – Available building data in the concept and preliminary stages

INFORMATION DETAILS IN EACH STAGE OF THE BUILDING			Concept stage	Preliminary stage
				
Type of building (occupation)	residential/office low/medium/high rise		yes	yes
Location data	Location of building		yes	yes
	Climatic characteristics		yes	yes
	Air quality		maybe	maybe
	Geotechnical data		maybe	yes
Dimensional data	Total area of building		yes	yes
	Area of floors		estimation	yes
	Height of floors		yes	yes
	Area of external walls		estimation	yes
	Area of roof		estimation	yes
	Area of fenestration		estimation	yes
	Horizontal plans of building		no	maybe
	Vertical plans of building		no	maybe
Structural data	Type of load-bearing structure		yes	yes
	Materials characteristics		estimation	yes
	Safety requirements		no	yes
	Detail design		no	estimation
	Bill of materials		no	estimation
Functional data	Building orientation		yes	yes
	Details of layers	external walls	estimation	yes
		internal walls	estimation	yes
		floors	estimation	yes
		roof	estimation	yes
	Thermal characteristics	external walls	estimation	yes
		internal walls	estimation	yes
		floors	estimation	yes
		roof	estimation	yes
	Acoustic characteristics	external walls	estimation	yes
		internal walls	estimation	yes
		floors	estimation	yes
		roof	estimation	yes
	Windows characteristics	Glazing	estimation	Yes
		Frames	estimation	yes
	Lighting installation and daylight		estimation	yes
	Ventilation system		estimation	maybe
	Heating system		estimation	maybe
	Cooling system		estimation	maybe
	Domestic hot water production		estimation	maybe
	Internal loads		estimation	maybe

3.4 Classification of building typology

Buildings can be clustered into different classifications according to different criteria. Since some typical parameters will be adopted for cases where quantitative information is not available, the adopted classification scheme was developed in order to achieve the goal of the approach. 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 3-2 is proposed, in which the columns represent the building categories in terms of “steel content” and the rows the building typologies in terms of building functionality.

Table 3-2 - Matrix for classification of steel buildings

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

3.5 Climatic zoning

The climate is a key-factor for the energy consumption of buildings (Santos et al, 2012a). 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 addition, the efficiency of several passive strategies (e.g passive solar heating, natural ventilation, evaporative cooling) that enable to reduce the buildings energy consumption also depends on certain climate parameters (e.g. solar radiation, wind direction and intensity, relative humidity).

In the proposed approach the Köppen-Geiger climate classification (Kottek et al., 2006) was adopted. The climatic classification within Europe depends on the latitude, the altitude and coast vicinity (Santos et al., 2012a).

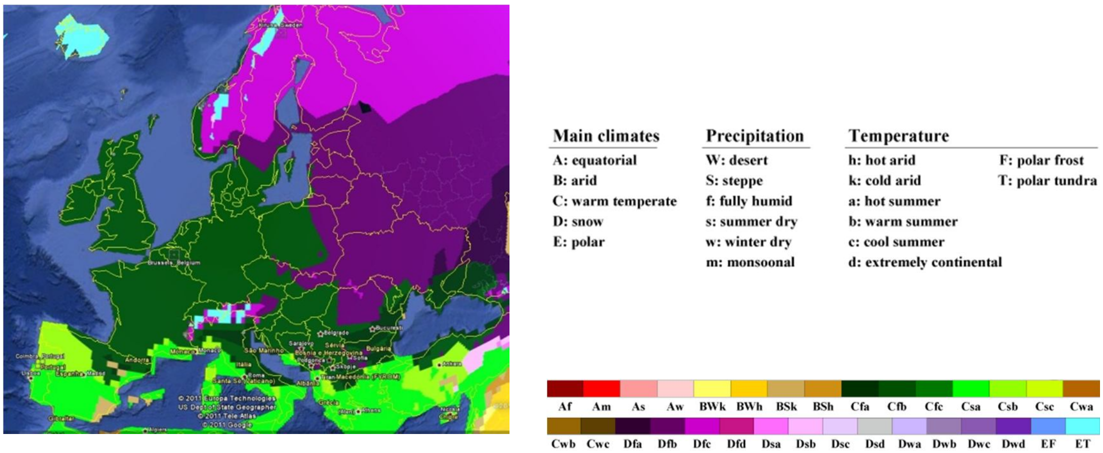


Figure 3-2 - Europe map of Köppen-Geiger climate classification (Kottek et al., 2006)

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. Additionally, the climatic data of a specific location may be assigned.

3.6 Scope of the analysis at the building level

As already referred the modular concept of the European standards EN 15643-2 (2011) and EN 15978 (2011), represented in Table 2, is adopted in the methodology. At the building level, 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).

In this case, module B6 is included in the scope of the analysis, as described further down in the text. On the other hand, 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 only considered through the domestic hot water.

3.7 Inputs

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.

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 first, if not existing, a representative value for each parameter is provided for each building typology; in the latter, the designer may select the parameters according to the availability of information.

In the following sections, a detailed description of the inputs and their influence in the sustainability performance of the building is presented.

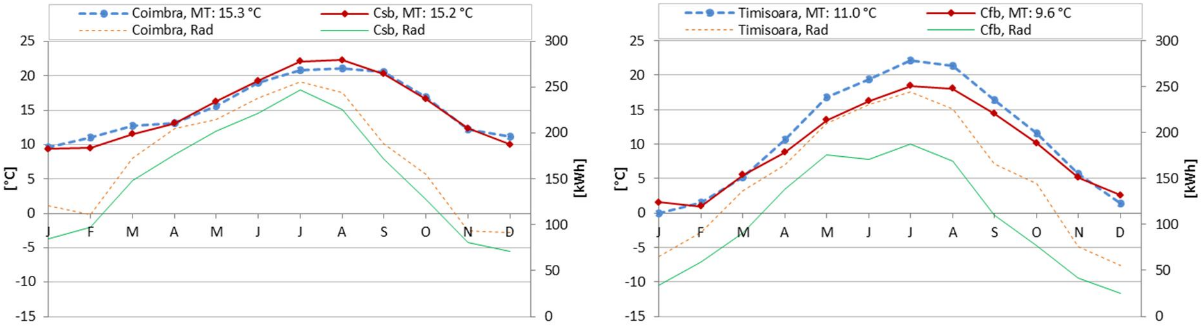
3.7.1 Climate

The location of the building, in terms of climate conditions, is of vital importance in thermal behaviour calculations (Santos, P., Gervásio, H., Simões da Silva, L., Lopes, 2011). Regarding this matter, it is possible to distinguish two major climate parameters that must be defined in order to undertake an energy need calculation: i) air temperature; ii) solar radiation on a surface with a given orientation.

Naturally, exterior and operative air temperature are two of the most important factors in the quantification of the building's energy need, as a great majority of heat exchanges in the envelope are due to heat transfer by transmission, which is highly influenced by the temperature difference between internal and external mediums. In fact, according to ISO 13790 (2008) prescriptions it is proportional to this temperature difference.

Solar radiation is another key-component of the climate data necessary to carry out the calculations. Its effect is relevant in heating and cooling mode calculations. In the latter, solar radiation is regarded as gains to the energy quantification, i.e. it presents a negative effect in the building's cooling energy need quantification. However, for the heating mode it is advantageous to promote heat gains due to solar radiation.

The variation of this type of the exterior air temperature and the solar radiation with the location is illustrated in Figure 3-3.



a) Clima Csb e em Coimbra (PT) b) Clima Cfb e em Timisoara (RO)

Figure 3-3 – Air temperature and solar radiation in three cities and two climatic regions

3.7.2 Building geometry and orientation

It is highly advisable to integrate the study of the building geometry in the process of decision making since the early stages of design. In fact, the assessment of the effect of shading by external obstructions (overhangs and the geometry of the building itself) can result in energy savings (Mandalaki et al. 2012; Farrar-Nagy et al. 2002). Being also conscious that the building orientation may be regarded as a passive solar technique itself (Morrissey, Moore, & Horne, 2011), the tool allows to rotate the façades through the four main orientations (North, South, East and West). However, it is advisable to orientate the larger areas towards North and South, since effective shadowing is more easily achieved than orientating these areas towards East and West (this type of guidelines are also presented to the user of the tool).

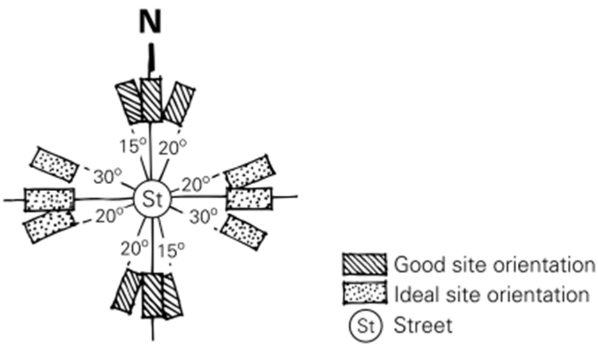
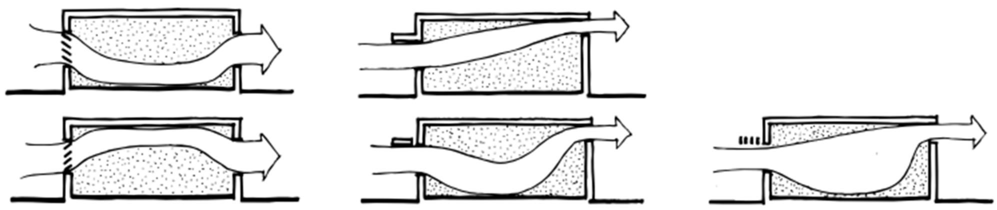


Figure 3-4 – Façade orientation (Reardon et al, 2010)

The building's plan layout influences, mainly, solar gains (orientation and shading coefficients), heat transfer to the ground (exposed perimeter) and the compactness factor of the building. The dimensions of the building to estimate areas and volume are interiors.

3.7.3 Ventilation and air tightness

The correct control of the airflow inside of a building is another technique to improve its environmental performance by means of natural or mechanical ventilation (Santos & Leal 2012; Szokolay 2012), in order to minimize energy consumption, and also to guarantee a good interior air quality (Stanke et al, 2007). Furthermore, in cold climates, it is especially important to guarantee high levels of air tightness, as higher air change rates lead to lower internal air temperature, thus more heating. On the contrary, in hot climates, it is advisable to allow for high air flow rates, since this leads to lower cooling loads. The direction of the air flow is influenced by the shape and type of external shading provisions (see Figure 3-5), which can be used to guarantee the comfort of the users.



a) Louvre angle influences the air flow direction

b) Overhang shape to achieve the desired direction of air flow

c) Louvred overhang to increase downward air flow pressure

Figure 3-5 – Strategies to achieve the desired direction of the air flow (Reardon et al, 2010)

Given the importance of the airflow rate, and the techniques to reduce the energy need, the tool allows to set different airflow rates for the heating and cooling modes.

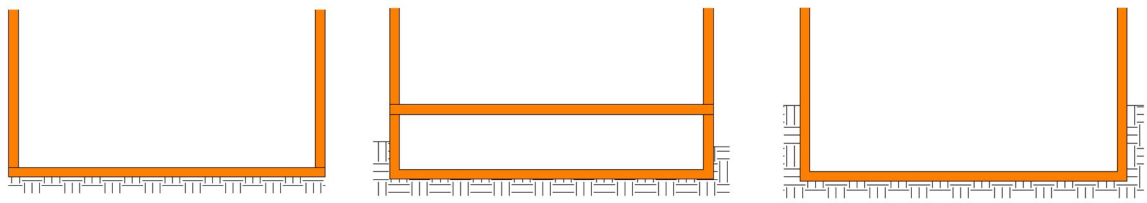
It is also possible to assess the effect of a mechanical heat recovery system by defining its technical characteristics and the fraction of the airflow that goes through the heat recovery unit.

3.7.4 Building envelope

The properties of all opaque and glazed elements are extremely important in the environmental performance of the building, as they influence both the thermal efficiency and the embodied impacts of the building.

The characteristics of the insulation layers should be adequate to the climate conditions (P. Santos et al. 2012), as well as the glazed elements. The U-value should also be adequate to the type of element of the envelope (P. Santos et al., 2012). Given the importance of a thorough study of these aspects, the tool is prepared to deal with their key-parameters, namely: i) U-values; ii) absorption coefficient for solar radiation; iii) internal heat capacity; iv) solar heat gain coefficient (SHGC). In addition, as the opaque elements of the envelope are selected within the macro-components scheme, the software possesses an algorithm to deal with the variation of the thickness of the layers. This allows for the calculation of the U-value in bridged elements (e.g. bridges formed by cold formed steel profiles) according with the method presented in ISO 6946 (2007) and improved by Gorgolewski (2007) or thermal bridges in the insulation layer. The internal heat capacity is also calculated in the tool under the guidance of the simplified calculations given in ISO 13786 (2007).

Another feature of the Early Stage Sustainability Assessment Tool – Energy Module (ESSAT-EM) is the possibility to choose the type of ground floor. Figure 3-6 illustrates the three types of solutions available, namely: i) slab on ground floor; ii) suspended ground floor; iii) heated basement.



a) Slab on ground floor b) Suspended ground floor (crawl space) c) Heated basement

Figure 3-6 – Types of ground floor solutions available in the tool

3.7.5 Shading devices and overhangs

These elements are of great importance to the thermal behaviour of the building. In fact, solar passive techniques may be achieved by adopting the correct movable shading device (Mehrotra 2005; Mandalaki et al. 2012; Farrar-Nagy et al. 2002), applying automated controls

(Tzempelikos & Athienitis 2007) and by the correct positioning of these devises (P. Santos et al. 2012); Tzempelikos & Athienitis 2007). To assess the effect that these measures may introduce in the behaviour of the building, several types of movable shading devices are available in the tool and also the option to assign user values, namely, of the solar transmission. The effect of automated shading devices is accounted for through the calculation of the fraction of the day in which the solar incident radiation on a given orientation exceeds a predefined setpoint. In ISO13790 (2008) this parameter is defined as $f_{sh,with}$. Furthermore, the effect of night heating is taken into account by a correction of the U-value of the window with a factor, f_{shut}, which is dependent of the accumulated difference of hours with and without shading device (Annex G, of ISO13790 (2008)). Since the solar data depends on the latitude of the location, several tables of shading coefficients were produced for different latitudes (see also 4.2.1).

3.7.6 Building services

The building services comprise appliances for heating and cooling, domestic hot water production, humidification/de-humidification, ventilation, lighting and auxiliary energy used for pumps, control and automation (EN 15978, 2011).There is also the energy used for auxiliary systems, as lifts, escalators, safety and communication systems (EN 15978, 2011). According to the latter standard, energy and potential impacts are assigned in a modular system. Building energy consumption shall be assigned in Module B6.

Renewable sources of energy should be studied and implemented in the building, in order to meet with the targets set by the European Committee for the building energy consumption. In fact, the energy produced on site should be nearly equal or higher than the needed energy ("Directive 2010/31/EU," 2010).

The effect of different solutions for the building services in the analysis are computed, especially, in the delivered energy and the reduction factor for intermittent cooling or heating. To allow the study of these parameters, it is possible to choose the systems' efficiency (typical values of these systems are also provided) and their working schedule. As conversion factors for primary energy vary with the country where the building is located and the reference year, the user may also provide its country values, in order to convert delivered energy into primary energy.

3.7.7 Schedules

Energy consumption in a building is influenced by the type of utilization, occupancy schedule (Guerra Santin et al., 2009) (e.g. residential, office, commercial or industrial) and by the users' behaviour (Reinhart et al. 2004). For these reasons the default internal gains and schedules that are used in the calculations are assigned with the selection of the building type (see Table 3-3). The patterns of occupancy (schedule) also play an important part in the energy consumption of a building, although the latter may be only be possible to implement rigorously through an algorithm developed with a basis of the use pattern of the occupants (Reinhart et al. 2004) or, possibly, by monitoring occupancy rates through radio frequency identification (RFID) (Li et al., 2012). In the absence of such detailed data and a more detailed method than the one used in the tool, typical schedules are assumed in accordance with the building type (see Table 3-3 - the tool uses this type of data).

Table 3-3 – Internal heat gains according to type of building (ISO 13790, 2008)

Human Factors	**Default values**	
Utilization Type:	Internal Heat Gains	Occupancy Schedule
Residential	1 to 8 W/m^2	12 h/day
Offices	1 to 20 W/m^2	6 h/day
Commercial or Industrial	10 W/m^2	6 h/day

3.8 Engine

As above mentioned the sustainability assessment undertaken in the tool comprises the quantification of the energy needs and embodied impacts produced throughout the life-cycle of the building. In order to accomplish this two module were developed - Energy module and Embodied impacts module - since, even though some of the input data is used in both modules (e.g. macro-components information), most of it is used in only one of the modules. In the following sections each of the modules is presented and discussed.

3.8.1 EM – Energy Module

As referred above, the operational energy constitutes an environmental burden of the use stage of the building, assigned in module B6. The tool enables the user to calculate energy needs on a monthly basis for: (i) heating mode; (ii) cooling mode; (iii) DHW production. The calculations follow three steps: (i) assignment of the input data; (ii) quantification of energy; (iii) outputs of the energy need/use. In order to determine the contribution of each parcel involved in the thermal calculations it is necessary to rely on several standards, as shown in the flowchart of Figure 3-7.

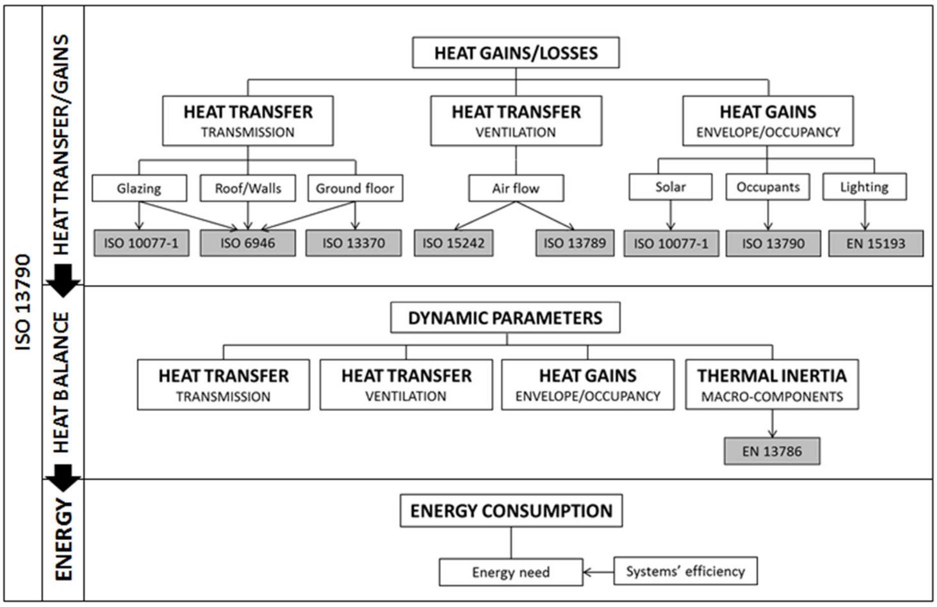


Figure 3-7 – Flowchart of the standards used in the thermal calculations

As shown in Figure 3-7, ISO13790 (2008) is the main standard, which addresses specific calculations to other standards. More detailed information about the algorithm is presented in section 3.8.1.1.

Taking into account the importance of the energy need for DHW production, its value is also quantified. This is undertaken under the guidance of EN15316-3-1 (2007).

3.8.1.1 Energy needs calculation: Space heating, cooling and DHW production

The prediction of the energy need for heating and cooling is undertaken by using a quasi-steady-state approach, which relies in utilization factors to simulate dynamic effects. Additional parameters essential to the method are calculated in separate modules (sub-modules). Moreover, the energy for DHW production is also quantified in an independent module.

The procedure and architecture of the algorithm used to determine these energy needs is presented in Figure 3-8.

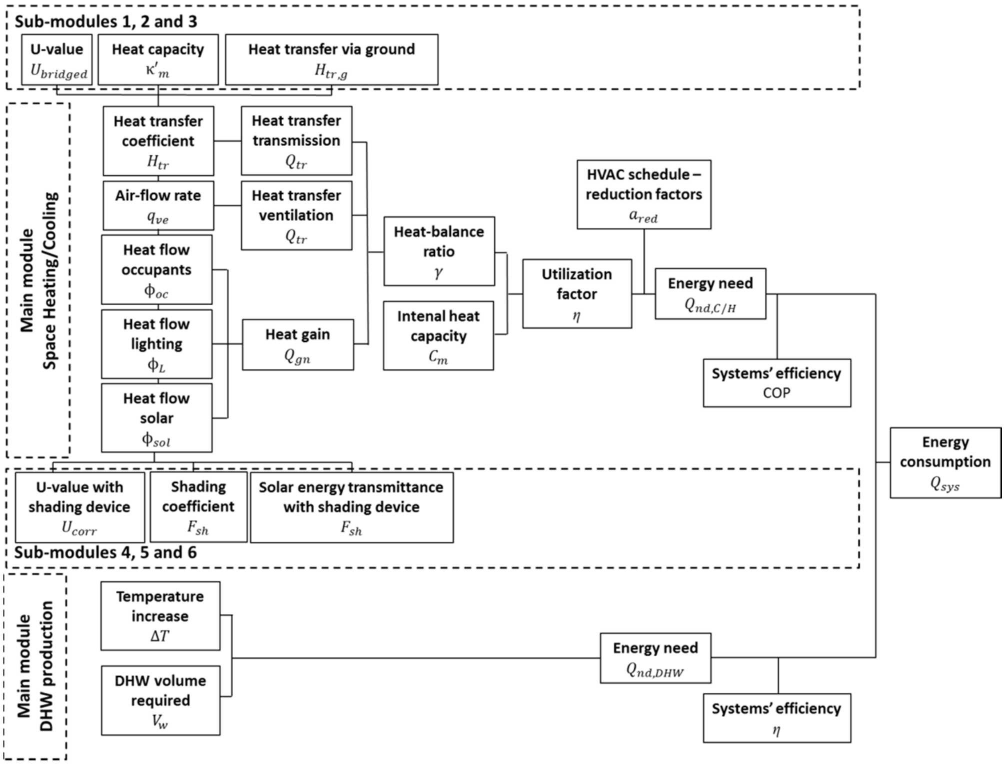


Figure 3-8 – Flowchart of the calculations to determine the energy consumption of the building

The energy needs for space cooling and heating for systems working in continuous mode are calculated through equations (1and (2) (follow Figure 3-8):

$$Q_{H,nd,cont,m} = (Q_{H,tr,m} + Q_{H,ve,m}) - \eta_{H,gn.m} \cdot Q_{H,gn,m} \qquad (1)$$
$$Q_{C,nd,cont,m} = Q_{C,gn,m} - \eta_{C,Is,m} \cdot (Q_{C,tr,m} + Q_{C,ve,m}) \qquad (2)$$

where, $\eta_{H,gn.m}$ and $\eta_{C,Is,m}$, are the monthly utilization factors used in the heating and cooling modes; respectively. However, when the HVAC systems operate on a schedule (i.e. in intermittent mode), ISO13790 (2008) gives guidance to determine a reduced energy need based in the calculations for the continuous mode. In this case, the energy need for space heating and cooling are given by equations (3) and (4), respectively.

$$Q_{H,nd,interm,m} = f_{H,m} a_{H,red} \cdot Q_{H,nd,cont,m} \qquad (3)$$
$$Q_{C,nd,interm,m} = f_{C,m} \cdot a_{C,red} \cdot Q_{C,nd,cont,m} \qquad (4)$$

Another parcel of the energy need of a building is the energy needed for DHW production and it is calculated under the guidance of EN15316-3-1 (2007). It is influenced by the type of building, its floor area and the temperature difference between the inlet water and the one desired at the tapping point, as presented in (5).

$$Q_{DHW,nd} = 4{,}182.V_W.\left(\theta_{W,t} - \theta_{W,O}\right) \tag{5}$$

where, V_W is the monthly DHW volume need; $\theta_{W,t}$ is the temperature of DHW at tapping point (˚C); $\theta_{W,O}$, temperature of the inlet water (˚C).

The energy consumption of each of the above referred parcels depends on the systems' efficiency, as shown in Equation (6).

$$Q_{sys} = \frac{Q_{nd}}{eff} \tag{6}$$

where, Q_{nd} is the energy need (heating, cooling or DHW production); and *eff* is respective the system's efficiency.

Naturally, given that the systems do not present the same efficiency, the total energy consumption is given by (7).

$$Q_{cons} = \frac{Q_{H,nd}}{COP} + \frac{Q_{C,nd}}{COP} + \frac{Q_{DHW,nd}}{\eta} \tag{7}$$

where, COP is the coefficient of performance of the systems used to heat and cool the space; and η is the efficiency of the DHW production system.

3.8.2 EIM - Embodied Impacts Module

The calculation of the embodied impacts of the life-cycle of the building are performed under the guidance of EN 15804 (2011) and EN 15978 (2011) for the materials/products and for the building, respectively. The calculations follow an order of three steps, or three levels, that regard the quantification of impacts related to:

1. Materials/products;
2. Construction solutions for the envelope (macro-components);
3. Building.

Each one of these calculations is undertaken after the definition of scenarios for the transportation of materials, use of the building and end-of-life of the elements that integrate the building (see Figure 3-9). Naturally, the operational energy of the building is also a scenario of the use stage of the building, as above mentioned.

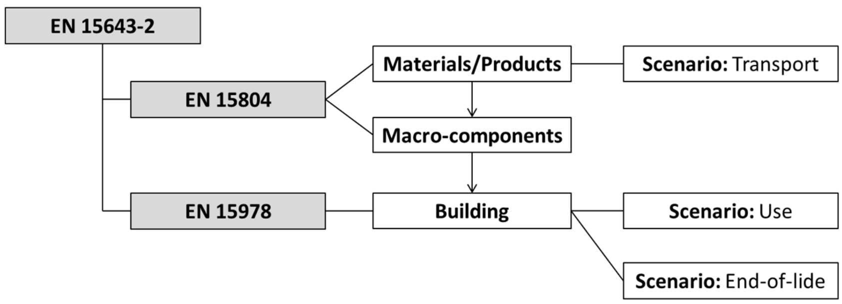


Figure 3-9 – Framework of the calculation of the embodied impacts

3.8.2.1 Scenarios and assumptions

In order to fulfil the environmental information in all modules, scenarios and assumptions are needed.

The functional unit of each macro-component is related to a time-span of 50 years. This means that each material in the macro-component needs to fulfil this requirement. Hence, materials with an expected service life lower than 50 years need to be maintained or even replaced during this period. Therefore, different scenarios are assumed for each material in order to comply with the time span of the analysis. Likewise, in the end-of-life stage, each material has a different destination according to its inherent characteristics. Thus, for each material an end-of-life scenario is considered taking into account the properties of each material.

All the aforementioned scenarios are set in accordance with the rules provided in EN 15643-2 (2011), EN 15804 (2011) and EN 15978 (2011).

3.8.2.2 Scenarios for the transportation of materials (Modules A4 and C2)

The transportation distances between the production plants to the construction site (module A4) and the distances between the demolition site and the respective recycling/disposal places (module C2) are assumed, by default, to be 20 km and the transportation is made by truck with a payload of 22 tonnes. However, the designer is able to specify other distances, enabling sensitivity analysis to be made in relation to the transportation of different materials.

3.8.2.3 Scenarios for the use stage (Modules B1:B7)

Scenarios are pre-defined for the different materials in order to fulfil the required time span of 50 years. Therefore, in relation to the above macro-components assembly, the following scenarios are set:

- substitution of ceramic tiles every 25 years;
- painting of ceiling every 10 years.

3.8.2.4 Scenarios for the end of life stage (Modules C1:C4) and recycling (Module D)

Different end-of-life scenarios are specified for the materials according to their inherent characteristics, as indicated in Table 3-4. Thus, OSB is considered to be incinerated (80%) in a biomass power plant and credits are given to energy recovery. Steel is recycled, assuming a recycling rate of 90%, and credits are obtained due to the net scrap in the end of the life-cycle process. Likewise, rock wool is considered to be recycled (80%). However, due to the lack of data of the recycling process, no credits are obtained apart from the reduction of waste sent to landfill.

Table 3-4 – EOL options for materials

Material	Disposal/Recycling scenario	Credits
Ceramic tiles	Landfill (100%)	-
Concrete screed	Landfill (100%)	-
Gypsum plasterboard	Landfill (100%)	-
Rock wool	Recycling (80%) + Landfill (20%)	-
OSB	Incineration (80%) + Landfill (20%)	Credit due to energy recovery
Light-weight steel	Recycling (90%) + Landfill (10%)	Credit due to net scrap

All remaining materials were considered to be sent to a landfill of inert materials.

3.9 Outputs

The environmental performance analysis of the building is assessed through the energy consumption of the building and the embodied impacts generated throughout its life cycle. Thus, the outputs are given in terms of: (i) energy data; and (ii) environmental impacts. The details of the outputs are discussed below.

3.9.1 Building energy use

The main results provided by the EM are the energy for space heating, cooling and DHW production. However, the designer is presented with detailed data about several key aspects related to the energy performance of the building as it is presented in Figure 3-10.

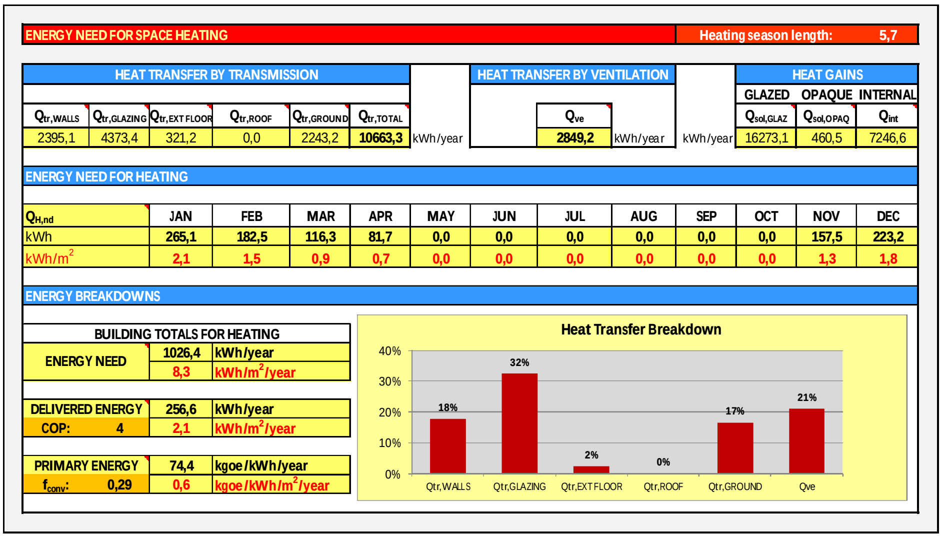
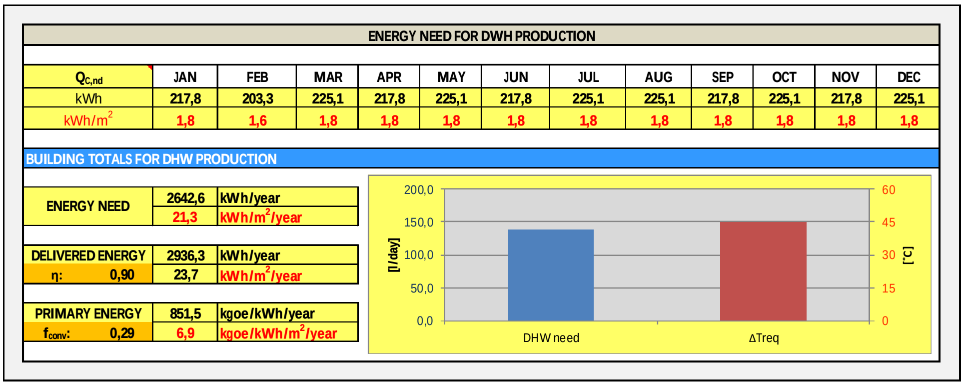


Figure 3-10 – Layout of the tool: energy for space heating

As it is shown in Figure 3-10, the energy is presented through monthly and yearly values. Other data concerning specific aspects of the thermal behaviour of the building are also presented to support the analysis of the designer. The energy need for space cooling is assessed through similar outputs.

The outputs of the energy for DHW production consist in predicted volume of DHW need and the temperature difference of the inlet water and the water in the tapping point (see Figure 3-11).



ENERGY NEED FOR DWH PRODUCTION

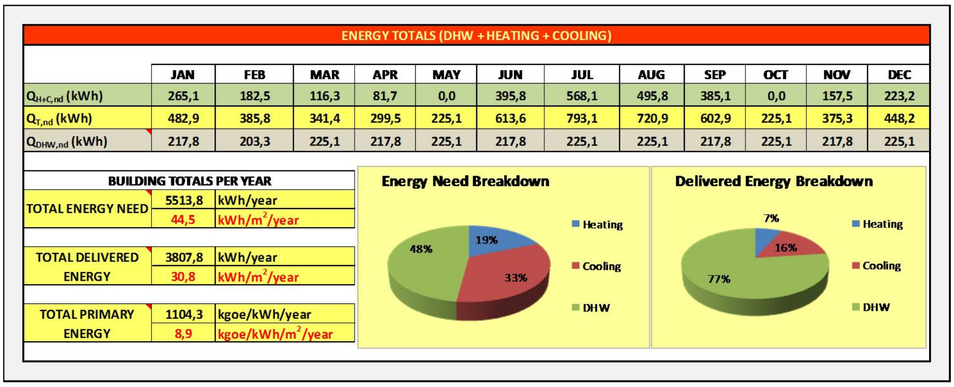
$Q_{C,nd}$	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
kWh	217,8	203,3	225,1	217,8	225,1	217,8	225,1	225,1	217,8	225,1	217,8	225,1
kWh/m^2	1,8	1,6	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8

BUILDING TOTALS FOR DHW PRODUCTION

ENERGY NEED	2642,6	kWh/year
	21,3	kWh/m^2/year
DELIVERED ENERGY	2936,3	kWh/year
η: 0,90	23,7	kWh/m^2/year
PRIMARY ENERGY	851,5	kgoe/kWh/year
f_{conv}: 0,29	6,9	kgoe/kWh/m^2/year

Figure 3-11 – Layout of the tool: energy for DHW

A global overview of the energy consumption of the building is given through the fuel breakdown of the operational energy of the building. The energy use and consumption is based on monthly and yearly values as it is presented in Figure 3-12.



ENERGY TOTALS (DHW + HEATING + COOLING)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
$Q_{H+C,nd}$ (kWh)	265,1	182,5	116,3	81,7	0,0	395,8	568,1	495,8	385,1	0,0	157,5	223,2
$Q_{T,nd}$ (kWh)	482,9	385,8	341,4	299,5	225,1	613,6	793,1	720,9	602,9	225,1	375,3	448,2
$Q_{DHW,nd}$ (kWh)	217,8	203,3	225,1	217,8	225,1	217,8	225,1	225,1	217,8	225,1	217,8	225,1

BUILDING TOTALS PER YEAR		
TOTAL ENERGY NEED	5513,8	kWh/year
	44,5	kWh/m^2/year
TOTAL DELIVERED ENERGY	3807,8	kWh/year
	30,8	kWh/m^2/year
TOTAL PRIMARY ENERGY	1104,3	kgoe/kWh/year
	8,9	kgoe/kWh/m^2/year

Figure 3-12 – Layout of the tool: energy totals (fuel breakdown)

3.9.2 Embodied impacts

The embodied impacts generated throughout the life cycle of the building are given in the stage in which they occur: (i) material production (modules A1-A3); (ii) construction stage (module A4); (iii) use stage (Modules B1 to B5); (iv) end-of-life (Modules C1 to C4); (v) benefits/loads due to recycling. The environmental information is described through the indicators suggested in EN15978 (2011), which are presented in Table 3-5.

Table 3-5 – Parameters describing the 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

In order to assist the designer in the decision making process, a series of charts containing the environmental information presented above are given at the macro-component and building levels. An example of this data is presented in Figure 3-13.

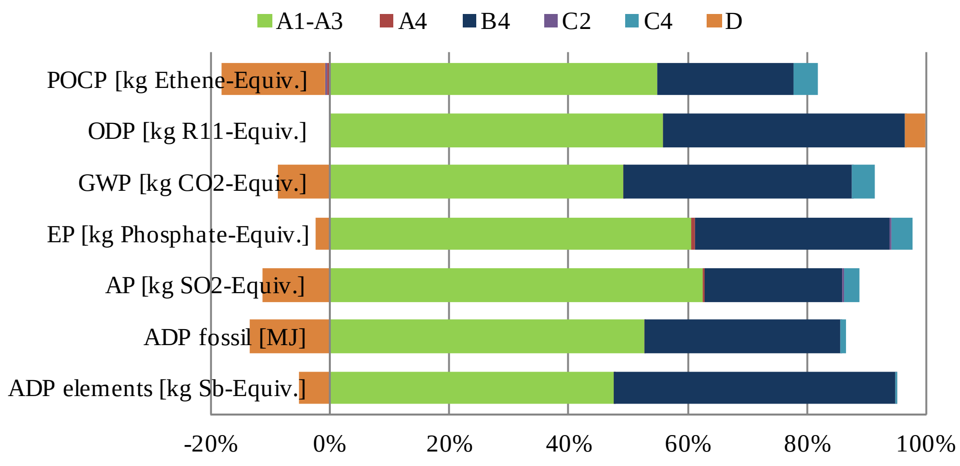
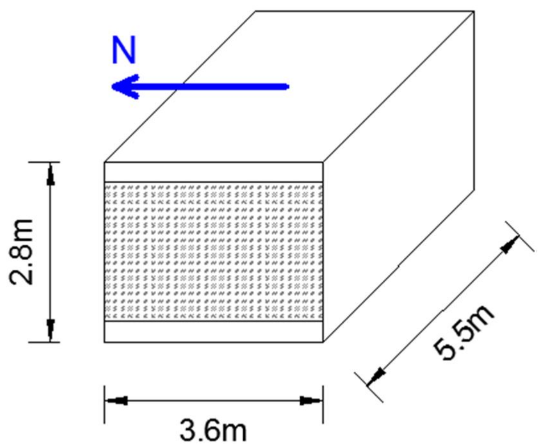


Figure 3-13 – Example of the information given for the life cycle environmental impacts

4 RESULTS AND DISCUSSION

4.1 Verification of the algorithm precision – EN15265 Test Case

In order to test the accuracy and consistency of the results given by the algorithm, a series of tests were conducted, under the guidance of EN 15265 (2007). Since there was interest in assessing the accuracy of the parcels that take part in the heat balance and these are not provided by the referred standard, the test cases were also calculated in a dynamic calculation software (EnergyPlus). The results obtained by this software (with a step of an hour or less) were then compared with the results given in EN 15265 (2007), in order to test the accuracy of the software. This standard uses a reference room with a glazed element facing west, as illustrated in Figure 4-1.



	External wall	**Glazing**	**North Wall**	**South wall**	**East wall**	**Floor**	**Ceiling**
Area [m^2]	3.08	7	15.4	15.4	10.08	19.8	19.8

Figure 4-1 – CEN test room (internal dimensions)

The results given in EN 15265 (2008) shall be compared with the results obtained with the ones given by a numerical approach, in order to validate it. The accuracy of a method is graded in three levels: (i) Level A: rQ_C and rQ_H less than 5%; (ii) Level B: rQ_C and rQ_H less than 10%; and (iii) Level C: rQ_C and rQ_H less than 15%.

Where,

$$rQ_H = \frac{Q_H - Q_{H,ref}}{Q_{tot,ref}} \tag{8}$$

$$rQ_C = \frac{Q_C - Q_{C,ref}}{Q_{tot,ref}} \tag{9}$$

The error of the dynamic calculation is presented in Figure 4-2. It is noteworthy that only the results of test cases 5 to 12 should be regarded to test the accuracy of algorithms.

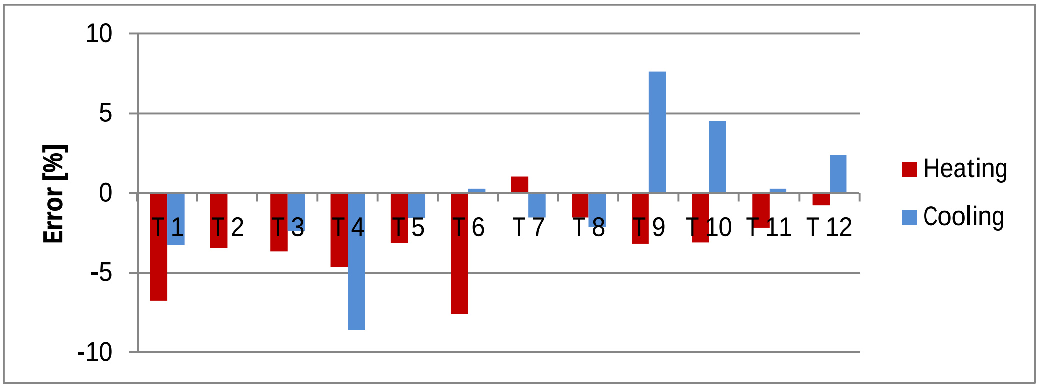
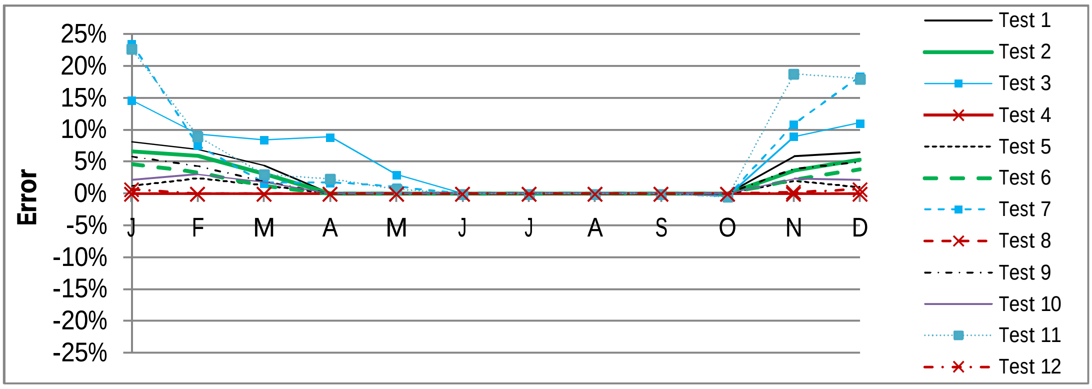


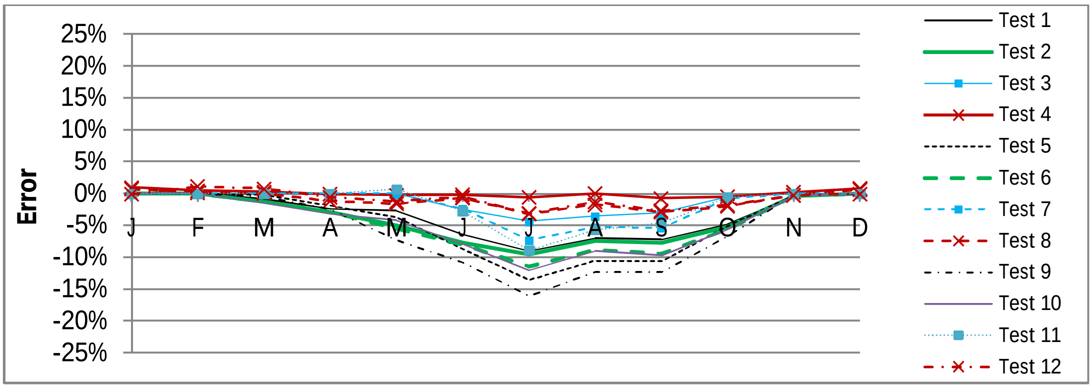
Figure 4-2 – Error of the results given by the dynamic analysis - reference results: EN 15265 (2007)

As it can be seen, the results obtained from the dynamic calculations are obtained with an error lower than 5%, except for the heating mode of test 6 and the cooling mode of test 4 and 9. These errors occur due to dynamic convection and radiation heat transfer coefficients used in *EnergyPlus*, whereas in the CEN test rooms these coefficients are fixed, regardless of the internal and external conditions.

If the errors produced by the steady-state approach are presented on a monthly basis (with reference to the dynamic simulation results) and calculated as a percentage of the total yearly energy need (similarly as it is presented in ISO 13790 (2008), then results come with an error lower than 15%, except for the unrealistic cases of no internal gains (tests 3 and 7), as proven in Figure 4-3.



a) Heating mode



b) Cooling mode

Figure 4-3 – Errors produced by the steady-state method (heating and cooling)

The results obtained for the heating mode are overestimated, whereas for the cooling mode they are underestimated. This suggests that the quasi-steady-state method does not take in account correctly the effect that the gains (solar and internal) present in the internal air temperature, i.e., in reality the gains are used in a much more efficient way to heat the space than considered in the simplified method. This is emphasized when the solar gains are compared: ISO 13790 (2008) provides are higher values than the ones estimated in the dynamic calculation. The heat transfer by ventilation during summer months is higher in the room modeled with in the dynamic software, and lower in the winter months. This also proves that the parcel of the thermal balance are not correctly taken into account.

Tests 4, 8 and 12, which correspond to the set of tests without shading devices, present the lowest errors. This also supports the issue on the efficiency of the gains in air temperature, since when the gains are higher (no shading vs. shading on) the error of the energy needs estimation is lower. However, without shading devices there is more agreement in the solar gains values between the two methodologies, whereas, with shading devices they are much more overestimated. Taking this into account, if with shading devices the energy needs are overestimated in winter and underestimated in the summer, it would be expected that the latter produced lower errors in the energy needs estimation. Moreover, the gains utilization factor is very close to 1, i.e., the results of the energy need for space heating would only come lower if this value was higher than 1, which is the same as saying that the building could use more than 100% of the gains to heat the air temperature, which is not physically coherent. However, there is margin for improving the loss utilization factor, since it is much higher than zero and the results of the space cooling energy need are underestimated when using ISO 13790 (2008) method.

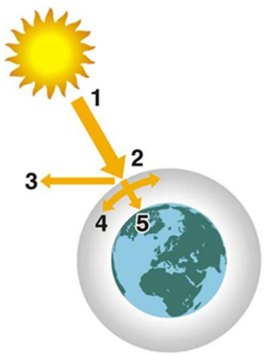
Regarding the thermal inertia of the buildings, the results come with a lower error for the rooms with lower internal heat capacity, except when there are more flutuations in the internal temperature, as occurs in the test cases with non-adiabatic roof.

4.2 Calibration of the tool

In the application of the tool to case studies, it was found (besides the results presented in section 4.1) that the recommendations given in the standards and documents used to determine some of the parameters used in the tool did not give the best results. Thus, it was necessary to calibrate them in order to produce more accurate results. This is presented in the following sub-sections.

4.2.1 Shading coefficients

The effect of the external obstacles in the building may be regarded as a solar passive technique. Furthermore, it is important to study the effect of the shading produced by external obstacles since they influence both the heating and cooling energy needs. As it is known, the solar radiation is composed of direct radtiation and diffuse radiation, as presented.



1) Radiation from the sun (63000kW/m^2);
2) Radiation arriving in the earth (1370W/m^2);
3) Solar radiation reflected by the atmosphere;
4) Diffuse radiation in the atmosphere
5) Direct radiation (max 1000W/m^2).

Figure 4-4 – Solar radiation components

According with clause 11.4..4.1 of ISO 13790 (2008), the shading coefficients should be determined considering that only the direct radiation is reduced due to the external obstacle, i.e., the diffuse radiation would no be changed. This is a good approximation in the case of fins, but does not provide good results when applied to overhangs.

The shading coefficients determined with the approach given in ISO 13790 (2008) were derived from equation

$$F_{sh,Ob} = \frac{I_{dir,sh} - I_{dif,sh} + I_{dif,u}}{I_{tot,u}} \tag{10}$$

Where, sh and u refers to shaded and unshaded surfaces, respectively; I_{dir} is the direct radiation; I_{dif}, the diffuse radiation; and I_{tot} is the total incident radiation.

However, as previously stated, this formulae is not suited for shading due to overhangs, since it fails when a most of the direct radiation does not reach the surface, as it happens during a great part of the day when this obstacle is present. In order to determine if the direct radiation is affected to a point where equation (10) falis, the following expression is used:

$$q_r = \left. \frac{I_{dir,sh}}{I_{tot,sh}} \middle/ \frac{I_{dir,u}}{I_{tot,u}} \right. \tag{11}$$

In order to obtain better results the shading factor for overhangs is calculated with:

If $q_r < x$, then

$$F_{sh,Overh} = \frac{I_{tot,sh}}{I_{tot,u}} \cdot \frac{I_{dif,sh}}{I_{dif,u}} \tag{12}$$

Else, equation (10) applies.

The improvement of this method is presented in Figure 4-5, where the shading coefficients obtained with expression (12) are used to calculate the incident radiation in a South-oriented surface with an overhang of 45°. These results are compared with the ones obtained with Energyplus (E+).

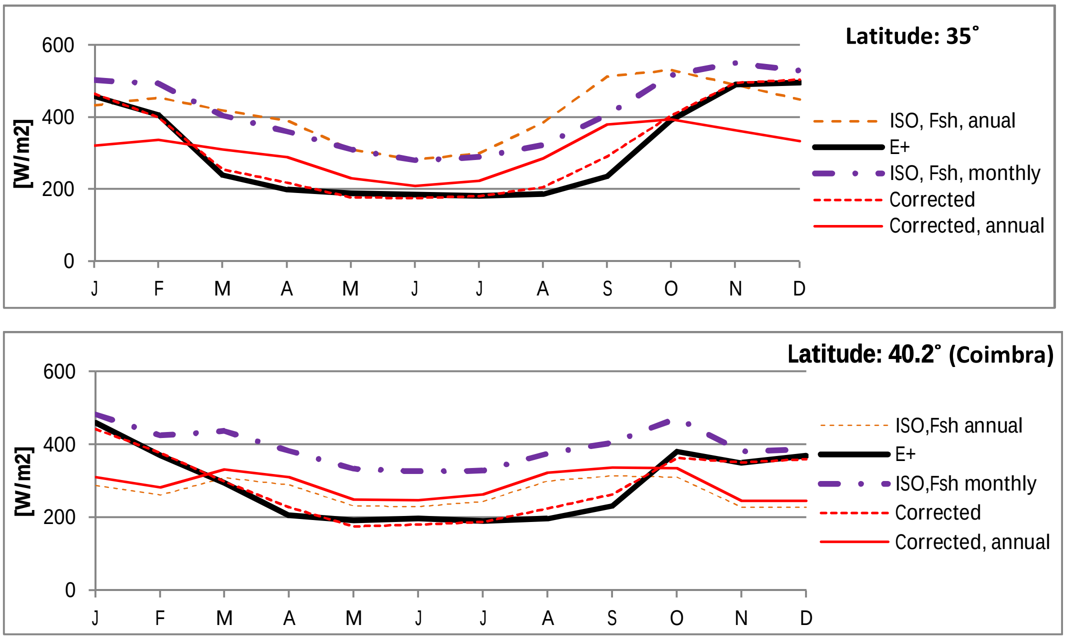


Figure 4-5 – Comparison of the application of the shading coefficients obtained with the corrected method (overhang with a 45° angle with the vertical)

The improvement of the method is evident and gives similar results for other orientations and angles of the overhang. However, the error increases with the increase of the angle of the overhang.

Since the shading coefficients are latitude dependent, these are calculated for latitudes from 35° to 65° with a 10° step and interpolated afterwards for the latitude of the specific location. This is applicable to fins with errors lower than 3%. For overhangs the error is higher but still within reasonable accuracy (maximum of 10%), as presented in Figure 4-6. These shading coefficients were calculated with the method presented above and by interpolation for a South oriented wall with an overhang of 45° in Coimbra.

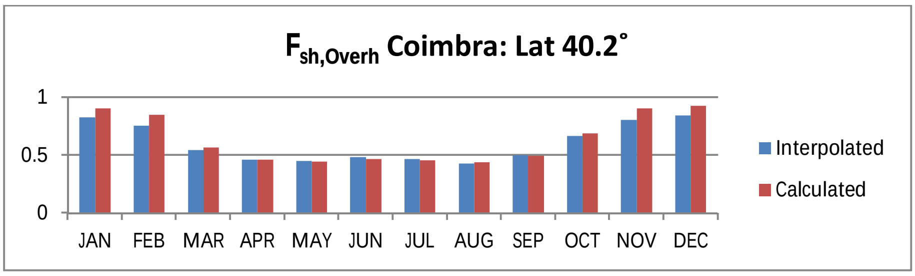


Figure 4-6 –Shading coefficients obtained byinterpolation

Similar results are obtained for other orientations, with an increase of the error with the angle of the obstacle.

4.2.2 U-value of bridged elements

The U-value of thermal bridged elements (by a steel stud) were determined with the method presented in ISO 6946 (2007) and perfected by Gorgolewski (2007), since the first is only applicable if the insulation layer is not bridged. The second method relies in the determination of two limits for the resistance of the construction element and correction factors dependent on the stud dimensions and spacing. A lower limit is calculated by combining the parallel resistances of the layers, i.e. assuming that each plane is at the same temperature. An upper limit of thermal resistance is also calculated by summing the resistances of each heat path. Although this method provides fairly accurate results for studs with height lower than 100mm, the divergence of results increases when applying it to construction elements typically composed by deeper studs and even higher when the air cavities are not completely filled by the insulation layer. An example of this type of element is presented in Figure 4-7.

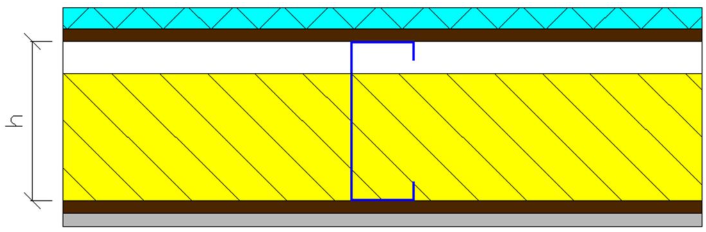


Figure 4-7 – Example of the construction element described

In light steel construction, these type of construction elements are found in roofs and floors, typically with cold formed steel studs with 200*mm* height and spaced of 600*mm*. The procedure to determine more accurate results was to calculate in parallel the U-value with the simplified method proposed by Gorgolewski (2007) and with a finite element software: *Therm v.6*. The analysis focused on three types of construction elements: (i) 30*mm* insulation and air cavity in the exterior; (ii) 50*mm* insulation in the exterior; (iii) 75*mm* insulation in the exterior. In each of which the insulation thickness of the insulation layer intersected by the steel stud was varied from 0 to 200*mm* (no air cavity situation) with 25*mm* step. The errors between the simplified and detailed method were ploted and a polynomial trend line was found for the three tested elements. This was applied to the final result given by the Gorgolewski (2007) method and more accurate results were obtained, as it is presented in Figure 4-8.

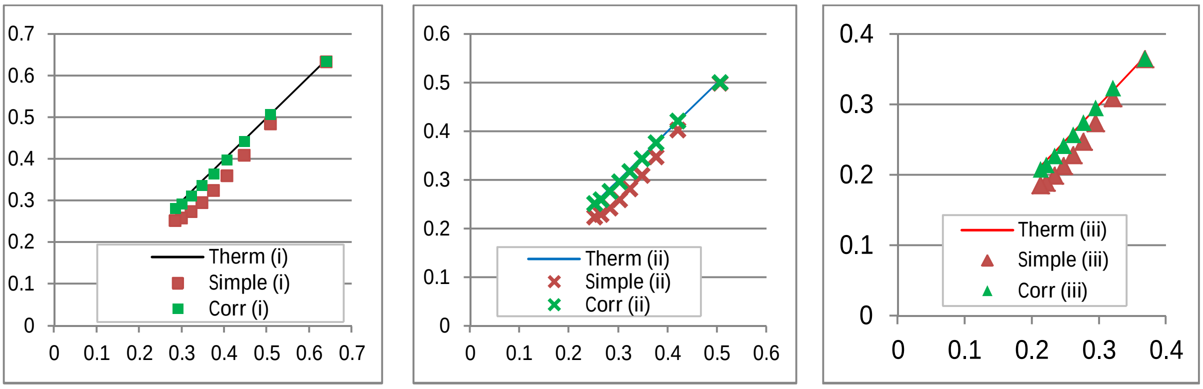


Figure 4-8 – Results obtained with and without the correction (results in W/m^2.K)

As it is show in Figure 4-8 the results increase its divergence to the finite element method when the thickness of the insulation increases until approximately 150*mm*, then inverting the tendency. The maximum error of the corrected results is 3%.

4.2.3 Adjustment coefficients to improve the estimation of the energy need

In order to reduce the error of the estimation of the energy calculated with ISO 13790 (2008), a study of calibration of the algorithm was conducted. This was undertaken by applying correcting coefficients to: (i) heat transfer by transmission; (ii) heat transfer by ventilation; (iii) internal gains; (iv) solar gains; (v) dimensionless parameters *a* and *τ*. These correcting coefficients were applied to several case studies in order to reduce the error of the energy need estimated by the algorithm when compared with the dynamic simulations. The tests vary in terms of window area, roof adiabatic and non-adiabatic, floor area and shading activation.

The correction factors obtained through this procedure are presented in Table 4-1.

Table 4-1 – Correction factors

	Heating						Cooling					
TEST	a_{H0}	τ_{H0}	Q_{tr}	Q_{ve}	Q_{sol}	Q_{int}	a_{C0}	τ_{C0}	Q_{tr}	Q_{ve}	Q_{sol}	Q_{int}
Mean values SHADING ON	1,36	14,86	0,81	0,84	1,37	1,54	0,57	18,36	0,83	0,86	1,29	1,46
Mean values SHADING OFF	1,18	14,43	0,84	0,85	1,29	1,30	1,29	16,29	0,97	0,96	1,04	1,09

By applying these correction factors, the results come with lower error, as illustrated in Figure 4-9.

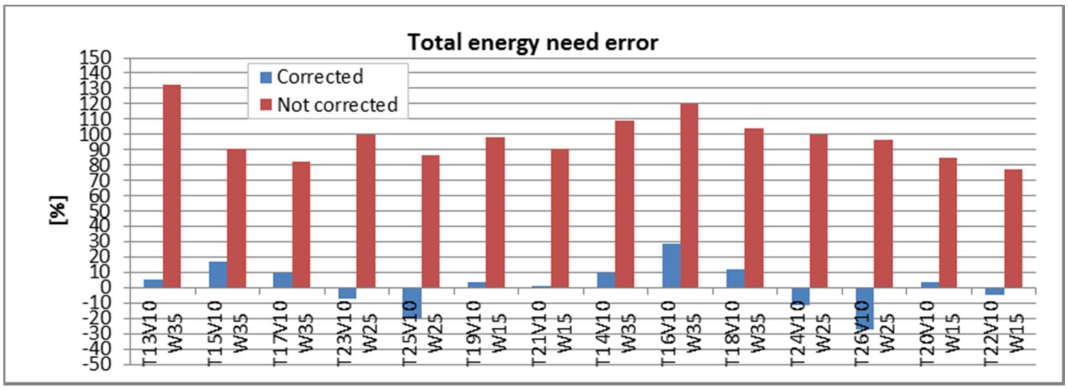


Figure 4-9 – Error of the energy need estimation with and without the correction factors

4.3 Case study – AHouse

The building under study is located in Coimbra, Portugal. It is a two-story single family house with, roughly, 120 m^2 of conditioned floor area. The building has a lightweight steel framed (LSF) structure, with flat roof and suspended ground floor (with unventilated crawl space).

In this case study only two stages of design are studied, since the preliminary stage and developed project (third and final stage) present similar solutions. In the following sections, all the input data is presented for both stages, as well as a comparison of the results given by ESSAT-EM with the ones obtained by a dynamic analysis provided by EnergyPlus.

4.3.1 Climate data

The calculations undertaken in ESSAT-EM rely on the climate data of the location, which is composed of dry bulb temperatures and solar radiation. This data was gathered in the IWEC database and the mean monthly values of environment temperature and the solar incident radiation on a given surface were determined with Energyplus algorithm. The latter were derived from a cubic block exposed to the IWEC climatic data. The abovementioned values are presented Figure 4-10.

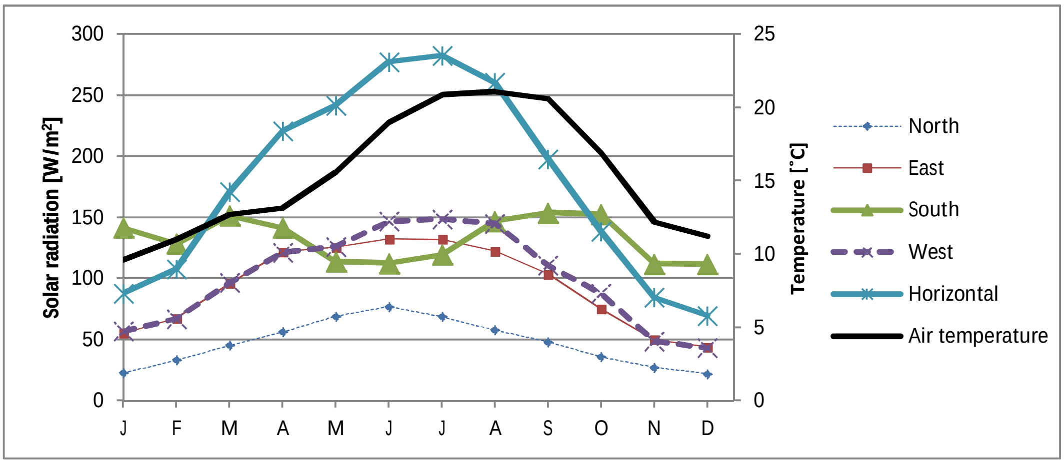


Figure 4-10 – Climate data of Coimbra: solar radiation and outside air temperature

The heat transfer to the sky was calculated considering a temperature difference between the air temperature and the sky apparent temperature of 11˚C, as given in ISO13790 (2008), Clause 11.4.6. The radiative heat transfer coefficient was taken as $5.\varepsilon$, as recommended in this standard (common construction materials present a ε of 0.9).

As already mentioned, the ground floor of the building possesses an unventilated and unconditioned crawl space with a height of 0.50m. The adopted thermal characteristics of the ground are given in Table 4-2.

Table 4-2 – Thermal properties of the ground (default values given in ISO 13370: 2007)

Thermal conductivity [W/m.K]	**Heat capacity** [kJ/m^3.K]
2.000	2000

4.3.2 Occupancy related data

The schedules and heat flow due to internal loads (occupants activity, appliances and lighting) are based in the information given in ISO13790 (2008) and in EN 15316-3-1 (2007), which is presented in Table 4-7.

Table 4-3 – Occupancy schedule and internal heat gains due to occupancy (from ISO13790:2008)

Days	**Occupancy period**	**Living room and kitchen** [W/m²]		**Other conditioned areas** [W/m²]	
		Oc + Ap	Lighting	Oc + Ap	Lighting
Monday to Friday	07:00 to 17:00	8.0	0.0	1.0	0.0
	17:00 to 23:00	20.0	6.0	1.0	6.0
	23:00 to 07:00	2.0	0.0	6.0	0.0
Saturday and Sunday	07:00 to 17:00	8.0	0.0	2.0	0.0
	17:00 to 23:00	20.0	6.0	4.0	6.0
	23:00 to 07:00	2.0	0.0	6.0	0.0

Oc: Occupants; Ap: Appliances.

As ISO13790 (2008) does not provide a method to calculate the effect of heat gains due to lighting, the methodology presented in EnergyPlus (US DoE, 2011) was analysed. This assumed that part of the visible radiation is absorbed by the surfaces and the rest is directly transmitted to the air. The monthly heat gain, given in kWh, calculated under these conditions is obtained by,

$$Q_{gn,L,z,m} = \left(P_{tot,z} \cdot A_{f,z} \cdot f_{L,On,z} \cdot \left(\gamma_{SW,A} \cdot \alpha_{s,z} + \gamma_{SW,T} + \gamma_{LW}\right)\right) \cdot \frac{n}{1000} \quad (1)$$

where, $P_{tot,z}$ is the total power installed in zone z (W/m^2); $A_{f,z}$ is the floor area of zone z (m^2); $f_{L,On,z}$ represents the fraction of the number of hours per day in operation in zone z; $\gamma_{SW,V}$ is the fraction of visible radiation (short wavelength); $\gamma_{SW,T}$, fraction of thermal radiation (short wavelength); γ_{LW} is the fraction of convection (long wavelength); n, number of days of the month.

However, it was identified that considering the heat flow from the lights was completely used to heat the air, the results given by the tool presented a lower error when compared with the dynamic simulation. Thus, the fraction terms $\gamma_{SW,V}$ and $\gamma_{SW,A}$ of Equation (1) were taken as zero and γ_{LW} as 1.

The comfort temperatures were considered as 20 and 25˚C for winter and summer seasons, respectively.

4.3.3 Building services

The technical information and schedule of the building services (heating, cooling, ventilation and DHW production) may be introduced by the user or selected from a set of default values. The values used in this case study are presented in Table 4-4.

Table 4-4 – Building systems' input data

Building Services	**Values**
Air conditioning (Set-point 20ºC – 25ºC) (1)	COP Heating = 4.0 COP Cooling = 3.0
Energy need for hot water production 2	Efficiency: 0.9
Ventilation + infiltration rate (3) (Constant values)	0.6 ACH (Heating mode) 1.2 ACH (Cooling mode)

(1) from ISO13790 (2008) – Table G.12;

(2) according with EN 15316-3-1 (2007);

(3) depends on air tightness of the building envelope and passive cooling strategies.

4.3.4 Operational specifications

The information regarding windows and thermal properties of the external opaque envelope is addressed in this section. The characteristics and properties of the glazed elements are presented in Table 4-5.

Table 4-5 – Optical and thermal properties of the glazing (glass + frames)

Materials	**U-value** [W/m^2.K]	**SHGC**
PVC frame and Double pane (8+6 mm, with air gap of 14 mm)	2.597	0.780

In order to apply cooling/heating passive techniques produced by the shading devices, it is necessary to define its properties (see Table 4-6). The solar passive technique used in this case study consists in a radiation set point (300W/m^2) that activates the shading devices in order to prevent overheating. The positive effect that the shading devices develop when activated during the night was also taken into account by correcting the U-value of the window, as indicated in Clause 8.3.2.2.1 of ISO13790 (2008).

Table 4-6 – 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*

*shutter and air space included (ISO 10077, 2006)

The colour of the external surface of the building affects the solar gains in the opaque envelope. It was considered that the building presents a light colour with an absorption coefficient of 0.4.

4.3.5 Concept stage of design

In concept design the building data is sparse, as it was demonstrated in Table 3-1. Thus, it is necessary to develop assumptions in order to estimate the inexistent data. The methodology undertaken to overcome this limitation is addressed in the following sections.

4.3.5.1 Additional inputs – Geometry and envelope

The client's demands for the floor areas were the basis to extrapolate the total conditioned area, considered as 120 m^2 (60m^2 per floor), with a height between floors of 2.70m.

In order to estimate the main envelope areas (external walls including windows), a rectangular plan with width-to-length ratio of 1:2 was considered. The glazing areas were estimated with the following percentages of the respective wall:

- North-oriented: 20%;
- East-oriented: 10%;
- South-oriented: 25%;

- West-oriented: 8%.

This information is based in research work and guide lines for solar passive design strategies (Inanici & Demirbilek 2000; Farrar-Nagy et al. 2002; Milne et al. 2010). Once this information is computed, the resulting walls and glazing areas are presented in Table 4-7.

Table 4-7 – Walls and glazing areas assumed in the concept stage

Envelope	**North** [m^2]	**East** [m^2]	**South** [m^2]	**West** [m^2]	**Roof** [m^2]	**Floor** [m^2]	**Sum** [m^2]
Opaque	33.5	75.3	31.4	77.0	60	60	337.2
Glazed	8.4	8.4	10.5	6.7	-	n.a.	34.0

In respect with the definition of the envelope, the macro-components presented in Table 4-8 were adopted.

Table 4-8 – Macro-components adopted in the conceptual stage

Macro-component	**Material**	**Thickness** [mm]	$\mathbf{U_{bridged}}$ [W/°C.m^2]	$\boldsymbol{\kappa_m}$ [J/m^2.K]
Terrace slab	Mortar slab	30	0.351 (1) 0.302 (2)	13435
	XPS slab	30		
	Air cavity	30		
	Concrete screed	40		
	OSB	18		
	Air Cavity	80		
	Rock wool	120		
	Gypsum board	15		
	Light weight steel	17 kg/m^2		

Ground floor slab	Ceramic tiles	5.5	0.599 (not bridged)	65957
	Concrete screed	13		
	Precast concrete slab	180		
	XPS	40		
Internal slab	Ceramic tiles	5.5	$0.938^{*(1)}$ $0.910^{(2)}$	61062
	Concrete screed	13		
	OSB	18		
	Air cavity	160		
	Rock wool	40		
	Gypsum board	15		
	Light weight steel	14 kg/m^2		
External wall	ETICS	53	$0.296^{(1)}$ $0.301^{(2)}$	13391
	OSB	13		
	Rock wool	120		
	Gypsum board	15		
	Light weight steel	15 kg/m^2		
Internal wall	Gypsum Board	15	$1.069^{*(1)}$ $0.981^{(2)}$	26782
	Rock wool	60		
	Gypsum board	15		
	Light weight steel	10 kg/m^2		

*U-value only used in the dynamic calculations. (1) 2D FEM results. (2) ESSAT-EM results.

The thermal transmission coefficients were computed using the 2D finite element software THERM (Lawrence Laboratory National Laboratory, USA) in order to account for the influence of the thermal bridges originated by the cold rolled steel profiles. The U-values of the internal elements are also presented, since they were used in the dynamic simulations.

As previously stated, the U-value may be calculated using the tool algorithm developed under the guidance of ISO 6946 (2007) and Gorgolewski (2007). Table 4-8 also displays these U-values showing a good agreement with the FEM results provided by THERM software (see also Table 4-10 for external slab adopted in preliminary design stage).

4.3.5.2 Building energy use

The main variables needed to perform the building energy calculations (internal gains, solar gains, heat transfer by transmission and ventilation, COP of the systems and conversion factors for primary energy) are presented in a layouts developed to facilitate the assessment of these variables (see section 3.9.1). This information is useful when performing the optimization of designs and evaluating their performances. In Figure 4-11 the energy need for space heating and cooling in the conceptual stage is presented.

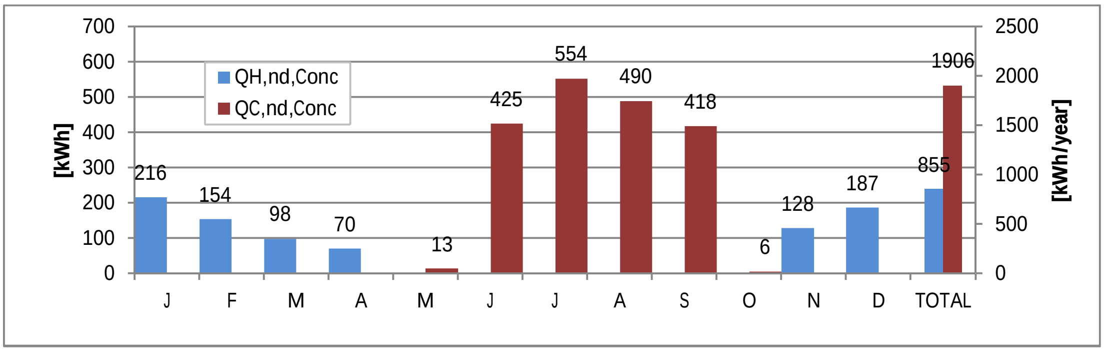


Figure 4-11 – Monthly and yearly energy need for space heating and cooling (concept stage)

The calculations undertaken for the building in the concept stage reveal that the energy for space heating and cooling is 2761 kWh/year (23.0 kWh/year/m^2), which is the sum of 855 and 1906 kWh/year for the heating and cooling energy need, respectively. The energy need for DHW production is 2605.0 kWh/year (21.7 kWh/year/m^2). This demonstrates the importance of the latter in the energy need of the building and the benefit of installing, for example, solar panels in order to minimize the consumption of electricity from the grid. Notice that the energy need for space cooling is significantly higher than for space cooling. However, if the ventilation rate during the cooling season (1.2 ACH) was greater, the share of cooling energy would be reduced. Furthermore, in spite of the higher energy need for cooling the space, the winter season is longer that the cooling season.

4.3.5.3 Environmental impacts

The environmental impacts were firstly calculated in the materials level, than they were compiled for the macro-components and the whole building impacts were calculated (see Figure 3-9). The environmental impacts of this building are presented in

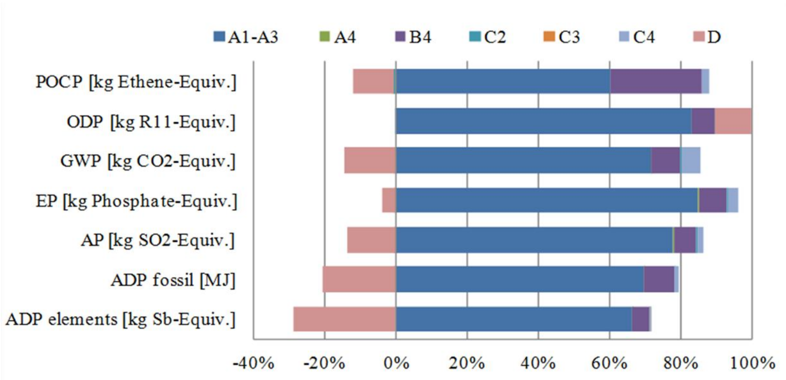


Figure 4-12 – Environmental impacts of the building (concept stage)

As it is demonstrated in Figure 4-12, the production materials stage (modules A1-A3) originates the higher burdens (approximately 60% of the total). The use stage of the building (module B4) is the second most important stage in its life cycle, followed by the end-of-life stage (modules C2-C4).

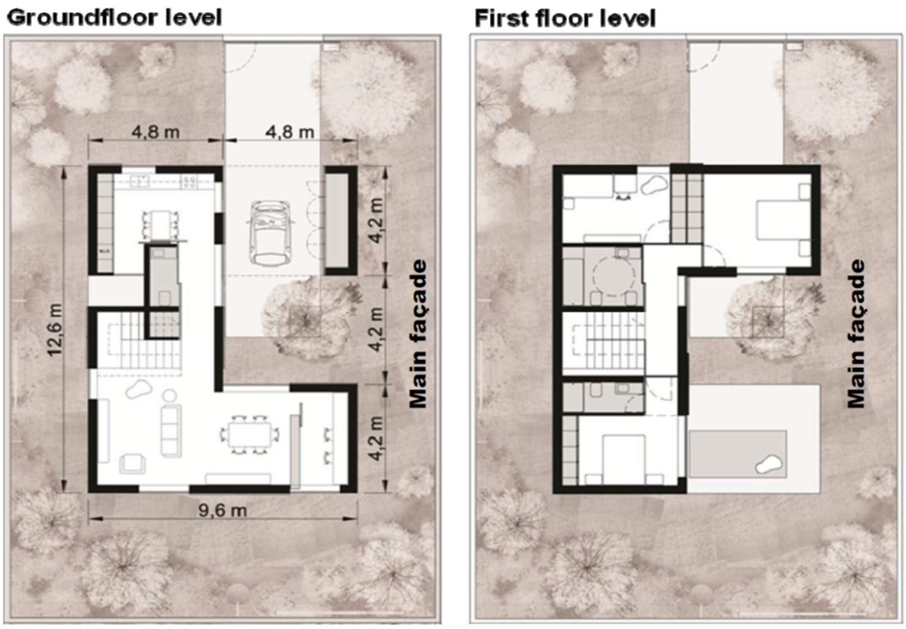
4.3.6 Preliminary stage of design

In this stage, the designer possesses more information on the building data. In this case study, at this stage, the project was already final, thus, this corresponds to the final stage of the building. The calculations are discussed in the next sections.

4.3.6.1 Additional inputs – Geometry and envelope

In terms of the calculations of the energy need, the building definition at this stage is enough to be considered as the final project. The geometry of the building is known through the elevations and plan drawings, illustrated in Figure 4-13.

a) Elevations layout



b) Floors layout

Figure 4-13 – Building’s architecture

After the definition of the architectural drawings, the total floor areas have now 123.8 m^2, with 63.9 m^2 in the ground floor and 60.0 m^2 in the first floor (21.0 m^2 in external slab). The floor height remains with 2.7 m. Table 4-9 presents the areas of other envelope elements, at this stage, including the difference to the conceptual stage.

Table 4-9 – Walls and glazing areas [m^2] in the preliminary design stage

	North	East	South	West	Roof	Floor	External Floor	Sum
Opaque	41.3	49.9	38.3	60.3	83.7	63.9	21.0	358
(difference)*	(+23%)	(-34%)	(+22%)	(-22%)	(+40%)	(+7%)	(n.a)	(+6%)
Glazing	13.0	17.3	15.6	4.6	-	n.a.	-	50.2
(difference)*	(-55%)	(-106%)	(+49%)	(-36%)				(+48%)

* Difference to conceptual stage

With the addition of an external slab, in preliminary design stage it was necessary to select an additional macro-component for this element (Table 4-10).

Table 4-10 – Macro-component adopted for the external slab in the preliminary design stage

Macro-component	Material	Thickness [mm]	$U_{bridged}$ [W/°C.m^2]	κ_m [J/m^2.K]
External slab	Ceramic tiles	5.5	0.359$^{(1)}$ 0.356$^{(2)}$	47627
	Concrete screed	13		
	OSB	18		
	Air cavity	140		
	Rock wool	60		
	OSB	13		
	ETICS	53		

(1) 2D FEM results. (2) ESSAT-EM results.

4.3.6.2 Building energy use

With all inputs computed, the energy need results for space cooling and heating and for DHW production are presented in similar layouts as the ones shown in section 3.9.1.

In this stage, the energy need estimated with ESSAT-EM was of 1066 and 1861 kWh for the space heating and cooling, respectively. The yearly energy need for space heating and cooling is 2927 kWh (23.6 kWh/m^2) and for the DHW production is 2642 kWh (21.3 kWh/m^2). In Figure 4-14 it is presented a comparison of the energy totals between the preliminary and concept stages, showing the same profile of energy need throughout the year, as well as a good approximation in the results. The building total energy need for space cooling and heating is 8.8% higher in preliminary design stage. The energy need for DHW production presents a difference of -2%, which is only due to the error in the estimation of the conditioned area.

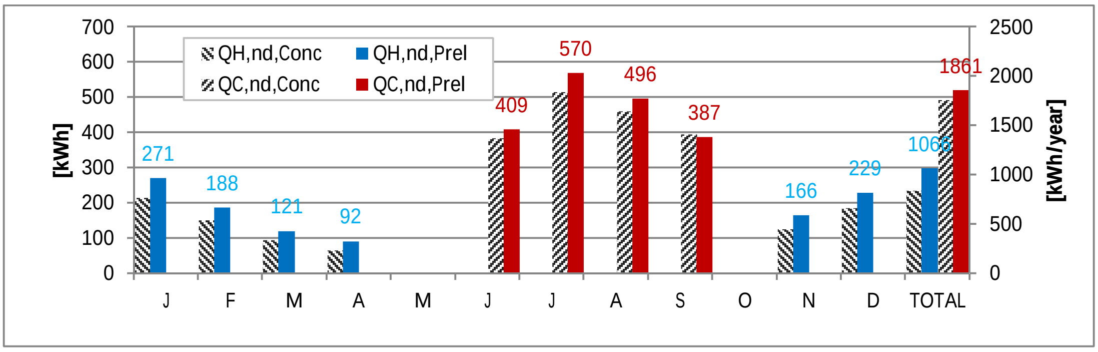


Figure 4-14 – Comparison of the energy need (for space cooling and heating) between the preliminary and concept stages (ESSAT-EM results)

Bearing in mind the uncertainty of the data available at the early stages of design, the error of the results obtained in the concept and preliminary stages is fairly low. Furthermore, in the concept stage, the energy needs are underestimated in both heating and cooling modes, as well as the heat transfer and solar gains (the preponderant aspect is the glazing areas).

The utilization factors are similar in both stages, since the heat-balance ratio and the time constant of the building do not present great divergence. This is motivated by the fact that, the opaque areas are similar and the heat transfer (transmission and ventilation) is higher in the preliminary stage. The latter has a much lower value than the internal heat capacity, thus, not inducing great changes in the time constant of the building. It is noteworthy that, although the opaque areas present similar values in both stages, the glazing area is higher in the preliminary stage. In respect with the heat-balance ratio, it is observed that in the preliminary stage the heat gains are higher, but the heat transfer by transmission is also higher. This suggests that the utilization factors are not as sensitive to the lack of definition of input data as the parameters influencing the heat transfer (by ventilation and transmission) and the heat gains (solar and internal).

4.3.6.3 Environmental impacts

The methodology undertaken in the calculation of the environmental impacts was already addressed in section 4.3.5.3. In this stage, the environmental impacts are summarized in Table 4-11.

Table 4-11 – Life cycle environmental analysis of building at preliminary stage of design

Impact category	Environmental loads	Units
ADP elements	1,11E-01	kg Sb-Equiv.
ADP fossil	4,38E+05	MJ
AP	1,35E+02	kg SO2-Equiv.
EP	1,53E+01	kg Phosphate-Equiv.
GWP	3,54E+04	kg CO2-Equiv.
ODP	1,00E-03	kg R11-Equiv.
POCP	3,71E+01	kg Ethene-Equiv.

The results obtained for each stage follow the same trend as it was obtained for the concept stage, i.e., the stage of material production is dominant, followed by the use stage and end-of-life.

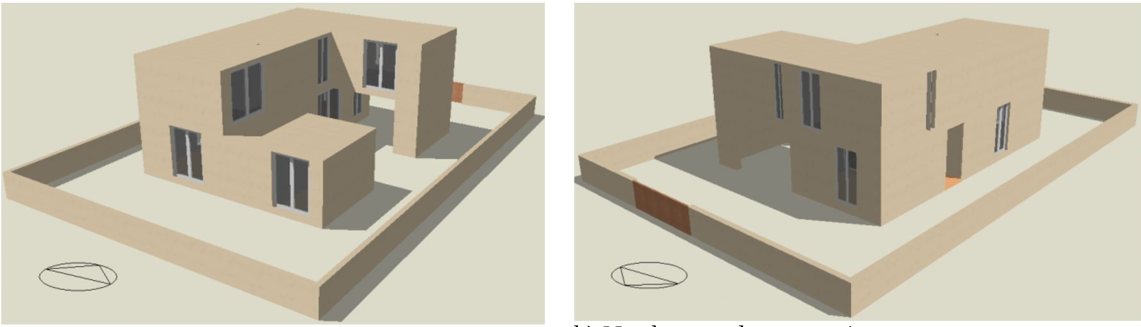
4.3.7 Advanced dynamic simulations

The dynamic simulation of this building energy was undertaken with EnergyPlus, using DesignBuilder interface. This is a powerful tool for energy need calculations, which was developed with BLAST and DOW-2 as basis. It features several modules with cutting-edge algorithms allowing performing simulations with variable time-steps, multi-zone airflow and complete input and output data structures (Crawley et al., 1994).

4.3.7.1 Inputs

The model of the building for the advanced dynamic simulations (Figure 4-15) comprised three main blocks: (i) suspended-floor (crawl space); (ii) ground floor; (iii) first floor. In these blocks the several zones (compartments) of the building were created, as illustrated in Figure 4-16. The ground floor contains four thermal zones: (i) living room; (ii) kitchen; (iii) bathroom; (iv) hall/stairwell. In the first floor the six thermal zones are: (i) three bedrooms; (ii) two bathrooms; (iii) corridor/stairwell. The crawl space is modelled as an unheated and unventilated single zone.

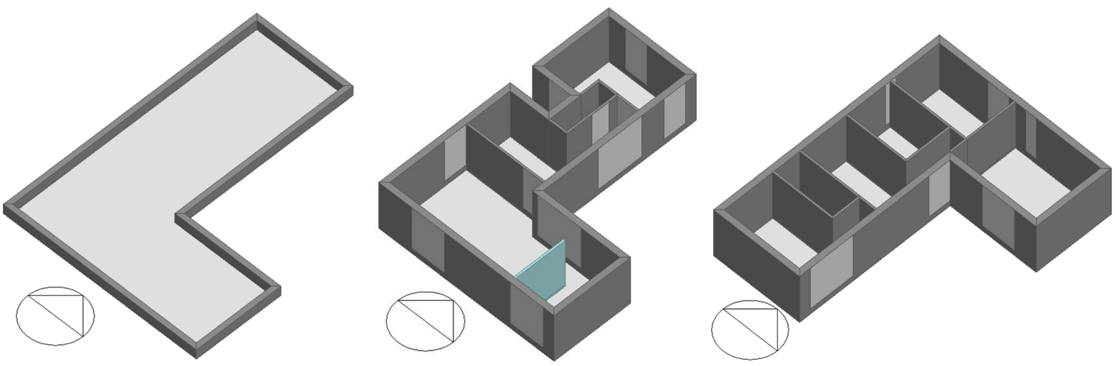
The opaque envelope was created with the characteristics presented in Table 4-8 and Table 4-10. The glazing and shading devices followed the data of Table 4-5 and Table 4-6, as well as the cooling and heating strategies considered in the ESSAT-EM tool.



a) Southern and western views

b) Northern and eastern views

Figure 4-15 – Elevation views of the DesignBuilder/EnergyPlus building model



a) Crawl space

b) Ground floor

c) First floor

Figure 4-16 – Blocks with thermal zones used in the dynamic simulations

The occupancy and systems' schedules are also coherent with the tool and presented in Table 4-3 and Table 4-4. The main difference between the ESSAT_EM tool and the advanced dynamic model is in the heat flow of the occupants. In the latter this is calculated with specific algorithm for the metabolism of the occupants that is influenced by the internal air temperature, whereas in the tool this heat flow is constant.

Similarly to the ESSAT-EM, here the ventilation rate was considered to be constant, including air infiltration, as previously presented in Table 4-4.

4.3.7.2 Outputs

For the preliminary stage of design, the advanced dynamic simulations produced the results presented in Figure 4-17 (compared with the results calculated given in the tool for the preliminary stage).

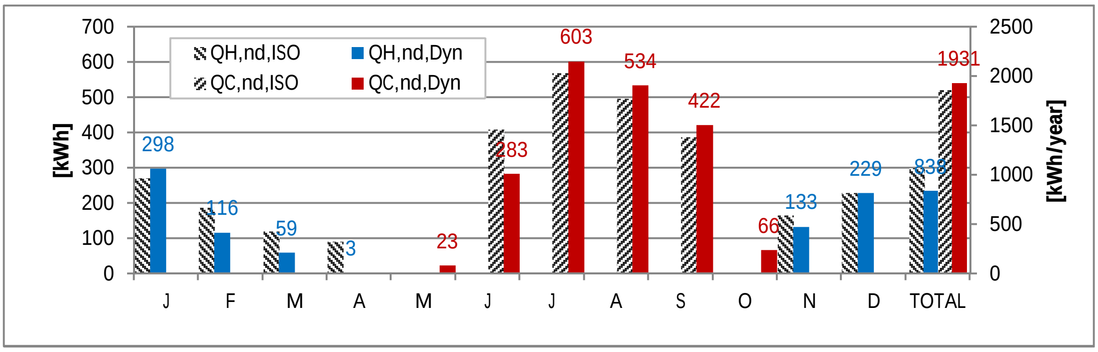


Figure 4-17 – Building energy need for space cooling and heating at preliminary design stage: dynamic simulations (Dyn) *versus* ESSAT-EM tool (ISO)

The yearly energy need for space heating, predicted by the EnergyPlus dynamic simulations, was 838 kWh and for space cooling 1931 kWh, with a total yearly energy need of 2769 kWh (22.6 kWh/m^2). The energy need calculated with the simplified method (ESSAT-EM tool) shows a good agreement with the results obtained from the dynamic calculations. When comparing the total energy needs (heating and cooling) of the preliminary stage (2927 kWh/year) with the dynamic calculation, the error is +5.7%. However, the error of ESSAT-EM for heating and cooling energy need, computed as prescribed in EN 15265 (2007), is +8.2% and -2.5%, respectively.

The heating and cooling energy need estimation follow the same trend as the results obtained in the verification of the algorithm precision (see Section 4.1), i.e., the results are overestimated in the winter and underestimated in the summer. It is important to refer that in those calculations (CEN test-room) the heat transfer to ground floor was null and there was only one active wall (mainly composed by glazing). In fact, if the ground floor is assumed to be adiabatic in this case study building, the error for the heating mode is 0% and the cooling mode is 7%. It was then shown that when the amplitude of the internal temperature was higher (lower thermal inertia due to adiabatic ground-floor), the errors of the quasi-steady-stateincreased.

5 CONCLUSIONS

In this dissertation, the energy module (EM) and Environmental Impacts Module (EIM) of a new early stage sustainability assessment tool (ESSAT) to evaluate the environmental performance of a building was presented. The algorithm implemented to predict the space heating and cooling was based in the ISO13790 (2008) prescriptions for a quasi-steady-state monthly method and in another relevant international standards. This module is able to predict energy consumption at early design stages: concept and preliminary, as well at final design stage. The environmental impacts were calculated in accordance with the most recent European standards developed by the TC 350, which cover the whole life cycle of the building.

The ESSAT was developed to be used by any player of the construction industry and has several interesting and useful features that allow the user to reduce the time consumption in intermediate computations to predict the operational energy of a building and quantify the environmental impacts of its life cycle. Firstly because the tool is organized in a macro-component approach with an extensive database of building construction components, that can be selected by the user. Furthermore, the ESSAT-EM algorithm is structured in sub-modules, allowing to automatically compute several values needed for the thermal computations that otherwise should be computed and inputted by the user. Some examples are: the U-value (even for steel bridged components), the heat capacity (thermal inertia), the heat transfer to the ground (for three different construction solutions) and shading coefficients (for overhangs, fins and obstructions, e.g. from the building itself). In addition it is possible to assess the impact of a given design solution since the early stages of design, since the algorithm relies in simple inputs.

The accuracy of the energy algorithm was verified at two different levels: (1) a single test-room referenced in EN15265 (2007); and (2) in a low-rise residential LSF building (case study). Besides the overall results obtained in the concept and preliminary stages were compared.

The verification of the tool regarding the single test-room showed that the results given by the ESSAT-EM are overestimated for the heating mode and underestimated for the cooling mode. Furthermore, the error obtained reaches a maximum value of 12% for heating mode. For cooling mode the error is lower than 7% for all test-cases, with one exception (test-case 9 as defined in EN 15265).

Through the case study (low rise residential single family LSF building), it was found that even though there is high uncertainty in the input data at the concept stage, the energy need in the preliminary stage was only 8.8% higher. Regarding the comparison of the results given by the tool and the dynamic calculations show that the first overestimated the energy need in 5.7%. Regarding the environmental impacts, it was also shown that the stages that present the higher burdens do not change from the conceptual stage to the preliminary stage, showing the robustness of the methodology.

The above mentioned shows that the developed tool is user-friendly and therefore may be used by any player in the construction industry, has a low amount of input data and provide fairly good results. In the near future, particularly when the algorithm is available online as web-platform, more buildings will be assessed as case studies and compared, not only with advanced dynamic simulations, but also with *in situ* building energy measurements. This will allow to verify these assumptions and even to improve the implemented algorithm by calibrating it accordingly with the obtained data.

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ANNEX A – Material properties

The thermal properties of the materials used in the case study are presented in table A.1.

Table A.1 – Materials thermal properties

	λ W/m.K]	ρ kg/m^3]	c J/(kg.K)]
Cement mortar	0.720	1650	840
Ceramic tile	0.800	1700	850
Cold rolled steel	50.000	7800	450
Concrete slab	1.900	2300	840
EPS	0.040	15	1400
Gypsum Plasterboard	0.250	900	1000
Mortar slab	0.900	1300	1500
OSB	0.130	650	1700
Rock wool	0.040	30	840
XPS	0.034	35	1400
Concrete screed	1.400	2100	840
Ceramic (bricks)	1.150	1800	840

The surface resistances used to determine the U-values are presented in table A.2.

Table A.2 – Surface resistances

	R_i m2.K/W]	R_e m2.K/W]
Wall	0.13	0.04
Roof winter	0.10	0.04
Roof summer	0.17	0.04
Ground floor	0.13	0.13
External floor winter	0.10	0.04
External floor summer	0.17	0.04

ANNEX B - Materials environmental impacts

The environmental impacts of the materials used in the macro-components are presented in table B.1.

Table B.1 – Materials environmental impacts

Code	Material	Functional Unit	Calulation base
1	Cement mortar	m2	Impacts per 20mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	8.6E+00	2.8E-01	0.0E+00	9.5E-01	0.0E+00	kg CO_2 eq
ODP	3.5E-07	4.6E-08	0.0E+00	1.9E-07	0.0E+00	kg CFC 11 eq
AP	1.4E-02	1.6E-03	0.0E+00	5.7E-03	0.0E+00	Kg SO_2 eq
EP	2.1E-03	3.4E-04	0.0E+00	1.4E-03	0.0E+00	kg $(PO_4)^{-3}$
POPC	5.7E-04	5.5E-05	0.0E+00	1.9E-04	0.0E+00	kg Ethene eq
ADP-E	2.2E-02	2.0E-03	0.0E+00	8.5E-03	0.0E+00	kg Sb eq
ADP-F	4.2E+01	4.5E+00	0.0E+00	1.9E+01	0.0E+00	MJ

Code	Material	Functional Unit	Calulation base
2	Ceramic tile	m2	Impacts per 5.5mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	7.7E+00	1.1E-01	0.0E+00	2.9E-01	0.0E+00	kg CO_2 eq
ODP	7.6E-07	1.7E-08	0.0E+00	5.7E-08	0.0E+00	kg CFC 11 eq
AP	2.6E-02	5.9E-04	0.0E+00	1.7E-03	0.0E+00	Kg SO_2 eq
EP	2.6E-03	1.3E-04	0.0E+00	4.1E-04	0.0E+00	kg $(PO_4)^{-3}$
POPC	1.4E-03	2.1E-05	0.0E+00	5.9E-05	0.0E+00	kg Ethene eq
ADP-E	5.9E-02	7.7E-04	0.0E+00	2.6E-03	0.0E+00	kg Sb eq
ADP-F	1.1E+02	1.7E+00	0.0E+00	5.6E+00	0.0E+00	MJ

Code	Material	Functional Unit	Calulation base
3	Cold rolled steel	m2	Impacts per 20kg

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	4.7E+01	2.9E-01	0.0E+00	3.2E-01	-4.9E+01	kg CO_2 eq
ODP	0.0E+00	4.7E-08	0.0E+00	5.7E-08	0.0E+00	kg CFC 11 eq
AP	1.3E-01	1.6E-03	0.0E+00	1.8E-03	-8.9E-02	Kg SO_2 eq
EP	1.0E-02	3.4E-04	0.0E+00	3.8E-04	-5.9E-03	kg $(PO_4)^{-3}$
POPC	2.0E-02	5.6E-05	0.0E+00	6.3E-05	-2.3E-02	kg Ethene eq
ADP-E	2.7E-01	2.1E-03	0.0E+00	2.5E-03	-2.6E-01	kg Sb eq
ADP-F	4.1E+02	4.6E+00	0.0E+00	5.4E+00	-3.4E+02	MJ

Code	Material	Functional Unit	Calulation base
4	Concrete slab	m2	Impacts per 250mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	1.3E+01	9.2E-01	0.0E+00	7.1E+00	-1.8E+00	kg CO_2 eq
ODP	2.7E-06	1.5E-07	0.0E+00	1.3E-06	0.0E+00	kg CFC 11 eq
AP	4.1E-02	5.1E-03	0.0E+00	4.6E-02	-3.3E-03	Kg SO_2 eq
EP	4.3E-03	1.1E-03	0.0E+00	1.1E-02	-2.7E-04	kg $(PO_4)^{-3}$
POPC	2.1E-03	1.8E-04	0.0E+00	1.4E-03	-8.3E-04	kg Ethene eq
ADP-E	4.7E-02	6.7E-03	0.0E+00	6.0E-02	-9.6E-03	kg Sb eq
ADP-F	7.5E+01	1.5E+01	0.0E+00	1.3E+02	-1.2E+01	MJ

Code	Material	Functional Unit	Calulation base
5	EPS	m2	Impacts per 50mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	4.1E+00	9.7E-03	0.0E+00	2.2E-01	0.0E+00	kg CO_2 eq
ODP	1.1E-07	1.6E-09	0.0E+00	2.4E-08	0.0E+00	kg CFC 11 eq
AP	1.5E-02	5.3E-05	0.0E+00	7.2E-04	0.0E+00	Kg SO_2 eq
EP	1.2E-03	1.1E-05	0.0E+00	5.8E-03	0.0E+00	kg $(PO_4)^{-3}$
POPC	6.8E-03	1.9E-06	0.0E+00	4.4E-05	0.0E+00	kg Ethene eq
ADP-E	4.6E-02	7.0E-05	0.0E+00	1.1E-03	0.0E+00	kg Sb eq
ADP-F	9.8E+01	1.5E-01	0.0E+00	2.4E+00	0.0E+00	MJ

Code	Material	Functional Unit	Calulation base
6	;ypsum Plasterboar	m2	Impacts per 20mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	3.9E+00	1.1E-01	0.0E+00	2.6E+00	0.0E+00	kg CO_2 eq
ODP	4.4E-07	1.8E-08	0.0E+00	5.6E-08	0.0E+00	kg CFC 11 eq
AP	1.2E-02	6.0E-04	0.0E+00	2.4E-01	0.0E+00	Kg SO_2 eq
EP	1.9E-03	1.3E-04	0.0E+00	5.8E-03	0.0E+00	kg $(PO_4)^{-3}$
POPC	5.3E-04	2.1E-05	0.0E+00	9.9E-03	0.0E+00	kg Ethene eq
ADP-E	2.8E-02	7.8E-04	0.0E+00	2.5E-03	0.0E+00	kg Sb eq
ADP-F	5.6E+01	1.7E+00	0.0E+00	5.5E+00	0.0E+00	MJ

Code	Material	Functional Unit	Calulation base
7	Mortar slab	m2	Impacts per 30mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	1.3E+01	6.4E-01	0.0E+00	1.6E+00	0.0E+00	kg CO_2 eq
ODP	5.3E-07	1.0E-07	0.0E+00	3.1E-07	0.0E+00	kg CFC 11 eq
AP	2.1E-02	3.5E-03	0.0E+00	9.7E-03	0.0E+00	Kg SO_2 eq
EP	3.2E-03	7.6E-04	0.0E+00	2.3E-03	0.0E+00	kg $(PO_4)^{-3}$
POPC	8.5E-04	1.2E-04	0.0E+00	3.3E-04	0.0E+00	kg Ethene eq
ADP-E	3.2E-02	4.6E-03	0.0E+00	1.4E-02	0.0E+00	kg Sb eq
ADP-F	6.3E+01	1.0E+01	0.0E+00	3.1E+01	0.0E+00	MJ

Code	Material	Functional Unit	Calulation base
8	OSB	m2	Impacts per 10mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	-1.1E+01	7.8E-02	0.0E+00	9.2E-02	0.0E+00	kg CO_2 eq
ODP	2.5E-07	1.3E-08	0.0E+00	1.3E-08	0.0E+00	kg CFC 11 eq
AP	2.8E-02	4.3E-04	0.0E+00	4.3E-04	0.0E+00	Kg SO_2 eq
EP	4.1E-03	9.3E-05	0.0E+00	1.2E-04	0.0E+00	kg $(PO_4)^{-3}$
POPC	3.5E-03	1.5E-05	0.0E+00	1.5E-05	0.0E+00	kg Ethene eq
ADP-E	6.2E-02	5.6E-04	0.0E+00	5.6E-04	0.0E+00	kg Sb eq
ADP-F	1.3E+02	1.2E+00	0.0E+00	1.2E+00	0.0E+00	MJ

Code	Material	Functional Unit	Calulation base
9	Paint	m2	mpacts per two coats

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	2.6E-01	4.8E-05	0.0E+00	8.7E-03	0.0E+00	kg CO_2 eq
ODP	3.7E-08	7.8E-12	0.0E+00	3.2E-10	0.0E+00	kg CFC 11 eq
AP	1.7E-03	2.7E-07	0.0E+00	7.3E-06	0.0E+00	Kg SO_2 eq
EP	3.5E-04	5.7E-08	0.0E+00	4.0E-04	0.0E+00	kg $(PO_4)^{-3}$
POPC	8.0E-05	9.3E-09	0.0E+00	1.8E-06	0.0E+00	kg Ethene eq
ADP-E	2.4E-03	3.5E-07	0.0E+00	1.4E-05	0.0E+00	kg Sb eq
ADP-F	4.8E+00	7.6E-04	0.0E+00	3.0E-02	0.0E+00	MJ

Code	Material	Functional Unit	Calulation base
10	Rock wool	m2	Impacts per 120mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	8.5E+00	1.2E-01	0.0E+00	1.6E-01	0.0E+00	kg CO_2 eq
ODP	3.5E-07	1.9E-08	0.0E+00	3.2E-08	0.0E+00	kg CFC 11 eq
AP	5.0E-02	6.4E-04	0.0E+00	8.9E-04	0.0E+00	Kg SO_2 eq
EP	5.5E-03	1.4E-04	0.0E+00	1.9E-04	0.0E+00	kg $(PO_4)^{-3}$
POPC	2.5E-03	2.2E-05	0.0E+00	3.2E-05	0.0E+00	kg Ethene eq
ADP-E	6.1E-02	8.4E-04	0.0E+00	1.4E-03	0.0E+00	kg Sb eq
ADP-F	1.1E+02	1.8E+00	0.0E+00	3.0E+00	0.0E+00	MJ

Code	Material	Functional Unit	Calulation base
11	XPS	m2	Impacts per 30mm

INDICATOR	PRODUCTION STAGE A1:A3	CONSTRUCTION STAGE A4:A5	USE STAGE B1:B7	END-OF-LIFE STAGE C1:C4	RECYCLING STAGE D	Units
GWP	2.8E+00	1.0E-02	0.0E+00	4.9E-02	0.0E+00	kg CO_2 eq
ODP	5.5E-10	1.6E-09	0.0E+00	5.9E-09	0.0E+00	kg CFC 11 eq
AP	6.5E-03	5.6E-05	0.0E+00	1.5E-04	0.0E+00	Kg SO_2 eq
EP	5.8E-04	1.2E-05	0.0E+00	1.3E-03	0.0E+00	kg $(PO_4)^{-3}$
POPC	2.7E-03	2.0E-06	0.0E+00	1.0E-05	0.0E+00	kg Ethene eq
ADP-E	8.4E-07	7.3E-05	0.0E+00	2.6E-04	0.0E+00	kg Sb eq
ADP-F	8.7E+01	1.6E-01	0.0E+00	9.8E-01	0.0E+00	MJ