LVS^3

Large Valorisation on Sustainability of Steel Structures

BACKGROUND DOCUMENT

February 2014

Deliverable of a project carried out with a financial grant
from the Research Fund for Coal and Steel of the European Community

Background document

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The present document related to the dissemination project (RFS2-CT-2013-00016) LVS^3 - Large Valorisation on Sustainability of Steel Structures, which has been co-funded by the Research Fund for Coal and Steel (RFCS) of the European Community.

ISBN 978-80-01-05439-0

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Printing in CMM Portugal

February 2014

CONTENTS

1 INTRODUCTION

The aim of this document is to provide in-depth information on the development and validation of life cycle methodologies focussing on the life cycle assessment of steel structures. This document was created in the framework of the dissemination project **LVS^3*: Large Valorisation on Sustainability of Steel Structures*** (RFS2-CT-2013-00016).

This document focuses on two complementary methodologies:

(i) the macro-components approach, addressing the life cycle assessment of buildings and/or building components but excluding the quantification of energy in the use stage of a building;

(ii) an approach focussing on the use stage of a building and enabling the quantification of the operational energy of buildings.

Both approaches were developed and validated within the scope of the European RFCS project *SB_Steel: Sustainability of Steel Buildings* (SB_Steel, 2014).

The adopted approaches were implemented into available software tools in the scope of the current project LVS^3. The former was implemented into *LCA calculator,* a tool developed by the University of Coimbra (Portugal) together with ECCS for iPad and iPhone applications; and AMECO, a tool developed by ArcelorMittal and CTICM. The latter was implemented by CTICM into AMECO.

The document is divided into three main parts. In the first part (Chapter 2), a brief introduction to life cycle thinking is provided, followed by the presentation of different approaches for the sustainability assessment of buildings and by a description of the general framework of life cycle analysis, according to international standards. Then, the second part of this document (Chapter 3) provides a detail description of the adopted approaches for the assessment of life cycle environmental impacts and for the evaluation of the energy needs of a building during its operational life. Finally, in the last part of this document (Chapter 4), a case study is introduced, which was used for the validation of the adopted approaches.

2 LIFE CYCLE ASSESSMENT OF BUILDINGS

2.1 Life cycle thinking

Life Cycle Analysis (LCA) is an objective process to evaluate the environmental burdens associated with a product process or activity and to evaluate and implement opportunities to affect environmental improvements.

It identifies and quantifies material usage, energy requirements, solid wastes, and atmospheric and waterborne emissions throughout the product life cycle (i.e. from raw material acquisition to end-of-life), as illustrated in Fig. 2.1~~Fig. 2.1~~.

Life cycle approaches are recommended by the Integrated Product Policy (COM (2003)302) for the assessment of potential impacts of products.

Potential environmental impacts occur throughout all life cycle stages of a building or other construction The main advantage of Life Cycle Thinking is that it avoids the shifting of burdens from one life cycle stage to another, from one geographic area to another and from one environmental medium (for example air quality) to another (for example water or land) (UNEP, 2004).

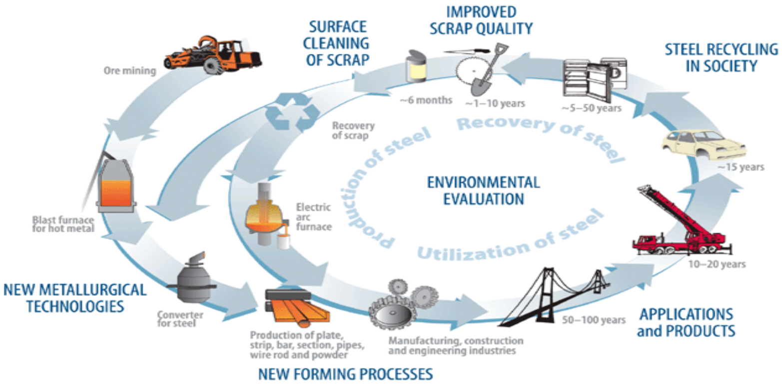


Fig. 2.1: Life cycle methodology (credits to stalkretsloppet.se)

Moreover, life cycle approaches enable better choices for the longer term. It implies that everyone in the whole chain of a product’s life cycle, from cradle to grave, has a responsibility and a role to play, taking into account all the relevant impacts on the environment (UNEP, 2004). By the quantification of all the emissions into air, water and land that take place in every life cycle phase, life cycle approach enables to identify the most critical processes over the product or system life, thus enhancing the potential for environmental improvement in the whole chain of the product.

However, this type of analysis has some disadvantages:

- ✓ LCA is usually time-consuming and expensive, often requiring expert knowledge;
- ✓ There is not a generally acceptable LCA methodology;
- ✓ Some of the assumptions taken in LCA might be subjective (for example the boundaries determination, the source of data and the impact assessment choice);
- ✓ The results of LCA may be focused on national and regional level and therefore, they might not be suitable for local applications;
- ✓ The accuracy of a LCA study depends on the quality and the availability of the relevant data.

The life cycle approaches adopted in this project aim to overcome some of the drawbacks referred above, as described in the next chapter.

In the next sub-section of this chapter, a brief summary of different methodologies and tools for the assessment of building sustainability is introduced.

2.2 Methodologies and tools for building sustainability assessment

Construction is responsible for a major proportion of environmental impacts in the industrial sector. During the last years there has been an increasing interest in the environmental assessment of the built environment.

Currently there are two major classes of assessment tools for the built environment (Reijnders and Roekel, 1999):

(i) Qualitative tools based on scores and criteria;

(ii) Tools using a quantitative analysis of inputs and outputs based on life cycle approach.

Within the first group of tools there are systems such as LEED (in the US), BREAM (in the UK), GBTool (International Initiative for a Sustainable Built Environment (iiSBE)), etc. These methods, also known as rating systems, are usually based on auditing of buildings and on the assignment of scores to pre-defined parameters. Although mainly qualitative some parameters may also be quantitative and even use Life Cycle Analysis (LCA), mainly in the quantification of material credits. Usually these systems are used to obtain green building certifications and eco-labels. However, this kind of tools is outside the scope of this document, thus in the following the focus will be on the second group of tools, which are based on life cycle approaches.

LCA can be directly applied to the building sector. However, due to its characteristics there are additional problems in the application of standard life cycle to buildings and other constructions. The main causes may be listed as (IEA, 2001):

(i) The life expectancy of buildings is long and unknown and therefore subjected to a high level of uncertainties,
(ii) Buildings are site dependent and many of the impacts are local,
(iii) Building products are usually made of composite materials which implies more data to be collected and associated manufacturing processes,
(iv) The energy consumption in the use phase of a building is very much dependent on the behaviour of the users and of the services,
(v) A building is highly multi-functional, which makes it difficult to choose an appropriate functional unit, (
(vi) Buildings are closely integrated with other elements in the building environment, particularly urban infrastructure like roads, pipes, green spaces and treatment facilities, and it can be highly misleading to conduct LCA on a building in isolation.

In relation to life cycle assessment of buildings and its components, a distinction is made between LCA tools developed with aim of evaluating building materials and components (e.g. BEES (Lippiatt, 2002) and LCA approaches for evaluating the building as a whole (e.g. Athena (Trusty, 1997), Envest (Howard et al. 1999), EcoQuantum (Kortman et al., 1998)). The latter are usually more complex as the overall building performance depends on the interactions between individual components and sub-systems as well as interactions with the occupants and the natural environment. The selection of an appropriate tool depends on the specific environmental objectives of the project.

The precision and the relevance of LCA tools as a design aid were analyzed in a project developed in the frame of the European thematic network PRESCO (Practical Recommendations for Sustainable Construction) (Kellenberger, 2005). In this project, several LCA tools were compared based on case studies, with the global aim of the harmonization of LCA based assessment tools for buildings. Other comparative analysis regarding tools for environmental assessment of the built environment may be found in Jönsson (2000) and Forsberg & von Malmborg (2004).

As already referred, this document focuses on LCA and, in particular, its application to steel structures. In the following sub-sections, the normative framework for LCA is introduced. First, the international standards ISO 14040 (2006) and ISO 14044 (2006), establishing the general framework for LCA, are presented followed by the new European standards for the sustainability of construction works. It is noted that while the former have a general application, the European standards focuses on the assessment of buildings and other construction works.

2.3 Normative framework for LCA

The International Standards ISO 14040 (2006) and 14044 (2006) specify the general framework, principles and requirements for conducting and reporting life cycle assessment studies. Regarding these standards, life cycle assessment shall include definition of goal and scope, inventory analysis, impact assessment, and interpretation of results. As represented in Fig. 2.2~~Fig. 2.2~~, the various phases are interrelated and sometimes an iterative procedure is necessary in order to fulfil the aim and goal of the study. The different stages are detailed in the following sub-sections.

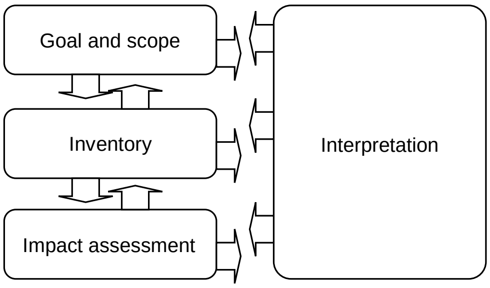


Fig. 2.2: LCA general framework (ISO 14044:2006)

2.3.1 Definition of goal and scope

The goal of an LCA study shall clearly state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated.

In the scope of an LCA Study the main issues to be considered and clearly described are the functional unit and the system boundaries.

2.3.1.1 Function and functional unit

The scope of an LCA study shall clearly specify the functions of the system being studied. A functional unit is a measure of the performance of the functional outputs of the product system.

The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of results is particularly critical when different systems are being assessed to ensure that such comparisons are made on a common basis.

2.3.1.2 System boundaries

The system boundaries determine which unit process shall be included within the LCA. For a generic material, a LCA covers all stages from raw material production to end-of-life, as illustrated in Fig. 2.3~~Fig. 2.3~~.

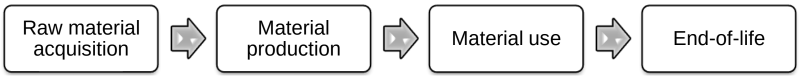


Fig. 2.3: Processes included in a LCA of a generic material

When the LCA covers only the initial stages of material production the LCA is called a cradle-to-gate analysis. If the complete cycle is addressed (from raw material production to end-of-life) than the analysis is called a cradle-to-grave analysis. When recycling processes are considered in the end-of-life and the secondary materials avoid the production of new materials than the analysis is often called a cradle-to-cradle analysis.

Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience.

The selection of inputs and outputs, the level of aggregation within a data category, and the modelling of the system should be modelled in such a manner that inputs and outputs at its boundaries are elementary flows.

2.3.1.3 Data quality requirements

In order to fulfil the goal and the scope of the analysis, the following requirements are indicated in ISO 14044:

- time-related coverage: age of data and the minimum length of time over which data should be collected;
- geographical coverage: geographical area from which data for unit processes should be collected to
- technology coverage: specific technology or technology mix;
- precision: measure of the variability of the data values for each data expressed (e.g. variance);
- completeness: percentage of flow that is measured or estimated;
- representativeness: qualitative assessment of the degree to which the data set reflects the true;
- consistency: qualitative assessment of whether the study methodology is applied uniformly to the various;

- reproducibility: qualitative assessment of the extent to which information about the methodology and data;
- values would allow an independent practitioner to reproduce the results reported in the study;
- uncertainty of the information (e.g. data, models and assumptions).

2.3.2 Life cycle inventory analysis

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. These inputs and outputs may include the use of resources and releases to air, water and land associated with the system.

The qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundaries.

Data collection can be a resource - intensive process. Practical constraints on data collection should be considered in the scope and documented in the study report.

2.3.3 Life cycle impact assessment

2.3.3.1 General calculation method

The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. In general, this process involves associating inventory data with specific environmental impacts, and is made of two parts:

(i) Mandatory elements, such as classification and characterization;
(ii) Optional elements, such as normalization, ranking, grouping and weighting.

The classification implies a previous selection of appropriate impact categories, according to the goal of the study, and the assignment of LCI results to the chosen impact categories. Characterization factors are then used representing the relative contribution of a LCI result to the impact category indicator result. According to this method impact categories are linear functions, i.e. characterization factors are independent of the magnitude of the environmental intervention, as given by expression 2.1:

$$impact_{cat} = \sum_i m_i \times charact\_\ factor_{cat,i}$$

Eq. (2.1)

where m_i is the mass of the inventory flow *i* and $charact\_factor_{cat,\ i}$ is the characterization factor of inventory flow *i* for the impact category.

In relation to the optional steps in LCA, normalization is usually needed to show to what extend an impact category has a significant contribution to the overall environmental impact. In the weighting step the normalized indicator results for each impact category are assigned numerical factors according to their relative importance. Weighting is based on value-choices rather than natural sciences, thus the ISO standard 14044 distinguishes between internal and external applications, and if results are intended to be compared and presented to the public, then weighting should not be used.

Grouping is another optional step of life cycle assessment in which impact categories are aggregated into one or more sets. In this case, according to ISO 14044, two possible procedures can be used: sorting of the category indicators on a nominal basis and ranking of the category indicators on an ordinal scale.

This document focuses on the mandatory steps of LCA; therefore, the optional elements referred above are not further addressed in this text.

2.3.3.2 Calculation of potential environmental impacts

It is observed that the aim of LCA is to assess the potential environmental impacts associated with identified inputs and releases. In the following paragraphs a brief introduction to the most common environmental categories in LCA is provided, together with the respective calculation method adopted in the simplified approach described in this document

2.3.3.2.1 Global warming potential (GWP)

The “Greenhouse effect”, represented in Fig. 2.4~~Fig. 2.4~~ is due to the Infrared (IR) gases, which are naturally present in the Earth’s atmosphere (e.g. H_2O, CO_2 and O_3), that absorb the terrestrial (infrared) energy (or radiation) leaving the Earth and reflect some of this heat back to earth, contributing to warm the surface and the lower atmosphere.

The concentration of these gases, also known as Green House Gases (GHG), has been increasing since the industrial period, and is enhancing the natural Earth’s greenhouse effect, causing a temperature rise at the Earth’s surface and giving rise to concern over potential resultant climate changes

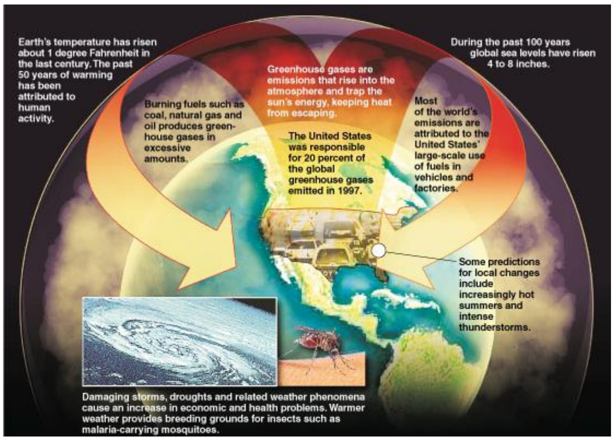


Fig. 2.4: Global warming (EPS, 2009)

Not all GHG are alike. While CO_2 is the most ubiquitous GHG, there are a number of other gases which contribute to climate change in the same way as CO2. The effect of different GHG is reported using Global Warming Potential (GWP).

GWP is a relative measure of the amount of CO_2 which would need to be released to have the same radiative forcing effect as a release of 1 kg of the GHG over a particular time period. GWP is therefore a way of quantifying the potential impact on global warming of a particular gas.

GWPs were calculated by the Intergovernmental Panel on Climate Change (IPCC, 2007) for three time horizons of 20, 100 and 500 years and they are indicated in Table 2.1~~Table 2.1~~ for three of the most important greenhouse gases and for the three time horizons.

Table 2.1 – GWPs for given time horizons (in kg CO_2 eq./kg) (IPCC, 2007)

	20 years	100 years	500 years
Carbon Dioxide (CO_2)	1	1	1
Methane (CH_4)	62	25	7
Nitrous oxide (N_2O)	275	298	156

Hence, according to expression (2.2), the determination of the indicator "Global Warming" is given by,

$$Global\ Warming = \sum_i GWP_i \times m_i$$

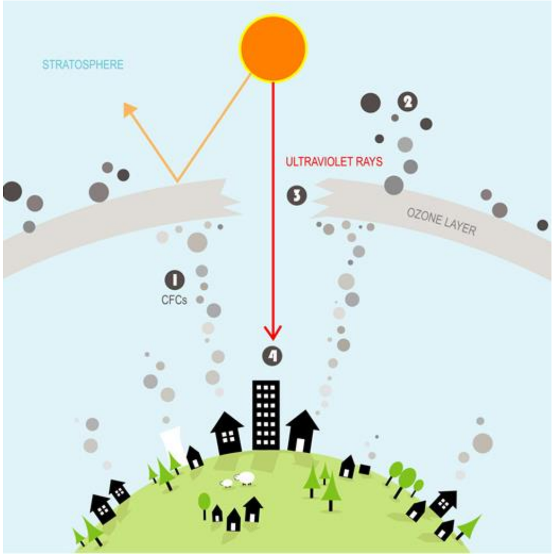
Eq. (2.2)

where, m_i is the mass of substance *i* released (in kg). This indicator is expressed in *kg of CO_2 equivalents*.

In the adopted approach, only the time horizon of 100 years is considered.

2.3.3.2.2 Ozone Depletion Potential (ODP)

Ozone-depleting gases cause damage to stratospheric ozone or the “ozone layer” by releasing free radical molecules which breakdown ozone (O_3).



Damage to the ozone layer reduces its ability to prevent ultraviolet (UV) light entering the earth’s atmosphere, increasing the amount of carcinogenic UVB light hitting the earth’s surface.

This in turn results in health problems in humans such as skin cancer or cataracts and sun related damage to animals and crops.

The major ozone depleting gases are CFCs, HCFCs and halons..

Fig. 2.5: Ozone depletion (Blendspace, 2013)

Growing concern in the 1980s led to world-wide efforts to curb the destruction of the ozone layer, culminating in the Montreal protocol which banned many of the most potent ozone depleting gases.

Ozone depletion potential is expressed as the global loss of ozone due to a substance compared to the global loss of ozone due to the reference substance CFC-11. This gives ODP a reference unit of kg chlorofluorocarbon-11 (CFC-11) equivalent. The characterization model has been developed by the World Meteorological Organization (WMO) and defines the ozone depletion potential of different gases. Hence, OPDs, assuming a steady-state, are indicated in Table 2.2~~Table 2.2~~ for selected substances (Heijungs et al., 1999).

Table 2.2 – *OPDs* for some substances (in kg CFC-11 eq./kg) (Heijungs et al., 1999)

	Steady-state (t ≈:)
CFC-11	1
CFC-10	1.2
Halon 1211	6.0
Halon 1301	12.0

Thus, the determination of the indicator Ozone Depletion is given by,

$$Ozone\ \ Depletion = \sum_i ODP_i \times m_i$$

Eq. (2.3)

where, m_i is the mass of substance *i* released (in kg). This indicator is expressed in *kg of CFC-11 equivalents*.

2.3.3.2.3 Acidification Potential (AP)

Acidification is the process where air pollution (mainly ammonia (NH_3), sulphur dioxide (SO_2) and nitrogen oxides (NO_x)) is converted into acid substances, as illustrated in Fig. 2.6~~Fig. 2.6~~. Acidifying compounds emitted into the atmosphere are transported by wind and deposit as acidic particles or acid rain or snow. When this rain falls, often a considerable distance from the original source of the gas, it causes ecosystem damage of varying degrees, depending upon the nature of the landscape ecosystems.

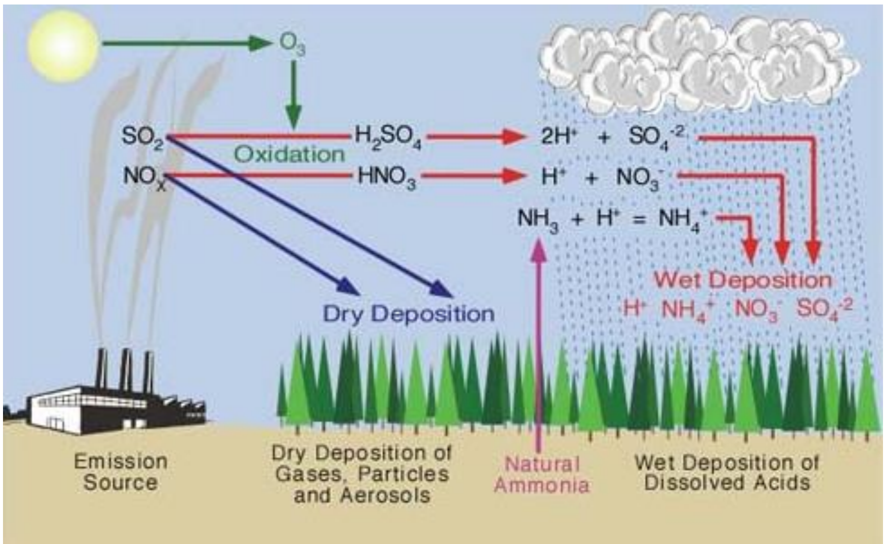


Fig. 2.6: Acidification potential (The energy library, 2013)

Acidification potential is measured using the ability of a substance to release H+ ions, which is the cause of acidification, or it can be measured relative to an equivalent release of SO_2.

The characterisation factors adopted in this work are based in the model RAINS-LCA, which takes fate, background depositions and effects into account (Huijbregts, 2001). Thus, the average European characterisation factors for acidification are represented in Table 2.3~~Table 2.3~~.

Table 2.3 – Acidification potentials (in kg SO_2 eq.) (Huijbregts, 2001)

	Ammonia (NH_3)	Nitrogen Oxide (NO_x)	Sulfur Dioxide (SO_2)
APi	1.60	0.50	1.20

Thus, the determination of the indicator acidification is given by,

$$Acidification = \sum_i AP_i \times m_i$$

Eq. (2.4)

where, m_i is the mass of substance *i* released (in kg). This indicator is expressed in *kg of SO_2 equivalents.*

2.3.3.2.4 Eutrophication Potential (EP)

Nutrients, such as nitrates and phosphates, are usually added to the soil through fertilization to stimulate the growth of plants and agricultural products. These nutrients are essential for life, but when they end up in sensitive natural water or land areas, this unintended fertilization may result in overproduction of plants or algae, which, in turn, can smother other organisms when they die and begin to decay. Therefore, Eutrophication or nutrient enrichment, illustrated in Fig. 2.7~~Fig. 2.7~~, can be classified as the over-enrichment of water courses. Its occurrence can lead to damage of ecosystems, increasing mortality of aquatic fauna and flora and to loss of species dependent on low-nutrient environments. This leads to an overall reduction in the biodiversity of these environments and has knock-on effects on non-aquatic animals and humans who rely on these ecosystems.

Eutrophication is measured using the reference unit of kg nitrogen or phosphate equivalents. As such it is a measure of the extent to which a substance in the water causes the proliferation of algae, with nitrogen or phosphate as the reference substance. The major contributors to eutrophication are nitrogen compounds, such as nitrates, ammonia, nitric acid and phosphoric compounds including phosphates and phosphoric acid.

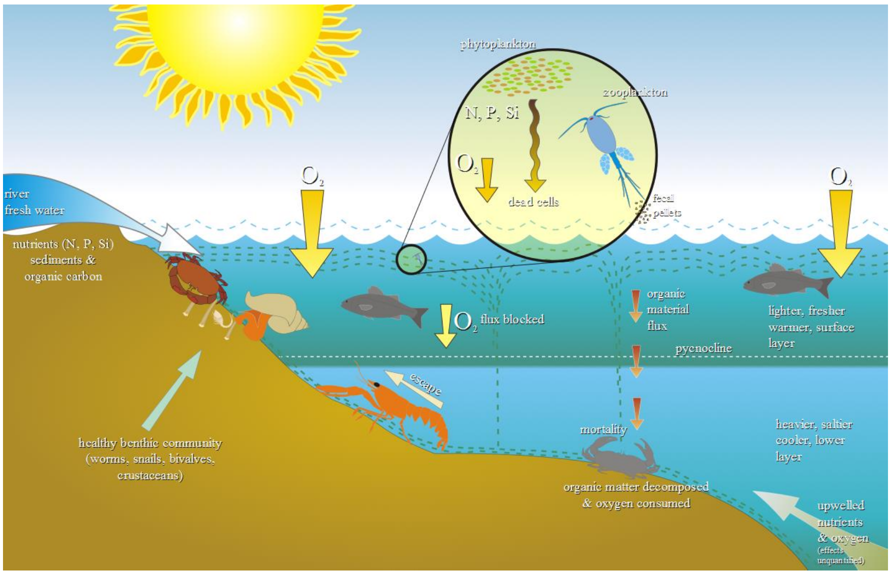


Fig. 2.7: Eutrophication potential (Wikipedia, 2013a)

Taking phosphate as the reference substance, the characterization factors for selected substances are indicated in Table 2.4~~Table 2.4~~ (Heijungs et al., 1999).

Table 2.4 – Eutrophication potentials (in kgPO_4^{3-} eq.) (Heijungs et al., 1999)

	Ammonia (NH_3)	Nitrogen Oxide (NO_x)	Nitrate (N)	Phosphate (P)
EPi	0.35	0.13	0.10	1.00

Hence, the eutrophication indicator is given by,

$$\mathit{Eutrohication} = \sum_i EP_i \times m_i$$

Eq. (2.5)

where, m_i (kg) is the mass of substance *i* released to the air, water or soil. This indicator is expressed in *kg* PO_4^{3-} *equivalents*.

2.3.3.2.5 Photochemical Ozone Creation Potential (POCP)

In atmospheres containing nitrogen oxides (NOx), a common pollutant and volatile organic compounds (VOCs), ozone and other air pollutants can be created in the presence of sunlight. Although ozone is critical in the high atmosphere to protect against ultraviolet (UV) radiation, low level ozone is implicated in impacts as diverse as crop damage and increased incidence of asthma and other respiratory complaints.

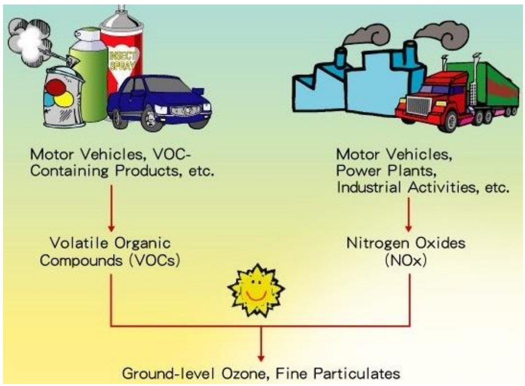


Fig. 2.8: Photochemical Ozone Creation Potential (EPD, 2013)

The most common manifestation of the effects of high levels of POCP-contributing gases is in the summer smogs seen over large cities such as Los Angeles or Beijing. The principal source of NOx emissions is fuel combustion while VOCs are commonly emitted from solvents, which are heavily used in paints and coatings.

The POCP impact category is a measure of the relative ability of a substance to produce ozone in the presence of NOx and sunlight. POCP is expressed using the reference substance ethylene. Characterization factors for POCP have been developed using the United Nations Economic Commission for Europe (UNECE) trajectory model.

POCPs were calculated for two scenarios (Heijungs et al., 1999):

(i) a scenario with a relatively high background concentration of NO_x;

(ii) a scenario with a relatively low background concentration of NO_x.

These two characterization factors are indicated in Table 2.5~~Table 2.5~~ for some selected substances.

Table 2.5 – *POCPs* for different concentration of NO_x and for some substances (in kg C_2H_4 eq./kg) (Heijungs et al., 1999)

	High-NO_x POCPs	Low-NO_x POCPs
Acetaldehyde (CH_3CHO)	0.641	0.200
Butane (C_4H_{10})	0.352	0.500
Carbon monoxide (CO)	0.027	0.040
Ethyne (C_2H_2)	0.085	0.400
Methane (CH_4)	0.006	0.007
Nitrogen oxide (NO_x)	0.028	no data
Propene (C_3H_6)	1.123	0.600
Sulphur oxide (SO_x)	0.048	no data
Toluene ($C_6H_5CH_3$)	0.637	0.500

Thus, the determination of the indicator Photo-oxidant formation is given by,

$$Photo-oxidant\ \ formation = \sum_i POCP_i \times m_i$$

Eq. (2.6)

where, m_i is the mass of substance *i* released (in kg). This indicator is expressed in *kg of ethylene* (C_2H_4) *equivalents*.

In the adopted approach, only the characterization factors relative to the scenario with a high background concentration of NO_x are considered.

2.3.3.2.6 Abiotic Depletion Potential

Abiotic depletion indicators aim to capture the decreasing availability of non-renewable resources as a result of their extraction and underlying scarcity. Two types of indicators are herein considered:

- Abiotic Depletion Elements, addressing the extraction of scarce elements (and their ores);
- Abiotic Depletion Energy/Fossil Fuels, addressing the use of fossil fuels as fuel or feedstock.

Fig. 2.9: Abiotic Depletion Potential (Wikipedia, 2013b)

The Abiotic Depletion Potential for elements ($ADP_{elements}$) is determined for each extraction of elements based on the remaining reserves and rate of extraction. The ADP is based on the equation Production/Ultimate Reserve which is compared to the reference case, Antimony (Sb) (Guinée et al., 2002). Different measures use the economic or ultimate reserve within the earth's crust.

Therefore, the Abiotic Depletion Potential (Elements) of resource *i* (ADP_i) is given by the ratio between the quantity of resource extracted and the recoverable reserves of that resource, expressed in kg of the reference resource, Antimony, and the characterization factors for some selected resources are indicated in Table 2.6~~Table~~

Table 2.6 – Abiotic depletion potentials for some elements (in Sb eq./kg) (Guinée et al., 2002)

Resource	ADP element
Aluminium	1.09E-09
Cadmium	1.57E-01
Copper	1.37E-03
Iron	5.24E-08
Lead	6.34E-03

Thus, the determination of the indicator Abiotic Depletion (Elements) is given by,

$$Abiotic\ Depletion = \sum_i ADP_i \times m_i$$

Eq. (2.7)

where, m_i is the quantity of resource *i* extracted (in kg). This indicator is expressed *in kg of antimony* (the reference resource).

Fossil Fuels were originally measured in the same way, but since 2010 they have been calculated slightly differently. In this case, an absolute measure is considered, based on the energy content of the fossil fuel (Guinée et al., 2002). This does not take into account the relative scarcity of different fossil fuels as fossil fuels are largely transferable resources, but in reality these only vary by 17% between coal (the most common) and gas (the most scarce). The indicator Abiotic Depletion Fossil is expressed in MJ.

2.3.4 Life cycle interpretation

Interpretation is the last step of LCA, in which the findings from the inventory analysis and the impact assessment are combined together. The main aim of this stage is to formulate the conclusions that can be drawn from the results of the LCA. In addition, the results of previous stages of LCA and the choices made during the entire process should be analyzed, namely the assumptions, the models, the parameters and data used in the LCA should be consistent with the Goal and Scope of the study.

2.3.5 Illustrative example

In order to illustrate the different steps of life cycle assessment described in the previous paragraphs, a small example is herein provided.

Assuming that for the production of 1 kg of a generic insulation material, the following emissions (see Table 2.7~~Table 2.7~~) were collected in the inventory stage:

Table 2.7 – Emissions collected from the production of 1 kg of an insulation material

Emissions	Value (in kg)
carbon monoxide (CO)	0.12
carbon dioxide (CO_2)	0.60
ammonia (NH_3)	0.01
methane (CH_4)	0.05
nitrogen oxides (NO_x)	1.02
phosphorus (P)	0.35
sulfur dioxide (SO_2)	0.10

Then, in the following step, the impact assessment, the selected environmental categories are, for instance:

(i) global warming potential (GWP),
(ii) acidification potential (AP),
(iii) eutrophication potential (EP).

The characterization factors of each emission for each environmental category are provided in Table 2.8~~Table 2.8~~.

Formatiert: Englisch (USA)

Table 2.8 – Characterization factors for selected environmental categories

	GWP	**AP**	**EP**
	(kg CO_2 eq.)	**(kg SO_2 eq.)**	**(kg PO_4- eq.)**
carbon monoxide (CO)	1.53	-	-
carbon dioxide (CO_2)	1.00	-	-
ammonia (NH_3)	-	1.60	0.35
methane (CH_4)	25.00	-	-
nitrogen oxides (NO_x)	-	0.50	0.13
phosphorus (P)	-	-	3.06
sulfur dioxide (SO_2)	-	1.20	-

Hence, the results of each environmental category are obtained from the product of each contributing emission by its respective characterization factor (e.g., for GWP: 0.12 x 1.53 + 0.60 x 1.00 + 0.05 x 23 = 1.93 kg CO_2 eq.) leading to the results indicated in Table 2.9~~Table 2.9~~.

Table 2.9 – Final results of the selected environmental Indicators

GWP (kg CO_2 eq.)	**AP (kg SO_2 eq.)**	**EP (kg PO_4- eq.)**

1.93	0.65	1.21

2.4 European standards for life cycle assessment of buildings

2.4.1 CEN TC350

The European Committee for Standardization (CEN) was mandated in 2004 for the development of horizontal standardised methods for the assessment of the integrated environmental performance of buildings.

CEN TC350 expanded this mandate to sustainability, and opted for a life cycle approach as the basis for all assessment. Hence, the TC develops standards, technical reports and technical specifications to provide methodology and indicators for the sustainability assessment of buildings.

The normative framework for the sustainability assessment of buildings, provided by CEN-TC 350 series of standards, covers environmental, economic and social aspects (EN 15643-1, 2010), as illustrated in Fig. 2.10~~Fig. 2.10~~.

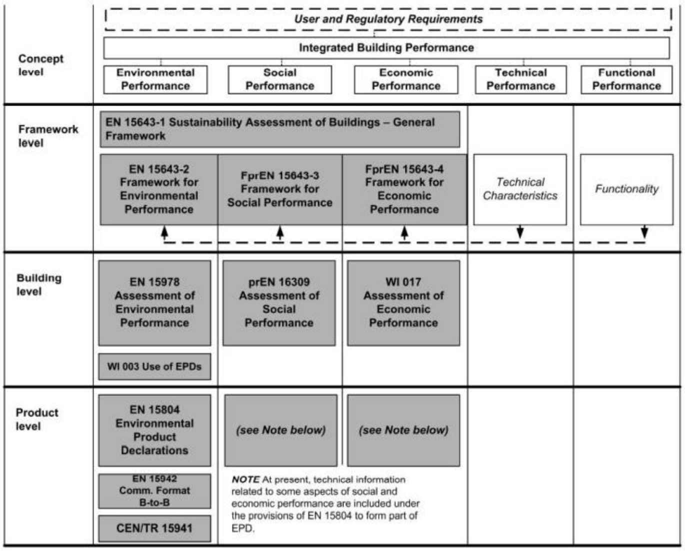


Fig. 2.10: Work program of the CEN TC350 (EN 15643-1, 2010)

As observed from Fig. 2.10~~Fig. 2.10~~, the TC works at four levels (concept/ framework/ building/ product) and for five types of performances (environmental/ social/ economic/ technical/ functional). The environmental assessment is the most advanced aspect, with standards developed at the building level and at the product level.

The life cycle environmental approach adopted in this project follow the two standards dedicated to the evaluation of the environmental impacts of buildings: the EN 15978 (2011) and the EN 15804 (2012), for the building and material levels, respectively.

2.4.2 Building level (EN 15978)

EN 15978 (2011) provides calculation rules for the assessment of the environmental performance of new and existing buildings based on a life cycle approach. It is intended to support the decision-making process and documentation of the assessment of the environmental performance of a building.

For a complete overview of the methodology the reading of the standard is referred; this section focuses on the following key aspects: functional equivalent, life cycle stages and environmental indicators.

2.4.2.1 Functional equivalent

The functional equivalent is defined by the standard as the "quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison". Hence, comparison between buildings or systems will only be acceptable if the functions provided are the same. At least the following aspects shall be included in the functional equivalent of a building:

(i) building typology (e.g. residential, office, etc);
(ii) pattern of use;
(iii) relevant technical and functional requirements; and
(iv) required service life.

2.4.2.2 Life cycle stages

The system boundaries establish the scope of the life cycle analysis, i.e., determines the processes that are taken into account in the analysis. As stated in the standard, the environmental assessment "includes all upstream and downstream processes needed to establish and maintain the function(s) of the building".

Of course, information linked to the products integrated in the building is required to assess the environmental performance at building level. This information should be consistent, and therefore follow the category rules defined in EN 15804 (see next sub-section).

In this standard the life cycle of the building is represented by a modular concept as illustrated in Fig. 2.11.

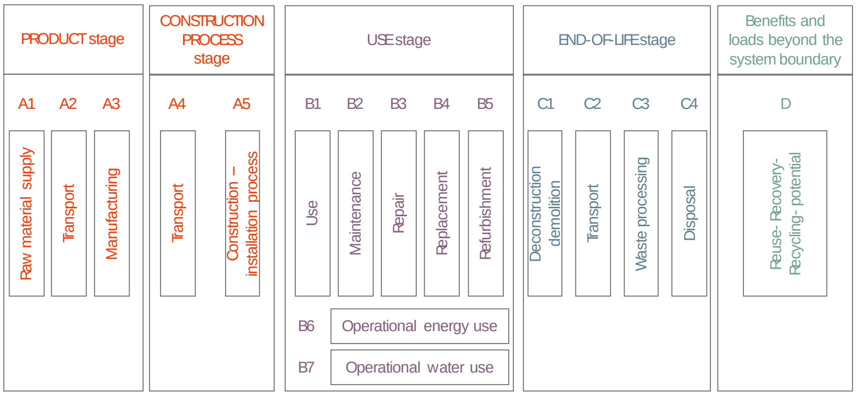


Fig. 2.11: Modules of a building life cycle (EN 15978, 2011)

The production stage includes modules A1 to A3, the construction stage includes modules A4 and A5, the use stage includes modules B1 to B7, the end-of-life stage modules includes C1 to C4, and module D that includes the benefits and loads beyond the system boundary. In the following paragraphs a brief description of each stage and corresponding modules is provided.

2.4.2.2.1 Product stage

The product stage includes the information modules A1 to A3. The system boundary with nature is set to include those processes that provide the material and energy inputs into the system and the following manufacturing, and transport processes up to the factory gate as well as the processing of any waste arising from those processes. This stage includes:

- ✓ A1 - Extraction and processing of raw materials; reuse of products or materials from a previous product system; processing of secondary materials used as input for manufacturing the product;
- ✓ A2 - Transportation up to the factory gate and internal transport;
- ✓ A3 - Production of ancillary materials, manufacturing of products and by-products; and manufacturing of packaging.

2.4.2.2.2 Construction stage

The construction process stage includes the information modules for:

- ✓ A4 - Transportation from the production gate to the construction site;

- ✓ A5 - Installation of the product into the building including manufacture and transportation of ancillary materials and any energy or water required for installation or operation of the construction site. It also includes on-site operations to the product.

2.4.2.2.3 Use stage

The use stage includes two types of information modules. Modules related to the building fabric (modules B1-B5) and modules related to the operation of building (modules B6-B7):

- ✓ B1 - Use of the installed product in terms of any emissions to the environment arising from components of the building and construction works during their normal (i.e. anticipated) use;
- ✓ B2 - Maintenance covers the combination of all planned technical and associated administrative actions during the service life to maintain the product installed in a building in a state in which it can perform its required functional and technical performance, as well as preserve the aesthetic qualities of the product;
- ✓ B3 - Repair covers a combination of all technical and associated administrative actions during the service life associated with corrective, responsive or reactive treatment of a construction product or its parts installed in the building to return it to an acceptable condition in which it can perform its required functional and technical performance;
- ✓ B4 - Replacement covers the combination of all technical and associated administrative actions during the service life associated with the return of a construction product to a condition in which it can perform its required functional or technical performance, by replacement of a whole construction element;
- ✓ B5 - Refurbishment covers the combination of all technical and associated administrative actions during the service life of a product associated with the return of a building to a condition in which it can perform its required functions;
- ✓ B6 - Energy use to operate building integrated technical systems, together with its associated environmental aspects and impacts including processing and transportation of any waste arising on site from the use of energy;
- ✓ B7 - Operational water use by building integrated technical systems, together with its associated environmental aspects and impacts considering the life cycle of water including production and transportation and waste water treatment.

2.4.2.2.4 End-of-life stage

The end-of-life stage of the building includes all outputs that have reached the "end-of-waste" state, resulting from dismantling, deconstruction or demolition of the building. The end-of-life stage includes the optional Information modules:

- ✓ C1 - Deconstruction, including dismantling or demolition, of the product from the building, including initial on-site sorting of the materials;
- ✓ C2 - Transportation of the discarded product as part of the waste processing, e.g. to a recycling site and transportation of waste e.g. to final disposal;
- ✓ C3 - Waste processing e.g. collection of waste fractions from the deconstruction and waste processing of material flows intended for reuse, recycling and energy recovery.
- ✓ C4 - Waste disposal including physical pre-treatment and management of the disposal site.

2.4.2.2.5 Benefits and loads beyond the product system boundary

Information module D includes all the net benefits or loads resulting from reusable products, recyclable materials and/or useful energy carriers leaving a product system e.g. as secondary materials or fuels.

2.4.2.3 Life Cycle Impact Assessment

For the stage of life cycle impact assessment, two types of environmental categories are considered according to EN 15978: environmental indicators describing environmental impacts and environmental indicators describing input and output flows. Both types of indicators are indicated in the following paragraphs.

2.4.2.3.1 Indicators describing environmental impacts

Six indicators are provided for the description of the impacts on the natural environmental, which are indicated in Table 2.10~~Table 2.10~~.

Table 2.10 – Indicators describing environmental impacts (EN15978)

Indicator	**Unit**
Global warming potential, GWP	kg CO_2 equiv
Depletion potential of the stratospheric ozone layer, ODP;	kg CFC 11 equiv
Acidification potential of land and water; AP;	kg SO^{2-} equiv

Eutrophication potential, EP;	kg $(PO_4)^{3-}$ equiv
Formation potential of tropospheric ozone photochemical oxidants, POCP;	kg Ethene equiv
Abiotic Resource Depletion Potential for elements; ADP_elements	kg Sb equiv
Abiotic Resource Depletion Potential of fossil fuels ADP_fossil fuels	MJ

These indicators were already presented in the previous section of this document.

2.4.2.3.2 Indicators describing input and output flows

Additional indicators are deemed for describing inputs and output flows. Therefore, indicators describing the resource use are indicated in Table 2.11~~Table 2.11~~. These indicators describe the use of renewable and non-renewable primary energy and water resources and they are calculated directly from input flows of the LCI.

Table 2.11 – Indicators describing resource use (EN15978)

Indicator	Unit
Use of renewable primary energy excluding energy resources used as raw material	MJ, net calorific value
Use of renewable primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy excluding primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy resources used as raw material	MJ, net calorific value
Use of secondary material	kg
Use of renewable secondary fuels	MJ
Use of non-renewable secondary fuels	MJ
Use of net fresh water	m^3

Also directly based on the input flows of the LCI are the indicators describing waste categories and categories and output flows. The former are indicated in Table 2.12~~Table 2.12~~ and the latter in

Table 2.13~~Table 2.13~~. Moreover, for the quantification of these indicators, scenarios are established for the appropriate processes and stages.

Table 2.12 – Indicators describing waste categories (EN15978)

Indicator	Unit
Hazardous waste disposed	kg

Non-hazardous waste disposed	kg
Radioactive waste disposed	kg

Table 2.13 – Indicators describing the output flows leaving the system (EN15978)

Indicator	Unit
Components for re-use	kg
Materials for recycling	kg
Materials for energy recovery (not being waste incineration)	kg
Exported energy	MJ for each energy carrier

2.4.3 Product level (EN 15804)

At the product level, EN 15804 standard defines the product category rules to develop Environmental Product Declarations (EPD) of construction products. EPDs are Type III environmental declarations, according to ISO 14025 (2006) and are often a good source of environmental data for a life cycle analysis.

An EPD is a particular type of LCA, conducted using a defined set of Product Category Rules (PCR), as illustrated in Fig. 2.12. Many PCR can be used for construction products (CPA, 2012) but only EPD following the same PCR can be compared.

Fig. 2.12: EPD process as described in CPA (2012)

The objective of the common set of rules in EN 15804 is to provide the assessor consistent, comparable and reliable information allowing aggregation at the building level.

The calculation rules for the LCA at the material level are similar with the ones described before at the building level. The scope of an LCA carried out at the material level may be the same as the one described for the building level (see Fig. 2.11). However, only the declaration of the product stage (modules A1 to A3) is mandatory in EN 15804, the declaration of the other life cycle stages is optional.

Likewise, in this standard the functional unit provides a reference by which material flows of construction product´s LCA results are normalized. However, in this standard, an additional unit is provided: the declared unit. The declared unit may be used instead of the functional unit when the function of the product at the building level is not stated or is unknown.

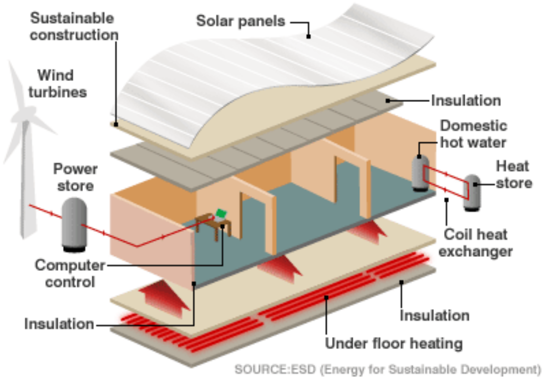
2.5 Other standards and regulations (mainly for the use phase)

As previously mentioned, EN15978 (2011) assigns all potential environmental impacts of all aspects related with the building throughout its life cycle in a modular system (Fig. 2.11). In this system, Module B6 corresponds to the operational energy, i.e., energy used by building-integrated technical systems during the operation stage. Thus, it includes the consumption of energy for space cooling, space heating, domestic hot water (DHW) supply, ventilation, lighting and auxiliary energy used for pumps, control and automation. However, EN15978 does not provide the rules for energy calculation; however, it refers that it should comply with the Energy Performance of Building Directive (EU 2002) and its National implementations.

The Directive on energy performance of buildings is the main legislative instrument at EU level to achieve energy performance in buildings. The four key issues of the EPBD to be applied by the Member States are as follows (EU 2002):

- ✓ Common methodology for calculating the integrated energy performance of buildings;
- ✓ Minimum standards on the energy performance of new buildings and existing buildings that are subject to major renovation;
- ✓ Systems for the energy certification of new and existing buildings and, for public buildings, prominent display of this certification and other relevant information.
- ✓ Regular inspection of boilers and central air-conditioning systems in buildings and in addition an assessment of heating installations in which the boilers are more than 15 years old.

The recast of the EPBD (in 2010) sets a legal framework to upgrade the national building codes and presents a policy of nearly zero energy buildings, so that all new buildings will be nearly zero energy as of 2020 (e.g. key features for zero carbon buildings are indicated in Fig. 2.13).



SOURCE:ESD (Energy for Sustainable Development)

Fig. 2.13: Zero carbon house key features

Despite the general requirements provided by the EPBD, it does not provide the calculation method and each Member State in EC is allowed to choose their own implementation. Most countries claim to use CEN standards or other international standards to some extent. In this respect, two additional standards are considered in this document:

(i) ISO 13790 (2008), which covers all aspects of the heat components involved in the thermal calculations and provides correlation factors to take dynamic thermal effects into account in the calculation,

(ii) EN 15316-3-1 (2007) which addresses the energy needs for Domestic Hot Water (DHW) production.

3 SIMPLIFIED METHODOLOGIES FOR BUILDING ASSESSMENT

3.1 Introduction

The construction sector is increasingly subjected to sustainability pressures: environmental product declarations, low energy building, etc. However, stakeholders are not always properly trained to be able to analyse the environmental performances of construction products.

Thermal performances of new buildings have been framed by regulations for a few years, compelling architects to have a good control and knowledge of the use phase of buildings. On the opposite, embodied energy and carbon footprint of materials are less known, but progressively integrated in calls for tenders. Few actors of the sector have the expertise to address both aspects.

Therefore, in order to foster the implementation of life cycle analysis in the building sector, this chapter introduces two simplified approaches:

(i) an approach for simplified life cycle approach based on macro-components;

(ii) an approach for the calculation of the energy needs of a building for space cooling and space heating, which includes the energy need for domestic hot water production.

Both approaches were developed in the scope of the European Research project *SB_Steel* (2014) and they are based on the principles of the recent European standards EN 15978 and EN 15804.

First, the approach for life cycle assessment is described, followed by the simplified approach for energy calculation and respective calibration procedure.

3.2 Algorithm for life cycle assessment based in macro-components

The building fabric, external and internal, plays a major role in the behaviour of the building in terms of the energy consumption and environmental burdens. This led the way for the creation of pre-assembled solutions for the main components of the building, i.e., the macro-components. Therefore, macro-components are pre-defined assemblages of different materials that fully compose the same component of a building (Gervásio et al., 2014).

For each building component different solutions were pre-assembled and the model used for the life cycle analysis of building, based on macro-components, is detailed in the following paragraphs.

3.2.1 General steps

3.2.1.1 Goal and scope

The goal of the tool is to quantify the environmental impacts of a simple building or building components (in m^2), using predefined macro-components. Therefore, the approach enables the assessment to be made at two different levels: (i) the component level; and (ii) the building level.

3.2.1.1.1 Functional unit

At the building level, the functional unit is a building with a defined typology (e.g. residential, office, etc) designed for a predefined period of life (e.g. 50 years) fulfilling all the standard requirements.

At the level of a building component, the functional unit (in m^2) is a building component with a defined typology (e.g. external wall, internal slab, etc) used for a period of life (e.g. 50 years). In this case, the function of the building component may be included or not (in case of comparative assertions, then the function of the building component should be included).

3.2.1.1.2 System boundaries

The life cycle environmental analysis comprehends the stage of material production (modules A1 to A3), the construction stage (module A4), the use stage (modules B1 to B5), the end-of-life stage (modules C1 to C4) and the benefits and loads due to recycling processes (module D), as indicated in Table 3.1.

Module B6 is not considered in this approach. However, the methodology presented in the next section addresses the aspects included in this module

Likewise, 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) were found to be neglected at the building level (Gervásio et al., 2014).

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.

Table 3.1: Building life-cycle information modules (according to EN 15643-2:2011)

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

Considering that nowadays due to strict material legislation construction materials are low-emission, this module has little importance. Finally, the quantification of water use (module B7) is not considered as it does not depend on the construction options.

3.2.1.2 Life Cycle Inventory

As previously indicated, data quality check is a requirement of LCA standards. Therefore, in relation to construction products, data should be checked in terms of (EN 15804):

- Time coverage: data sets shall have been updated within the last 10 years for generic data and within the last 5 years for producer specific data;
- Data sets shall be based on 1 year averaged data;
- Geographical coverage: data sets shall reflect the geographical area for the declared product or product group;
- Technology coverage: data sets shall reflect the physical reality for the declared product or product group;
- Completeness: Data sets shall be complete according to the system boundary within the limits set by the criteria for the exclusion of inputs and outputs.

Most environmental datasets are provided from the PE International database (2006), except for the steel data. In addition, the steel datasets are provided by Worldsteel Association (2002) in collaboration with PE International. Therefore the methodology is very similar. This ensures a good consistency in terms of data collection and management, as well as methodology for allocation and cut off rules, as shown in Table 3.2, for the main materials used in the macro-components.

Table 3.2: Quality check for the main materials of the macro-components

3.2.1.3	Time coverage	Geographical coverage	Technology coverage	Completeness
Steel section	2007, annual average	Europe	European producers	> 99% of mass and energy
Steel rebar	2007, annual average	World	World producers	> 99% of mass and energy
Steel coil	2007, annual average	Europe	European producers	> 99% of mass and energy
Concrete C20/25	2011, annual average	Germany	German producers	> 95% of mass and energy
Oriented strand board OSB	2008, annual average	Germany	German producers	> 99% of mass and energy
Gympsum plasterboard	2008, annual average	Europe	European producers	> 95% of mass and energy
Bricks	2011, annual average	Germany	German producers	> 95% of mass and energy
Rock wool	2011, annual average	Europe	European producers	> 95% of mass and energy
Expanded polystyrene EPS	2011, no data	Europe	No data	No data
Extruded polystyrene XPS	2011, annual average	Germany	German producers	> 95% of mass and energy
Polyurethane rigid foam PUR	2011, annual average	Germany	German producers	> 95% of mass and energy
Expanded Cork	2011, annual average	Germany	German producers	> 95% of mass and energy
Glass wool	2011, annual average	Europe	European producers	> 95% of mass and energy
Polyethylene foam PE	2011, annual average	Germany	German producers	> 95% of mass and energy

3.2.1.4 *Life Cycle Impact Assessment*

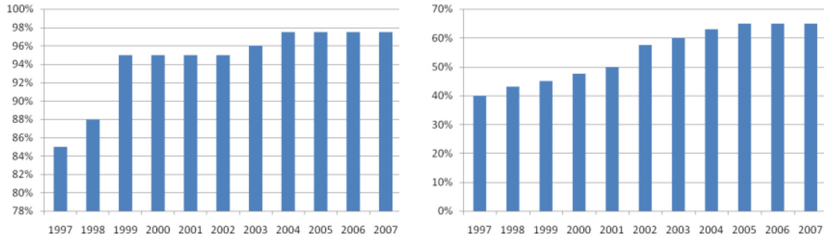
The environmental categories selected to describe the environmental impacts of the building are indicated in Table 2.10~~Table 2.10~~ and correspond to the environmental categories recommended in the European standards for the assessment of environmental performance of buildings (EN 15643-2 and EN 15978).

The modular concept of the aforementioned standards was adopted in the approach. Therefore, the output of the life cycle environmental analysis of each macro-component is provided per module or by the aggregate value of each stage.

The life cycle environmental analysis of each macro-component was performed by GaBi software (2012).

3.2.2 Allocation of recycling materials

Steel is 100% recyclable and scrap can be converted to the same quality of steel depending upon the metallurgy and recycling route (Worldsteel Association, 2009). Therefore, in the end-of-life of a steel structure, the structure is most probably dismantled and steel is sent for recycling or reusing (partially or completely). According to data from the Steel Recycling Institute (2009), in North America, the recycling rate of structural steel is about 97.5%. Graphs represented in Fig. 3.1, show the trend of the recycling rates of structural steel and reinforcement steel in the construction sector, respectively.



(a) (b)

Fig. 3.1: Recycling rates of (a) structural steel and (b) reinforcement steel (Steel Recycling Institute, 2009)

The reuse and recycling of steel is a multi-functionality issue, requiring the use of an allocation process, as described in the following text.

3.2.2.1 Introduction

Most industrial processes are multifunctional, i.e., their output entails more than one product and the inputs for the production of products often include intermediate or discarded products. An allocation problem occurs when an appropriate decision is needed in order to allocate the input/output flows to the functional unit provided by the product system under study.

Allocation is defined in ISO 14040 (2006) as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product system”. Thus, an allocation process addresses the partition of flows between unit processes or product systems.

According to ISO 14044 (2006), allocation should be avoided either by dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes or by expanding the product system to include the additional functions related to the by-products (system expansion).

System expansion includes the avoided burden approach, which eliminates surplus-functions from the multifunctional process by subtracting equivalent mono-functional processes to obtain a mono-functional process.

When neither subdivision of processes nor system expansion are feasible for the scope and goal of the study, then allocation is unavoidable. In this case, two alternatives are recommended by ISO 14044 (2006): (i) the partition of inputs and outputs of the system is based on physical (or chemical or biological) causal relationships; or (ii) the allocation is based on other relationships (e.g. economic value of the products).

The consideration of reuse and recycling of materials is a multi-functionality issue, implying the use of allocation processes. The allocation principles and procedures mentioned above also apply to recycling and reuse situations, although in this case, the changes in the inherent properties of materials shall be taken into consideration when choosing the allocation procedure to be used I(SO 14044, 2006).

In this case, three main situations may occur (Werner, 2005):

i) Material’s inherent properties are not changed over the considered product system and the material is to be reused in the same application;

ii) Material’s inherent properties are changed over the considered product system and the material is to be reused in the same application;

iii) Material’s inherent properties are changed over the considered product system and the material is to be used in other applications.

In the first case, there is a closed-loop situation in which the substitution of primary material is assumed to be complete and therefore, no environmental burdens from primary material production or final disposal are allocated to the product system. The second case corresponds to an open-loop approach assuming a closed-loop situation. In this case, the changed material properties are considered irrelevant and recycling is addressed as a closed-loop situation. Finally, in the last case, there is an open-loop situation where the substitution of primary material is assumed to be partial. In this case, environmental burdens due to primary material production or final disposal have to be partially allocated to the system under study.

According to ISO 14044 (2006), in the case of a closed-loop situation allocation is avoided since the use of secondary material replaces the use of raw materials.

3.2.2.2 Avoiding scrap allocation

During the life cycle of steel, scrap arises from the manufacture phase, the final processing phase and the end-of-life phase (see Fig. 3.2). Thus, an allocation procedure has to be taken into account for scrap outputs from the whole life system. Furthermore, as described further down in the text, steel is processed via different production routes, and the allocation of scrap inputs to steelmaking is another issue to be considered.

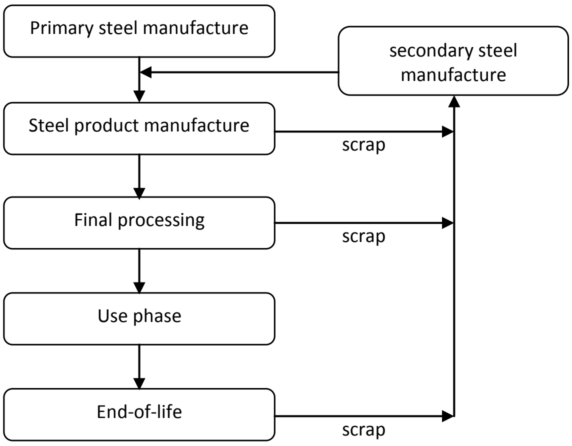


Fig. 3.2: System boundary of LCI including end-of-life data on scrap (LCI, 2002)

Finally, steel can be recycled or reused many times and an appropriate allocation method is needed to address multiple recycling and reuse of steel components.

Therefore, the adopted methodology to address the allocation problem of steel is the closed material loop recycling approach developed by the Worldsteel Association (LCI, 2002). This methodology was developed in order to generate LCI data of steel products, accounting for end-of-life recycling. The adoption of a closed-loop approach is justified by the fact that scrap is re-melted to produce new steel with little or no change in its inherent properties. In this case, following the guidance of ISO standard 14044, the need for allocation is avoided since the use of secondary material replaces the use of raw (primary) materials.

Steel may be produced through two main routes: the Blast Furnace (BF) route and the Electric Arc Furnace (EAF). The main difference between the two routes is the input of scrap in the steelmaking process: in the BF route, steel is produced almost exclusively from raw materials; while, in the EAF route, the production of steel is based mostly on scrap inputs.

Thus, considering the two main routes for steel processing, and assuming the LCI data for steel production via the BF route (assuming 100% raw material) given by X_{pr} and the LCI data for steel production via the EAF route (assuming 100% secondary steel) given by X_{re}, then the LCI data associated with scrap is given by expression (3.1)

$$LCI_{scrap} = Y\left(X_{pr} - X_{re}\right)$$

Eq. (3.1)

where, *Y* is the metallic yield, representing the efficiency of the secondary process in converting scarp into steel. According to the worldsteel association (LCI, 2002), about 1.05 kg of scrap is required to produce 1 kg of secondary steel.

Considering the BF route, assuming 100% input of raw material and a recovery rate (fraction of steel recovered as scrap over the life cycle of a steel product) of RR, then, at the end of the life-cycle, the net scrap produced is given by RR. Therefore, the LCI for 1 kg of steel, including the end of life, is given by the LCI for primary manufacture with a credit for the scrap produced, as given by expression (3.2)

$$LCI = X_{pr} - RR\left[Y\left(X_{pr} - X_{re}\right)\right]$$

Eq. (3.2)

On the other end, assuming that 1 kg of secondary steel is used to produce new steel via the EAF route, and at the end of life RR kg of steel is recovered for recycling, then, the net scrap consumed is given by (1/Y – RR). In this case, the LCI for 1 kg of steel, including the end of life, is given by the LCI for secondary manufacture with a debit for the scrap consumed, as expressed by (3.3)

$$LCI = X_{re} + \left(1/Y - RR\right)\left[Y\left(X_{pr} - X_{re}\right)\right]$$

Eq. (3.3)

Rearranging expression (3.3) it leads to expression (3.2), indicating that the LCI of the system does not depend upon the source of the material. It depends on the recycling ratio of steel at the end of life and the process yield associated with the recycling process. Hence, expression (3.3) allows allocating steel scrap independently of the production route of steel.

The previous expressions were derived assuming 100% primary production or 100% secondary production. In reality, steel products produced via the primary route may also include some scrap consumption and products from the EAF may also include a small percentage of raw materials. In this case, the debit or credit given by expression (3.1) may be re-written as:

$$LCI_{scrap} = (RR - S) \times Y\left(X_{pr} - X_{re}\right)$$

Eq. (3.4)

where, *(RR - S)* represents the net scrap at the end-of-life. Considering the LCI data of a finished steel product given by *X'*, then the LCI for the product, including the end-of-life recycling, is given by,

$$LCI = X' - \left[\left(RR - S \right) \times Y \left(X_{pr} - X_{re} \right) \right]$$

Eq. (3.5)

Expression (3.5) is adopted in the LCA methodologies presented in the next chapter, to produce LCI data for steel products, including recycling at the end-of-life.

3.2.3 Characterization of macro-components

Macro-components were defined for different building components according to the UniFormat classification scheme (2010). The following categories are considered: (A) Substructure, (B) Shell and (C) Interiors. Each main category is further sub-divided. The detailed classification scheme is represented in Table 3.3.

Table 3.3: Building component classification scheme (UniFormat, 2010)

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

Within each building component (see Table 3.3) the corresponding macro-components have the same function and have similar properties. The functional unit of each macro-component is 1 m^2 of a building component with similar characteristics, to fulfil a service life of 50 years.

This approach was developed for building assessment in early stage of design (Gervásio et al., 2014). Therefore, to cope with the lack of design data at early stages of design, the load bearing structure (for a hot-rolled structure, a light-weight steel structure or a concrete structure) is allocated to the macro-components referring to Floor structural frame (B1010.10) or Roof structural frame (B1020.10), per m^2.

The information provided by each macro-component is illustrated by the example in Table 3.4. Apart from the characteristics of the different layers of materials, the coefficient of thermal transmittance (U) (taking into account thermal bridges if applicable) and the thermal inertia (κ_m) are also provided to enable for the quantification of the operational energy of the building.

The macro-components were compiled into a database, which is provided in Appendix 1 of this document.

3.2.4 Illustrative example of a macro-components assemblage

In some cases, in order to fulfil the function of a building component, different macro-components have to be considered simultaneously. An illustrative example is herein provided for an interior slab of a residential building.

3.2.4.1 Assemblage of macro-components

For an interior slab of a building the following macro-components are selected:

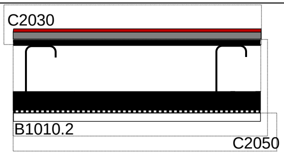
(i) a macro-component for flooring (C2030),
(ii) a macro-component for a floor structural system (B1010.10),
(iii) a macro-component for ceiling finishes (C2050).

The selected assemblage of macro-components is illustrated in Table 3.4.

In this case, the value of thermal transmittance (U) is not provided as the macro-component corresponds to an interior slab and therefore, it does not influence the calculation of energy needs.

Table 3.4: Macro-components assemblage for an interior slab

Macro-components assemblage	Macro-components	Material	Thickness (mm)/ Density (kg/m^2)	U-value (W/m^2. K)	κ_m (J/m^2. K)
	C2030 Flooring	Ceramic tiles	31 kg/m^2		

		Concrete screed	13 mm	-	61062
	B1010.10 Floor structural system	OSB	18 mm		
		Air cavity	160 mm		
		Rock wool	40 mm		
		Light weight steel	14 kg/m^2		
		Gypsum board	15 mm		
	C2050 Ceiling finishes	Painting	0.125 kg/m^2		

3.2.4.2 Functional unit and estimated service life of materials

The functional unit of the building component is an interior slab (per m^2) of a residential building, with a required service life of 50 years. The selected macro-components have to fulfil the same functional unit of the building component. Therefore, the estimated service life of the different materials has to be taken into account. Table 3.5 indicates the estimated service life of the materials.

Table 3.5: Estimated service life of the materials

Macro-component	Material	Unit	Estimated service life [years]
Flooring	Ceramic tiles	m^2	25
	Concrete screed	m^2	50
Floor structural system	Cold Formed Steel	kg/m^2	50
Floor deck	Rock wool	m^2	50
	OSB	m^2	50
	Gypsum Board	m^2	50
Ceiling finishes	Paint	m^2	10

Therefore, in order to fulfil the functional unit, some of the materials have to be replaced or rehabilitated according to a pre-defined scenario.

3.2.4.3 Scenarios and assumptions

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

The functional unit 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 and EN 15978.

3.2.4.3.1 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.

3.2.4.3.2 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.

3.2.4.3.3 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 3.6. 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 3.6: 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 the remaining materials were considered to be sent to a landfill of inert materials.

3.2.4.4 Environmental analysis

The results of the macro-component assemblies illustrated in Table 3.4, are represented in Table 3.7, per m^2.

Table 3.7: Life cycle environmental analysis of macro-components (per m^2)

Impact category	A1-A3	A4	B4	C2	C4	D	TOTAL
ADP elem. [kg Sb-Eq.]	1.86E-03	6.59E-09	1.83E-03	5.76E-09	5.93E-07	-1.96E-04	3.49E-03
ADP fossil [MJ]	1.31E+03	2.45E+00	8.12E+02	2.14E+00	2.31E+01	-3.35E+02	1.82E+03
AP [kg SO_2 Eq.]	2.47E-01	7.91E-04	9.14E-02	6.85E-04	1.01E-02	-4.45E-02	3.05E-01
EP [kg PO_4^- Eq.]	2.61E-02	1.82E-04	1.40E-02	1.57E-04	1.54E-03	-1.01E-03	4.09E-02
GWP [kg CO_2 Eq.]	8.38E+01	1.77E-01	6.48E+01	1.54E-01	6.80E+00	-1.45E+01	1.41E+02
ODP [kg R11 Eq.]	2.80E-06	3.09E-12	2.04E-06	2.70E-12	1.27E-09	1.76E-07	5.01E-06
POCP [kg Ethene Eq.]	3.41E-02	-2.58E-04	1.43E-02	-2.23E-04	2.62E-03	-1.07E-02	3.98E-02

The contribution analysis per module is displayed in Fig. 3.3. Modules A1-A3 predominate for all impact categories (above 50% for most environmental categories), followed by Module B4 with a contribution varying from 10% to 20%. Module D has a significant contribution (close to 10%) for most impact categories. Less significant is the contribution of module C4 (close to 5% in some cases), followed by the remaining modules, with a negligible importance.

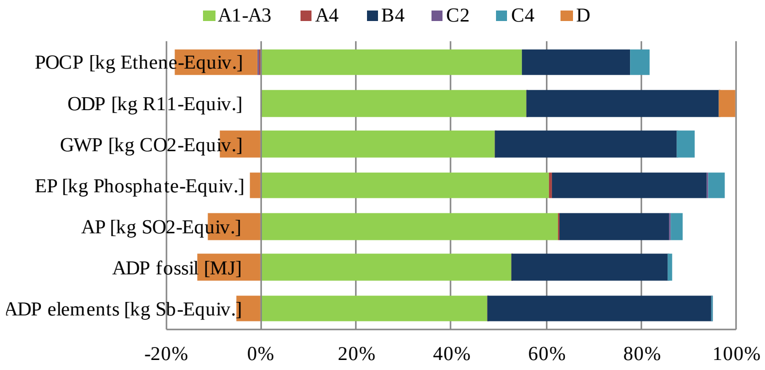


Fig. 3.4: Life cycle environmental impacts for a macro-component (per m^2)

All macro-components were computed in a similar way. As already referred, these macro-components enable to perform the life cycle analysis at the element level or at the building level.

3.3 Algorithm for energy quantification (use phase)

3.3.1 Introduction

As previously mentioned, EN 15978 (2011) assigns all potential environmental impacts of all aspects related with the building throughout its life cycle (materials production, use, end-of-life and reuse, recovery and recycling potential) in a modular system. According to this system, Module B6 corresponds to the operational energy use, i.e., building energy consumption.

Module B6 boundaries have to be compliant with EPBD through the use of EN 15603 (2008) and shall include the energy used for heating, cooling, domestic hot water supply, ventilation, lighting and auxiliary systems.

The adopted simplified approach is based on the characteristics of the building and its installed equipment. It addresses the quantification of the energy needs for space heating and cooling, and domestic hot water supply. The energy need for mechanical ventilation and lighting are not addressed, since these two components are not directly related to the construction system adopted for the building. The calculation of heating and cooling consumptions follows the monthly quasi-steady-state method provided by ISO 13790 (2008). This standard covers all aspects of the heat components involved in the thermal calculations and provides correlation factors to take the dynamic thermal effects into account. The energy needs for DHW production is calculated according to EN 15316-3-1 (2007).

3.3.2 Building location and climate

In order to compute the operational energy of a building during its use phase, it is important to take into account the most influencing variables related with thermal behaviour and energy efficiency of a building.

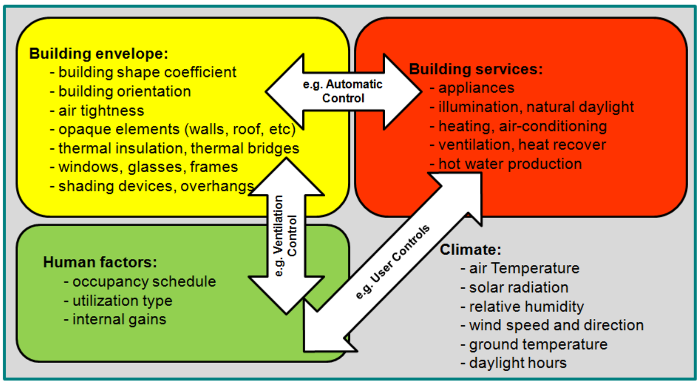


Fig. 3.5: Major key-factors with influence on buildings energy consumption (Santos et al., 2012)

The parameters could be grouped in four sets, namely: climate, building envelope, building services and human factors as illustrated in Fig. 3.5. Most of these factors are considered in the algorithm as detailed described in the next paragraphs.

The location of the building, in terms of climate conditions, is of vital importance in thermal behaviour calculations (Santos et al., 2011, 2012). Regarding this matter, two major climate parameters must be defined in order to undertake an energy need calculation:

i) air temperature;
ii) solar radiation on a surface with a given orientation.

Fig. 3.6 graphically illustrates this average monthly data for the city of Timisoara in Romania.

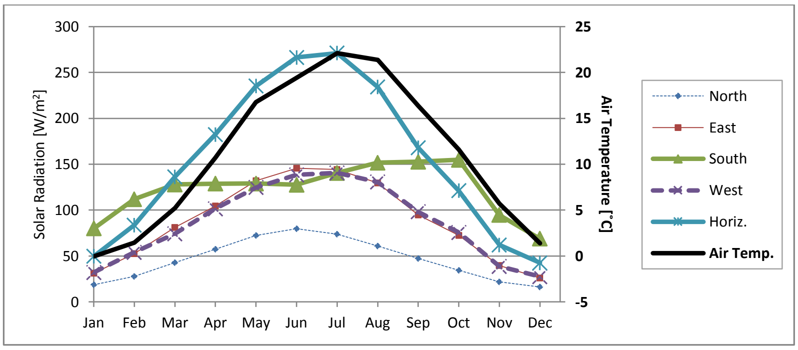


Fig. 3.6: Monthly average external air temperature and incident solar radiation: Timisoara (RO)

The methodology is currently calibrated for five climatic regions (classified according with the Köppen-Geiger climate classification): (i) Csa; (ii) Csb; (iii) Cfb; (iv) Dfb; (v) Dfc. The Köppen-Geiger climate classification is one of the most widely used climate classification systems (Kottek at al., 2006). Fig. 3.7 presents the Köppen-Geiger climate classification for Europe. It is clearly visible the importance of latitude, altitude and coast vicinity on the climate in these regions. In regions with lower latitudes (below 45ºN) (southern Europe, e.g. Mediterranean countries) the climate is labelled as Csa and Csb, i.e., “C - warm temperate” with “s - Summer dry” and “a - hot Summer” or “b - warm Summer”.

Above these latitudes (between 45-55ºN), in western central European countries, the climate is mainly categorized as Cfb, i.e., “C - warm temperate” with “f - fully humid” and “b - warm Summer”. In eastern central European countries (far away from the Atlantic coast) the climate is labelled as Dfb, i.e., “D - snow” with “f - fully humid” and “b - warm Summer”.

In regions with even higher latitudes (above 55ºN), in Nordic European countries, the climate is mostly frequently labelled as Dfc, i.e., “D - snow” with “f - fully humid” and “c - cool Summer”. This climate has some similarities with eastern central European countries, the main difference being the cooler Summer season.

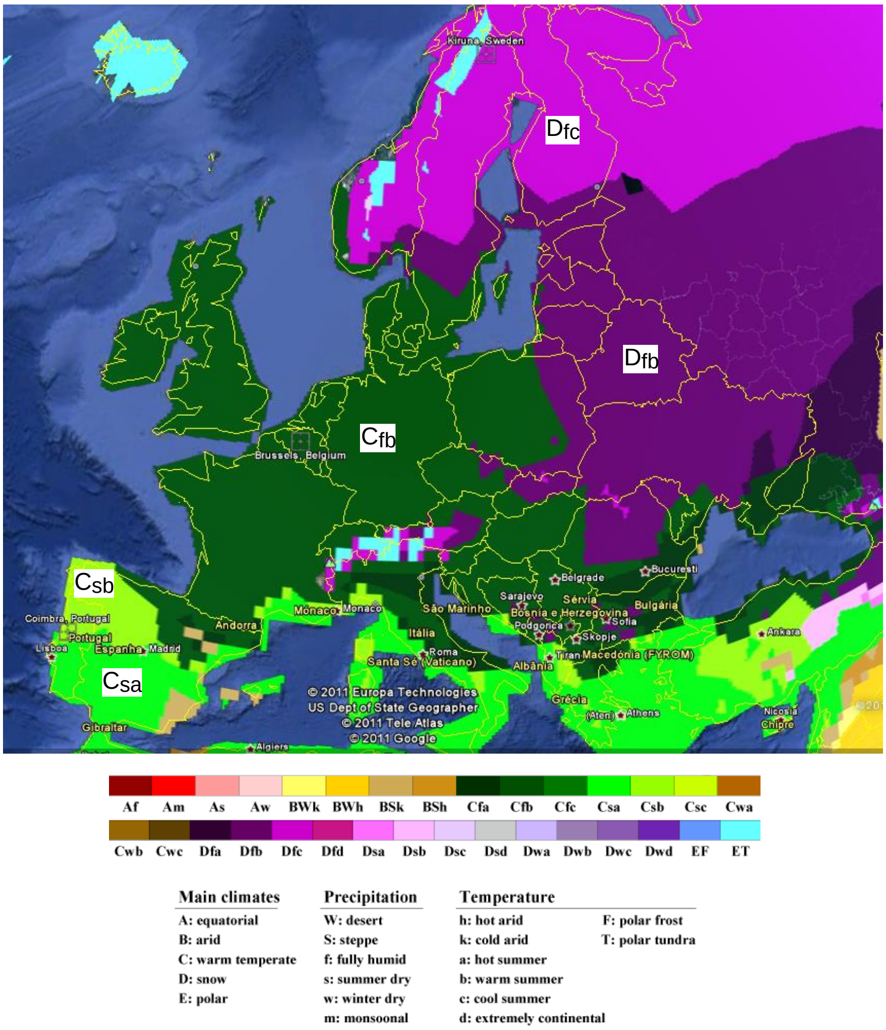


Fig. 3.7: European map of Köppen-Geiger climate classification (Kottek et al., 2006; Google Earth, 2014).

A database with weather data for different European locations will be implemented. Table 3.8 present a list of 48 cities for which this information was already obtained. Most of this climate data was obtained in the EnergyPlus energy simulation software weather database (EERE-USDoE, 2014) and the remaining was provided by research project partners.

Table 3.8: List of locations with obtained weather-data

City	Country	Climatic Region	Latitude
Amsterdam	Netherlands	Cfb	52
Ankara	Turkey	Csb	39
Arhanglesk	Russia	Dfc	64
Athens	Greece	Csa	37
Barcelona	Spain	Csa	41
Berlin	Germany	Cfb	52
Bilbao	Spain	Cfb	43
Bratislava	Slovakia	Cfb	48
Brussells	Belgium	Cfb	50
Bucharest	Romania	Cfa	44
Coimbra	Portugal	Csb	40
Genova	Italy	Csb	44
Graz	Austria	Dfb	47
Hamburg	Germany	Cfb	53
Helsinki	Finland	Dfb	60
Istambul	Turkey	Csa	40
Kiev	Ukraine	Dfb	50
Kiruna	Sweden	Dfc	67
La Coruña	Spain	Csb	43
Lisbon	Portugal	Csa	38
Ljubljana	Slovenia	Cfb	46
London	England	Cfb	50
Madrid	Spain	Csa	40
Marseille	France	Csa	43
Milan	Italy	Cfb	45
Minsk	Belarus	Dfb	53
Montpellier	France	Csa	43
Moscow	Russia	Dfb	55
Munich	Germany	Cfb	48
Nantes	France	Cfb	47
Nice	France	Csb	43
Oslo	Norway	Dfb	59
Ostersund	Sweden	Dfc	63
Paris	France	Cfb	48

Porto	Portugal	Csb	41
Prague	Czech Republic	Cfb	50
Rome	Italy	Csa	41
Salamanca	Spain	Csb	40
Sanremo	Italy	Csb	43
Sevilla	Spain	Csa	37
Stockholm	Sweden	Dfb	59
Tampere	Finland	Dfc	61
Thessaloniki	Greece	Cfa	40
Timisoara	Romania	Cfb	45
Vienna	Austria	Dfb	48
Vigo	Spain	Csb	42
Warsaw	Poland	Dfb	52
Zurich	Switzerland	Cfb	47

3.3.3 Energy need calculation method

The adopted approach enables to calculate energy needs on a monthly basis for space heating, space cooling and DHW production. In order to determine the contribution of each term involved in the thermal calculations it is necessary to rely on several standards, as shown in Fig. 3.8, for the space cooling and space heating.

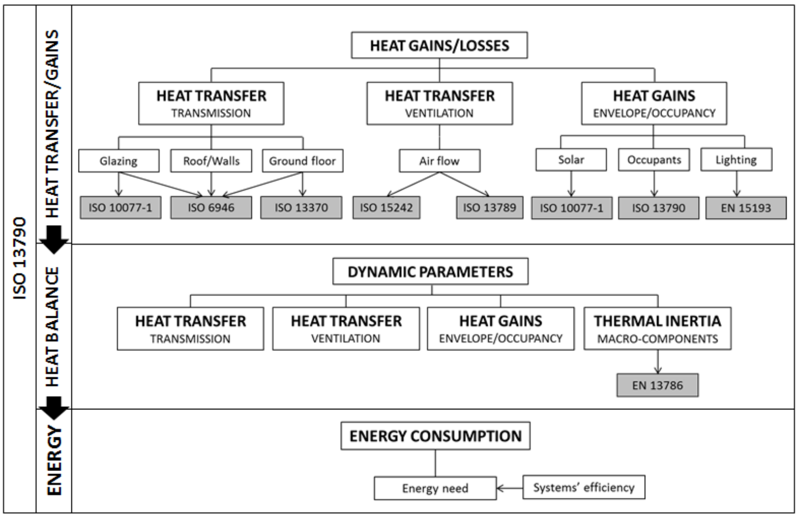


Fig. 3.8: Flowchart of the algorithm and the reference standards for space conditioning

As observed from Fig. 3.8, ISO 13790 (2008) is the main standard used, which addresses specific calculations to other standards. Taking into account the importance of the DHW production in the building's energy consumption, mainly at residential buildings, it is also essential to estimate its share. As mentioned before, this is undertaken under the guidance of EN 15316-3-1 (2007).

The procedure and architecture of the algorithm used to calculate energy needs are presented in Fig. 3.9.

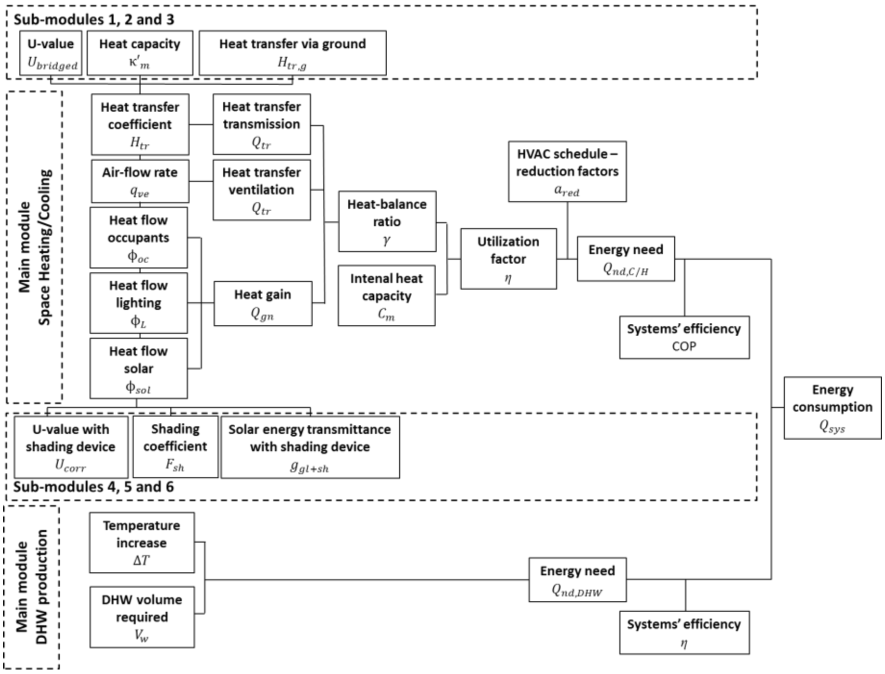


Fig. 3.9: Flowchart of the calculation of the energy consumption of the building

Sub-modules 1 and 2, corresponding, respectively, to the U-value and heat capacity of the envelope elements, were previously calculated for the macro-components selected by the user. Sub-module 3 covers the heat transfer through the ground. Sub-modules 4, 5 and 6 address the sub-routines used to calculate the effects of the shading devices and shading due to the shape of the floor plan. However, only rectangular floor plans are considered in the current version of AMECO.

3.3.3.1 Energy need for space heating and cooling

Eq. (3.6)~~Eq. (3.6)~~ and Eq. (3.7)~~Eq. (3.7)~~ are the basic main equations defined in ISO quantify the monthly, (m), energy need assuming continuous, ($cont$), systems operation (refer to ISO 13790 for nomenclature):

$$Q_{H,nd,cont,m} = (Q_{H,tr,m} + Q_{H,ve,m}) - \eta_{H,gn.m} . Q_{H,gn,m}$$

Eq. (3.6)

$$Q_{C,nd,cont,m} = Q_{C,gn,m} - \eta_{C,ls,m} . (Q_{C,tr,m} + Q_{C,ve,m})$$

Eq. (3.7)

where,

$Q_{H,nd}$, heating energy need (kWh);
$Q_{C,nd}$, cooling energy need (kWh);
Q_{tr} , total heat transfer by transmission (kWh);
Q_{ve} , total heat transfer by ventilation (kWh);
$\eta_{H,gn}$, gain utilization factor (-);
$\eta_{C,Is}$, loss utilization factor (-).

The methodology followed to calculate all these parcels of the energy need is addressed in the following sections.

3.3.3.1.1 HEAT TRANSFER BY TRANSMISSION

The heat balance of the building includes all types of heat transfer by transmission:

- (i) walls;
- (ii) roof;
- (iii) external floors (if present);
- (iv) glazing (glass + frames);
- (v) ground floor.

The heat transfer by transmission of types i) to iv) is undertaken considering the conduction mechanism without mass effects (implicitly), hence, the heat loss or gain is proportional to the temperature difference between interior and exterior environments and to the thermal transmittance coefficient of the element, as concluded from Eq. (3.8)~~Eq. (3.8)~~, Eq. (3.9)~~Eq. (3.9)~~ and Eq. (3.10)~~Eq. (3.10)~~. The heat transfer by transmission to the ground includes implicitly the effects of the inertia of the ground. This means that the heat transfer coefficient is calculated by a different approach than the other components, Eq. (3.11)~~Eq. (3.11)~~.

$$Q_{tr} = H_{tr,adj}(\theta_{int,sec} - \theta_e).t$$

Eq. (3.8)

$$\mathrm{H_{tr,adj}} = \mathrm{H_{D,W}} + \mathrm{H_{D,R}} + \mathrm{H_{D,EF}} + \mathrm{H_{D,Gl}} + \mathrm{H_{GF}}$$

Eq. (3.9)

$$H_D = \sum_i A_i.U_i$$

Eq. (3.10)

$$H_{GF} = b_{tr,g}.A_i.U_{GF}$$

Eq. (3.11)

where,

Q_{tr} , total heat transfer by transmission (kWh);

$H_{tr,adj}$, overall heat transfer coefficient (W/K);

$\theta_{int,sec,H}$ and $\theta_{int,sec,C}$, set-point temperatures of the building zone for heating and cooling modes, respectively (°C);

t, month duration given in ISO 13790 (Ms);

H_D, heat transfer coefficient by transmission to the external environment (W/K), through: walls, $H_{D,W}$; roof, $H_{D,R}$; external floor, $H_{D,EF}$; glazed elements, $H_{D,Gl}$;

H_{GF}, heat transfer coefficient by transmission to the ground (W/K);

$b_{tr,g}$, monthly ground adjustment factor (W/K);

A_i, area of element *i* (m^2);

U_i, thermal transmittance of element *i* ($W/m^2.K$);

U_{GF}, thermal transmittance of element of the system slab + ground ($W/m^2.K$).

The time related parameters used in the computations were obtained in ISO13790 and are presented in Table 3.9.

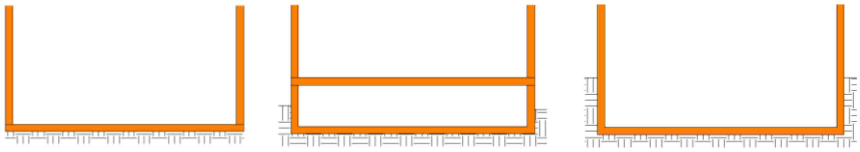
Table 3.9: Time related values

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
m	1	2	3	4	5	6	7	8	9	10	11	12
MonthLength, t (Ms)	2.6784	2.4192	2.6784	2.5920	2.6784	2.5920	2.6784	2.6784	2.5920	2.6784	2.5920	2.6784
MonthDay (days)	31	28	31	30	31	30	31	31	30	31	30	31
NbDayWorking (days)	23	20	21	22	23	20	23	22	21	23	21	22

All thermal transmittance coefficients, except the one referring to the heat transfer via the ground, are calculated in accordance with EN ISO 6946:2007.

Heat transfer to the ground

The heat transfer to the ground is quantified differently for the each type of the ground floor systems presented in Fig. 3.10.



a) Slab-on-ground floor

b) Suspended floor

c) Basement (heated or unheated)

Fig. 3.10: Types of ground floor

This is executed with the guidance of ISO 13370:2007. The amount of heat transferred to (or from) the ground is calculated by modifying the thermal transmittance coefficient, in order to take in account the additional insulation provided by the ground. Furthermore, the heat transfer coefficient is also modified to include the monthly heat flow rate, which is calculated taking in account the effect of the inertia of the ground. The adopted thermal properties of the ground are presented in Table 3.10.

Table 3.10: Ground thermal properties (ISO 13370:2007)

	Thermal conductivity λ [W/(m·K)]	Heat capacity per volume ρc [MJ/(m^3·K)]
Clay or silt	1.5	3.00
Sand or gravel	2.0	2.00
Homogeneous rock	3.5	2.00
Default	2.0	2.00

Heat transfer through windows

The algorithm contains a database with average values of optical and thermal properties for several types of windows (EN 15193) as listed in Table 3.11, where $g_{gl,n}$ is the solar energy transmittance for radiation perpendicular to the glazing and U_{Gl} is the thermal transmittance of window.

Table 3.11: Default values for optical and thermal properties of windows

Opening Type	$g_{gl,n}$,	U_{Gl}
Single glazing	0.87	5.8
Double glazing	0.78	2.9
Double glazing low-emissivity 1	0.72	1.7
Double glazing low-emissivity 2	0.67	1.4
Double glazing low-emissivity 3	0.65	1.2
Triple glazing	0.7	2.0
Triple glazing low-emissivity 1	0.5	0.8
Triple glazing low-emissivity 2	0.5	0.6

Heat transmission through windows is calculated with Eq. (3.10)~~Eq. (3.10)~~. However, to consider the positive effect of the shading device activated during the night, it is necessary to modify the thermal transmittance coefficient. The corrected thermal transmittance, $U_{Gl,corr}$ in W/m^2.K, is obtained through:

$$U_{Gl,corr} = U_{Gl+shut}.f_{shut} + U_{Gl}.(1 - f_{shut})$$

Eq. (3.12)

where,

$U_{Gl+shut}$, thermal transmittance of window and shutter together (W/m^{2}K);

f_{shut}, dimensionless fraction of accumulated temperature difference for period with shutter;

U_{Gl}, thermal transmittance of window without shutter.

The thermal transmittance of the window with shading device activated, $U_{Gl+shut}$, is calculated with equation:

$$U_{Gl+shut} = \frac{1}{\frac{1}{U_{Gl}} + R_{sh} + \Delta R}$$

Eq. (3.13)

where,

R_{sh}, thermal resistance of the shutter (m^2.K/W);

ΔR, additional thermal resistance at specific air permeability of the shutter (m^2.K/W).

In the algorithm, default values for R_{sh} and ΔR are provided, which were taken from ISO 10077-1 (2007). These values depend on the type of material of the shutter and its permeability to air, as illustrated in Table 3.12~~Table 3.12~~.

Table 3.12 – Thermal resistance of window shutters

Shutter type	**R_{sh}** [m²·K/W]	**Permeability to air**		
		High/Very High	**Average**	**Tight or low**
		ΔR [m².K/W]		
Exterior aluminium roller shutter (no insulation)	0.01	0.00	0.12	0.00
Exterior opaque wood device (no insulation)	0.10	0.00	0.16	0.00
Exterior wood roller shutter (no insulation)	0.10	0.00	0.16	0.00
Exterior plastic roller shutter (no insulation)	0.10	0.00	0.16	0.00
Exterior wood venetian blinds	0.01	0.09	0.00	0.00
Exterior metal venetian blinds	0.01	0.09	0.00	0.00
Exterior opaque roller blind	0.01	0.09	0.00	0.00
Exterior translucid roller blind	0.01	0.09	0.00	0.00
Interior shutter	0.01	0.00	0.00	0.24
Interior opaque curtains	0.00	0.00	0.00	0.00
Interior transparent curtains	0.00	0.00	0.00	0.00
Interior opaque wood device	0.10	0.00	0.00	0.31
Roller shutters of plastic with foam filling	0.15	0.00	0.19	0.00
Shutters of wood, 25mm to 30mm thickness	0.20	0.00	0.22	0.00

The dimensionless fraction of accumulated temperature difference for a period with shutter, f_{shut}, presented in the tool was derived from hourly values. It was considered as equal to the night time fraction (nocturnal protection).

3.3.3.1.2 HEAT TRANSFER BY VENTILATION

One type of passive cooling/heating techniques is to set the most advantageous conditions of ventilation in the building in order to optimize the thermal performance of the building. In the winter it is preferable to reduce the ventilation air flow in order to reduce the heat losses, whereas, in the summer it may be advantageous to increase the air changes of the interior air, if the exterior temperature is favourable to benefit from this passive technique. Thus, the algorithm allows defining different heating and cooling airflow rates.

The methodology to take in account the heat transfer by ventilation is prescribed in standard ISO 13790:2008, clause 9.3 and shown in the following formulas,

$$Q_{ve} = H_{ve,adj}\left(\theta_{int,sec} - \theta_e\right).t$$

Eq. (3.14)

$$H_{ve,adj} = \rho_a . c_a . \left(\sum_k b_{ve,k} . q_{ve,k,mn}\right)$$

Eq. (3.15)

$$q_{ve,k,mn} = f_{ve,t,k} . q_{ve,k}$$

Eq. (3.16)

where,

$\rho_a . c_a$, heat capacity of air per volume (J/m^3.K);
$q_{ve,k,mn}$, time-average airflow rate of element k (m^3/s);
$b_{ve,k}$, temperature adjustment factor of airflow element k (-).

If there is no system of pre-heating (e.g. heat recovery unit), then the temperature adjustment factor, $b_{ve,k}$, is 1. In the case of a building equipped with a heat recovery unit:

$$b_{ve,k} = \left(1 - f_{ve,frac,k} . \eta_{hru}\right)$$

Eq. (3.17)

where,

$f_{ve,frac,k}$, fraction of the airflow of element k that goes through the heat recovery unit;
η_{hru}, efficiency of the heat recovery unit.

3.3.3.1.3 INTERNAL HEAT GAINS

Heat generated by the occupants and appliances is computed through the internal gains. This is an important parcel in the heat balance of the building. The algorithm is capable of dealing with user data or default values (taken from ISO 13790:2008) composed of a weekly occupancy schedule and the corresponding heat flow rate. The formula used to calculate the heat gains due to internal heat sources is:

$$Q_{int} = \left(\sum_k \Phi_{int,mn,k}\right).t + \left(\sum_k (1 - b_{tr.l})\Phi_{int,mn,u,l}\right).t$$

Eq. (3.18)

where,

$\Phi_{int,mn,k}$, time-average heat flow rate from internal source *k* (W);

$\Phi_{int,mn,u,l}$, time-average heat flow rate from internal source l in adjacent unconditioned space (W);

$b_{tr.l}$, reduction factor for the adjacent unconditioned space;

t, length of the month (Ms).

Internal heat flows in a building may be from: i) occupants; ii) appliances. In Table 3.13~~Table 3.13~~ are presented reference values for heat flow from occupants and

Table 3.13 – Heat flow rate from occupants and appliances in residential buildings; schedules (from ISO 13790:2008)

Days	**Hours**	**Living room plus kitchen** $(\Phi_{int,Oc} + \Phi_{int,A})/A_f$ [W/m^2]	**Other conditioned areas** (e.g. bedrooms) $(\Phi_{int,Oc} + \Phi_{int,A})/A_f$ [W/m^2]
Monday to Friday	07:00 to 17:00	8.0	1.0
	17:00 to 23:00	20.0	1.0
	23:00 to 07:00	2.0	6.0
Saturday and Sunday	07:00 to 17:00	8.0	2.0
	17:00 to 23:00	20.0	4.0
	23:00 to 07:00	2.0	6.0

3.3.3.1.4 SOLAR HEAT GAINS

This type of heat gain is another major variable in the heat balance equation of the building. The general formulae to calculate it is:

$$Q_{sol} = \left(\sum_k \Phi_{sol,mn,k}\right).t + \left(\sum_k (1 - b_{tr.l})\Phi_{sol,mn,u,l}\right).t$$

Eq. (3.19)

where,

$\Phi_{sol,mn,k}$, time-average heat flow rate from solar heat source *k* (W);

$\Phi_{sol,mn,u,l}$, time-average heat flow rate from solar heat source *l* in adjacent unconditioned space (W);

$b_{tr.l}$, reduction factor for the adjacent unconditioned space;

t, length of the month (Ms).

It is necessary to calculate the effective collecting area of each element subject to solar radiation. The methods presented in ISO 13790 (2008) allow to take in account the effect of shading devices, shading due to the building itself and other climate dependent phenomena. This is addressed in the next paragraphs.

The heat flow by solar gains is obtained from,

$$\Phi_{sol,mn,k} = F_{sh,ob,k}.A_{sol,k}.I_{sol,k} - F_{r,k}.\Phi_{r,k}$$

Eq. (3.20)

where,

$F_{sh,ob,k}$, shading reduction factor for external obstacles (-);
$A_{sol,k}$, effective collecting area of element k (-);
$I_{sol,k}$, incident solar radiation per square meter of collecting area k (W/m^2);
$F_{r,k}$, form factor between the building element k and the sky (-);
$\Phi_{r,k}$, extra heat flow due to thermal radiation to the sky from element k (W/m^2).

The shading reduction factor for external obstacles, $F_{sh,ob,k}$, is neglected in this version of AMECO. The effective solar collecting area of **glazed elements** is calculated by,

$$A_{sol} = F_{sh,gl}.g_{gl}.(1 - F_F).A_{w,p}$$

Eq. (3.21)

where,

$F_{sh,gl}$, shading reduction factor for movable shading provisions (-);

g_{gl}, total solar energy transmittance of transparent part of the element (-);

F_F, frame area fraction of the window (-);

$A_{w,p}$, overall projected area of the window (m^2).

It is possible to take in account the positive effect (during the cooling season, for example) of shading devices applied in the windows. For that it is necessary to determine the shading reduction factor of that shading provision through,

$$F_{sh,gl} = \frac{\left(1 - f_{sh,with}\right).g_{gl} + f_{sh,with}.g_{gl+sh}}{g_{gl}}$$

Eq. (3.22)

where,

g_{gl+sh}, total solar energy transmittance of the window with the solar shading activated;

$f_{sh,with}$, weighted fraction of time with solar shading device in use.

The adopted values for the solar energy transmittance of the window with activated shading, g_{gl+sh}, are presented in Table 3.14 and were obtained from RCCTE (2006).

Table 3.14: Solar energy transmittance of the window with shading activate, g_{gl+sh}

	Shading device colour		
Shading device type	**Light**	**Intermediate**	**Dark**
Exterior opaque wood device (no insulation)	0.03	0.05	0.06
Exterior wood roller shutter (no insulation)	0.04	0.05	0.07
Exterior aluminum roller shutter (no insulation)	0.04	0.07	0.09
Exterior plastic roller shutter (no insulation)	0.04	0.07	0.09
Exterior wood venetian blinds	0.08	0.08	0.08
Exterior metal venetian blinds	0.09	0.09	0.09
Exterior opaque roller blind	0.04	0.06	0.08
Exterior translucid roller blind	0.16	0.18	0.2
Interior shutter	0.47	0.59	0.69
Interior opaque curtains	0.37	0.46	0.55
Interior transparent curtains	0.39	0.48	0.58
Interior opaque wood device	0.35	0.46	0.58
Exterior roller shutters of plastic (with insulation)	0.04	0.07	0.09
Shutters of wood, 25mm to 30mm thickness	0.04	0.05	0.07

The weighted fraction of time with solar shading in use, $f_{sh,with}$, is calculated for each orientation and it is based in hourly values of solar radiation (determined using *EnergyPlus*, which relies in the Perez model to perform solar calculations). It is the fraction of time that the solar radiation is above a set-point in a given orientation.

In the case of a window with non-scattering glass and without shading provision, the total solar energy transmittance, g_{gl}, is calculated according to:

$$g_{gl} = g_{gl,n}.F_w$$

Eq. (3.23)

where,

F_w, correction factor for non-scattering glazing (-);

$g_{gl,n}$, solar energy transmittance for radiation perpendicular to the glazing or SHGC (-).

However, if there are shading devices applied in the window, or if the glass is scattered, then it is necessary to calculate a time-average solar transmittance based a weighted sum of the direct and diffuse fractions of the solar radiation. This parameter is calculated on a monthly basis through Eq. (3.24)~~(3.24)~~.

$$g_{gl} = a_{gl} . g_{gl,alt} + \left(1 - a_{gl}\right) . g_{gl,dif}$$

Eq. (3.24)

$$alt_g = \frac{\sum_1^n \alpha_i . I_{dir,i}}{\sum_1^n I_{dir,i}}$$

Eq. (3.25)

$$a_{gl} = \frac{\sum_1^n I_{dir,i}}{\sum_1^n I_{sol,i}}$$

Eq. (3.26)

where,

a_{gl}, weighting factor, dependant of the position (orientation, tilt) of the window, climate and season (-);

$g_{gl,alt}$, solar energy transmittance for solar radiation from a given altitude angle, alt_{gl}, representative of the position (orientation, tilt) of the window, climate and season (-);

$g_{gl,dif}$, solar energy transmittance for isotropic diffuse solar radiation (-);

$I_{dir,i}$, direct mean solar radiation in hour i (W/m^2);

I_{sol}, total mean solar radiation in hour i (W/m^2);

α_i, solar incidence angle (˚);

n, number of hours in the month.

The direct and total solar radiation and the solar incidence angle, $I_{dir,i}$, I_{sol} and α_i, respectively, were obtained through *EnergyPlus*, which relies in the Perez model to perform solar calculations.

The frame fraction of the window, F_F, is calculated through standard ISO 10077-1 (2006). The values of 0.2 or 0.3 can be used, whichever gives the maximum transmittance value for the window. The default value for heating-dominated climates, 0.3, was adopted (ISO 13790, note of clause 11.4.5).

The overall projected area of the window, $A_{w,p}$, includes the glass and the frames, since the thermal properties of the window assigned in the tool are of the whole element (glass and frame). Furthermore, this methodology is also recommended by ISO 13789:2007 in Annex B.

The effective solar collecting area of **opaque elements** is calculated through equation,

$$A_{sol} = \alpha_{S,c}.R_{se}.U_c.A_c$$

Eq. (3.27)

where,

$\alpha_{S,c}$, dimensionless absorption coefficient for solar radiation of the opaque element;

R_{se}, external surface heat resistance coefficient of the opaque element, obtained from ISO 6946:2007 (m^2.K/W);

U_c, thermal transmittance of the opaque part, calculated according with ISO 6946:2007 (W/m^2.K);

A_c, projected (on to a plane parallel to the surface) area of the opaque element (m^2);

The dimensionless absorption coefficient for solar radiation depends on the colour of the external surface of the opaque element as presented in the next table (RCCTE, 2006).

Table 3.15: Absorption coefficient for solar radiation of the opaque element (RCCTE, 2006)

Colour	$\alpha_{S,c}$
Light	0.3
Medium	0.5
Dark	0.8

The incident solar radiation, $I_{sol,k}$, is a mean value for the time step of the month of the calculation. Obviously, this is climate, latitude and position (orientation and tilt) dependent.

The form factor between the element and the sky, $F_{r,k}$, is considered to be 1.0 and 0.5 for unshaded horizontal and vertical elements, respectively.

Thermal radiation to the sky, $\Phi_{r,k}$, is computed in the solar gains. However, this a heat transfer by radiation due to the temperature difference between the surface of the element (assuming it is equal to the external temperature) and the sky dome. Eq. (3.28)~~(3.28)~~ provides the way to calculate this heat transfer phenomenon,

$$\Phi_{r,k} = R_{se}.U_c.A_c.h_r.\Delta\theta_{er}$$

Eq. (3.28)

where,

h_r, external radiative heat transfer coefficient (W/m^2.K);

$\Delta\theta_{er}$, average difference between the external air temperature and the apparent sky temperature (˚C).

The standard ISO 13790:2008 postulates that the external radiative heat transfer coefficient, h_r (W/m^2.K), can be taken as 5.ε (where ε is the material emissivity), which corresponds to an average temperature of 10 ˚C of the surface and the sky temperature.

According with ISO 13790 (clause 11.4.6) the average difference between external air temperature and apparent sky temperature, $\Delta\theta_{er}$, may be taken as 9˚C in sub-polar regions, 13˚C in the tropics and 11˚C in intermediate zones.

3.3.3.1.5 DYNAMIC PARAMETERS

For the heating mode, the gain utilization factor, $\eta_{H,gn.m}$, is given by the following equations:

$$\text{If } \gamma_H > 0 \text{ and } \gamma_H \neq 1\text{, then:} \qquad \eta_{H,gn} = \frac{1-\gamma_H^{aH}}{1-\gamma_H^{aH+1}}$$

Eq. (3.29)

$$\text{If } \gamma_H = 1\text{, then:} \qquad \eta_{H,gn} = \frac{a_H}{a_H+1}$$

Eq. (3.30)

$$\text{If } \gamma_H < 0\text{, then:} \qquad \eta_{H,gn} = \frac{1}{\gamma_H}$$

Eq. (3.31)

where,

$\gamma_H = Q_{H,gn}/Q_{H,ht}$ is the heat-balance ratio;

$a_H = a_{H,0} + \tau/\tau_{H,0}$ is a dimensionless parameter;

$\tau = C_m/H$ is the time constant of the building zone and takes into account the thermal inertia of the building and the heat transfer by transmission and ventilation;

$a_{H,0}$ and $\tau_{H,0}$ are dimensionless parameters, which take the value of 1 and 15, respectively (ISO 13790 value).

The monthly utilization factor for the cooling mode is obtained through one of the following formula:

If $\gamma_C > 0$ and $\gamma_C \neq 1$, then: $$\eta_{C,ls} = \frac{1-\gamma_C^{-aC}}{1-\gamma_C^{-(aC+1)}}$$

Eq. (3.32)

If $\gamma_C = 1$, then: $$\eta_{C,ls} = \frac{a_C}{a_C+1}$$

Eq. (3.33)

If $\gamma_C < 0$, then: $$\eta_{C,ls} = 1$$

Eq. (3.34)

The parameters used to obtain the utilization factors are similar to the ones presented for the heating mode, but with the values correspondent to the cooling mode (the dimensionless parameters $a_{C,0}$ and $\tau_{C,0}$ are also taken as 1 and 15 in ISO 13790, respectively).

The internal mass of the building is introduced in the calculations through the time constant of the building zone, τ, expressed in hours. This value is obtained by,

$$\tau = \frac{C_m}{3600.\left(H_{tr,adj} + H_{ve,adj}\right)}$$

Eq. (3.35)

where,

C_m, internal heat capacity of the building or building zone (J/K);

$H_{tr,adj}$, representative overall heat transfer coefficient obtained from Eq. (3.9)~~Eq. (3.9)~~;

$H_{ve,adj}$, representative overall heat transfer coefficient obtained from Eq. (3.15)~~(3.15)~~.

Formatiert

The internal heat capacity of the building, C_m (J/K), was computed as the summation of the heat capacities of all building construction elements in direct thermal contact with the internal air of the building (ISO 13790), as given by,

$$C_m = \sum_j k_j . A_j$$

Eq. (3.36)

where,

k_j is the internal heat capacity per area of building construction element j (J/K.m^2);

A_j is the surface area of the building construction element j (m^2).

The internal heat capacity per area, k_j, was computed for each macro-component with the guidance of standard EN ISO 13786:2007, Annex A, which contemplates a simplified method for this assessment.

In order to determine in a swift way the internal heat capacity of the building, ISO 13790 provides default values per square meter of a given building class. These are presented in Table 3.16~~Table 3.16~~ for the monthly and seasonal method.

Formatiert: Rechtschreibung und Grammatik prüfen

Table 3.16 – Default values for internal heat capacity (ISO 13790, 2008)

Class	C_m [J/K]
Very light	80000.A_f
Light	110000. A_f
Medium	165000. A_f
Heavy	260000. A_f
Very heavy	370000. A_f

A_f - Area of floor

Length of heating and cooling months

In order to make an estimation of the months with cooling or heating energy need, ISO 13790 provides two methods to assess this, based in the heat-balance ratio and the dimensionless parameter, a_C and a_H. Even though the referred standard proposes two methods, only the detailed one is tackled and presented here (clause 7.4.1.1 – method b), since it is feasible to implement in the tool.

Heating mode:

The estimation of the fraction of the month where there is a need for energy to heat the space begins with the calculation of an ideal heat-balance ratio, $\gamma_{H,lim}$, which corresponds to an ideal gain utilization factor, $\eta_{H,gn}$. The latter takes a value that makes null the energy need to heat the space. This reasoning is adapted from an ideal building of infinite thermal inertia, where $\gamma_{H,lim} = 1.0$ and, thus, $\eta_{H,gn} = 1.0$. As a real building have finite thermal inertia, not all of the heat gains are effective to heat the space and contribute to elevate the internal temperature to the comfort temperature (due to overheating). Hence, the gain utilization factor is lower and it is necessary to have more gains to balance the heat balance equation to make the energy need null. This reasoning is not valid for the heat transfer (if the heat-balance ratio is lower than 1, it means that the heat transfer is higher than the heat gains; as the heat utilization factor cannot take a value higher than 1, it is not possible to make the energy need null, thus is not possible to determine a optimum heat-balance ration lower than 1.0). This is graphically explained in Fig. 3.11.

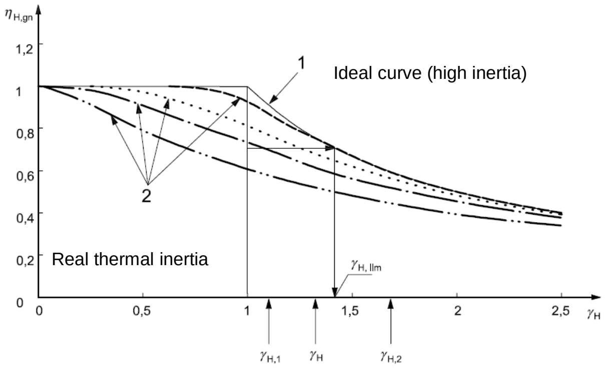


Fig. 3.11: Relevant parameters to determine the fraction of the month with cooling or heating energy need (ISO 13790)

The optimum heat-balance ratio is calculated with:

$$\gamma_{H,lim} = \frac{(a_H + 1)}{a_H}$$

Eq. (3.37)

For the calculation of the fraction of the month with heating energy need, it is necessary to determine γ_H at the beginning and at the end of the month. The average of the γ_H for the beginning of the months obtain by the average of the γ_H in the month in analysis and the previous month. The parameter for γ_H at the end of the month is obtained by the average of the γ_H of month in analysis and the following month. Furthermore, two "new" parameters are needed: $\gamma_{H,1}$ and $\gamma_{H,2}$. The first is obtained by the minimum of the two γ_H calculated by the previous process and $\gamma_{H,2}$ corresponds to the maximum. These parameters ($\gamma_{H,1}$ and $\gamma_{H,2}$) are the heat-balance ratios in the beginning and in the end, respectively, of the month, and are calculated as follows:

$$\text{If } \gamma_{H,2} < \gamma_{H,lim}, \text{ then } f_H = 1$$

Eq. (3.38)

$$\text{If } \gamma_{H,1} > \gamma_{H,lim}, \text{ then } f_H = 0$$

Eq. (3.39)

Equation (3.39)~~(3.39)~~ means that if the lower heat-balance ratio of the month edges is higher than the optimum, then, in that month, there will be no need for heating the space. However, if none of these conditions are met, the following applies:

$$\text{If } \gamma_H > \gamma_{H,lim}, \text{ then } f_H = 0{,}5.\frac{\gamma_{H,lim}-\gamma_{H,1}}{\gamma_H-\gamma_{H,1}}$$

Eq. (3.40)

$$\text{If } \gamma_H \leq \gamma_{H,lim}, \text{ then } f_H = 0{,}5 + 0{,}5.\frac{\gamma_{H,lim}-\gamma_H}{\gamma_{H,2}-\gamma_H}$$

Eq. (3.41)

These equations follow the same logic as equations (3.38)~~(3.38)~~ and (3.39)~~(3.39)~~, with the difference that in the case of equations (3.40)~~(3.40)~~ and (3.41)~~(3.41)~~ γ_H refers to a mean monthly value and not to a value in the edges of the month.

The length of the heating season may also be determined by the sum of f_H calculated for each month, i.e.:

$$L_H = \sum_{m=1}^{12} f_{H,m}$$

Eq. (3.42)

Cooling mode:

The reasoning made in the case of the heating mode may be applied in the case of the cooling mode. Hence, no further explanations will be produced here. The calculation of the fraction of the month with cooling energy need is calculated using the inverse of the optimum heat-balance ratio, $\left({}^{1}/_{\gamma_C}\right)_{lim}$.This parameter is calculated with:

$$\left({}^{1}/_{\gamma_C}\right)_{lim} = {}^{(a_C + 1)}/_{a_C}$$

Eq. (3.43)

Then, the limit parameters, $\left({}^{1}/_{\gamma_C}\right)_1$ and $\left({}^{1}/_{\gamma_C}\right)_2$ are obtained through equations (3.44)~~(3.44)~~ and (3.45)~~(3.45)~~:

$$\text{If } \left({}^{1}/_{\gamma_C}\right)_2 < \left({}^{1}/_{\gamma_C}\right)_{lim}, \text{ then } f_C = 1$$

Eq. (3.44)

$$\text{If } \left({}^{1}/_{\gamma_C}\right)_1 > \left({}^{1}/_{\gamma_C}\right)_{lim}, \text{ then } f_C = 0$$

Eq. (3.45)

As for the heating mode, if none of these conditions are verified, then:

$$\text{If } \left({}^{1}/_{\gamma_C}\right) > \left({}^{1}/_{\gamma_C}\right)_{lim}, \text{ then } f_C = 0{,}5.\frac{\left({}^{1}/_{\gamma_C}\right)_{lim} - \left({}^{1}/_{\gamma_C}\right)_1}{\left({}^{1}/_{\gamma_C}\right) - \left({}^{1}/_{\gamma_C}\right)_1}$$

Eq. (3.46)

$$\text{If } \left({}^{1}/_{\gamma_C}\right) \leq \left({}^{1}/_{\gamma_C}\right)_{lim}, \text{ then } f_C = 0{,}5 + 0{,}5.\frac{\left({}^{1}/_{\gamma_C}\right)_{lim} - \left({}^{1}/_{\gamma_C}\right)}{\left({}^{1}/_{\gamma_C}\right)_2 - \left({}^{1}/_{\gamma_C}\right)}$$

Eq. (3.47)

The cooling season may also be calculated by summing all the f_C of each month, as presented in Equation (3.48)~~(3.48)~~:

$$L_C = \sum_{m=1}^{12} f_{C,m}$$

Eq. (3.48)

Energy need for intermittent operating systems

When the HVAC systems operate on a schedule (i.e. in intermittent mode), ISO 13790 (2008) provides guidance to determine a reduced energy needs based on the calculations for the continuous mode, as previously presented in Eq. (3.6~~Eq. (3.6~~) and (3.7)~~Eq. (3.7)~~. This is determined by reducing the heating and cooling energy need, $Q_{C,nd}$, through a dimensionless reduction factor for intermittent cooling and heating, $a_{C,red}$ and $a_{H,red}$. The fractions of the month with energy need in heating and cooling modes, $f_{H,m}$ and $f_{C,m}$, are also applied here. Hence,

$$Q_{H,nd,interm,m} = f_{H,m} \cdot a_{H,red} \cdot Q_{H,nd,cont,m}$$

Eq. (3.49)

$$Q_{C,nd,interm,m} = f_{C,m} \cdot a_{C,red} \cdot Q_{C,nd,cont,m}$$

Eq. (3.50)

The building time constant, τ, and heat-balance ratios, γ_H and γ_C, also influence the reduction factor of the energy needs due to the intermittent operation of the HVAC systems, as observed in the following equations,

$$a_{H,red} = 1 - b_{H,red} \cdot \frac{\tau_{H,0}}{\tau} . \gamma_H . \left(1 - f_{H,hr}\right) \text{ , with } f_{H,hr} \leq a_{H,red} \leq 1.0$$

Eq. (3.51)

$$a_{C,red} = 1 - b_{C,red} \cdot \frac{\tau_{C,0}}{\tau} . \gamma_C . \left(1 - f_{C,day}\right) \text{ , with } f_{C,day} \leq a_{C,red} \leq 1.0$$

Eq. (3.52)

where,

b_{red} is a fixed parameter, taken as 3 (both for heating and cooling modes);

$f_{H,hr}$ is the fraction of the number of hours in which the systems are operating;

$f_{C,day}$, represents the fraction of the number of days in the week, with the systems in operation.

3.3.3.2 Energy need for DHW production

The energy needed for DHW production, in $MJ/month$, is calculated following EN 15316-3-1 (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, according to,

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

Eq. (3.53)

where,

$V_{W,m}$ is the monthly DHW volume need as prescribed in EN 15316-3-1 (2007);
$\theta_{W,t}$ is the temperature of DHW at tapping point [˚C];
$\theta_{W,O}$, temperature of the inlet water [˚C].

For a single dwelling the daily volume of domestic hot water need is based in the floor area and calculated (in m³/day) as follows,

$$V_w = \frac{a.N_U}{1000}$$

Eq. (3.54)

where,

a, unit requirement based on litres of water at 60˚C/day;

N_U, number of units to be taken into account.

The monthly volume of DHW needed, $V_{w,m}$, could be obtained by multiplying the daily value, V_w, by the number of days of the month.

The parameters, a and N_U, depend on the type of building and its occupation/activity and could be calculated depending on the floor area, A_f, as follows,

$$\text{If } A_f > 30m^2\text{, then } a = \frac{62.ln(A_f) - 160}{A_f}$$

Eq. (3.55)

$$\text{If } 15 \leq A_f \leq 30m^2\text{, then } a = 2$$

Eq. (3.56)

3.3.3.3 Energy consumption

The energy need calculated does not take into account the efficiency of the building's systems installed to condition the interior space neither to produce DHW. The algorithm considers that the building may have systems with different efficiencies, since it is not often that, for example, the heating and cooling COPs are the same. Hence, each energy need (space cooling, space heating, DHW production) is affected of the efficiency of the respective equipment. The general formulae to calculate the energy consumption that could be applied for each type of energy need is:

$$Q_{cons} = \frac{Q_{nd}}{\eta_{sys}}$$

Eq. (3.57)

where,

Q_{nd}, energy need;

η_{sys}, system's efficiency.

The adopted default values of system's energy efficiency and the type of energy consumed are presented in the following tables. Mostly of these values where obtained from RCCTE (2006).

Table 3.17: Space heating system's efficiency and energy used

Heat system	$\eta_{H,sys}$,	**Type of energy**
Electric resistance	1	Electricity
Gas Fuel Heater	0.87	Gas Fuel
Liquid Fuel Heater	0.8	Liquid Fuel
Solid Fuel Heater	0.6	Solid Fuel
Split (Heating)	4	Electricity

Table 3.18: Space cooling system's efficiency and energy used

Heat system	$\eta_{C,sys}$	**Type of energy**
Split (Cooling)	3	Electricity
Refrigeration machine (compression cycle)	3	Electricity
Refrigeration machine (absorption cycle)	0.8	Electricity

Table 3.19: DHW system's efficiency and energy used

Heat system	$\eta_{DHW,sys}$	**Type of energy**
Electric boiler	0.9	Electric
Gas boiler	0.6	Gas
Stand-alone heater condensation	0.72	Gas
Stand-alone heater	0.4	Gas

The total energy consumption in the building is determined through the sum of all energy use:

$$Q_{Tot,cons} = \frac{Q_{H,nd}}{\eta_{H,sys}} + \frac{Q_{C,nd}}{\eta_{C,sys}} + \frac{Q_{DHW,nd}}{\eta_{DHW,sys}}$$

Eq. (3.58)

The primary energy is computed by multiplying the conversion factor, F_{pu}, [kgoe/kWh] by the energy consumption,

$$Q_{Tot,prim} = F_{H,pu}.\, Q_{H,cons} + F_{C,pu}.\, Q_{C,cons} + F_{DHW,pu}.\, Q_{DHW,cons}$$

Eq. (3.59)

The conversion factor from energy consumption (or use) to primary energy depend on the fuel (or type of energy) for each system. The values default values were obtained from RCCTE (2006) and are presented in Table 3.20.

Table 3.20: Conversion factor from energy use to primary energy (RCCTE, 2006)

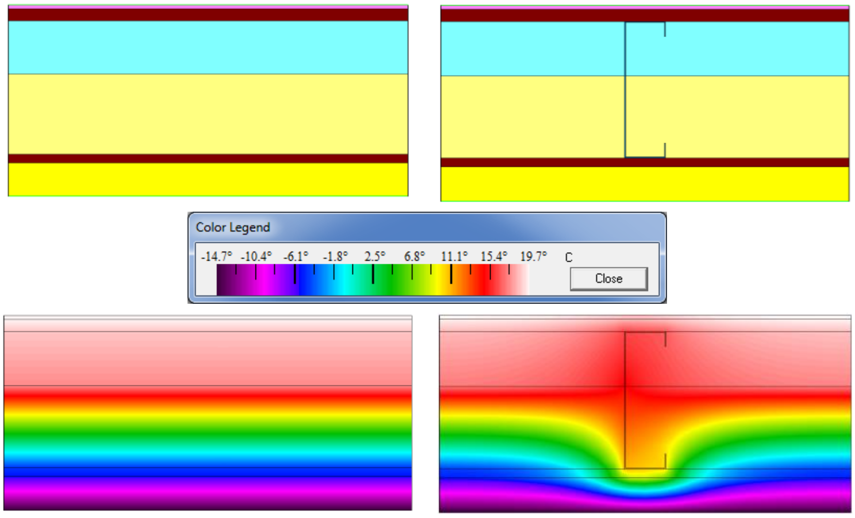
Energy type	$\boldsymbol{F_{pu}}$ [kgoe/kWh]
Electricity	0.29
Gas, liquid or solid fuel	0.086

3.3.3.4 Thermal inertia

Regarding thermal inertia, the internal heat capacity of the building, C_m calculations were performed as suggested by ISO 13790 and previously presented in Equation (3.36)~~(3.36)~~. The internal heat capacity per area of each macro-component was computed according the prescriptions within annex A of EN ISO 13786 (2007). This is a simplified procedure base in the penetration depth of the heat wave, calculated for the materials adjacent to the interior surface, which is suitable for this type of calculations. In the prescribed method, the heat capacity of the layers is considered, until a maximum thickness of 100 mm (counting from the internal surface).

3.3.3.5 Thermal bridges

The effect of repeating thermal bridges (e.g. originated by steel studs as illustrated in Fig. 3.12) within the construction elements (e.g. walls and slabs) are taken into account in the thermal transmittance (U-value). Linear and punctual thermal bridges effect is neglected. This U-value is included in the software database for each macro-component.



Neglecting thermal bridges
U = 0.162 W/(m^{2}K)

With steel frame thermal bridge
U = 0.227 W/(m^{2}K)

Fig. 3.12: Effect of thermal bridges in the thermal transmittance values for a lightweight steel frame external floor

The U-value of thermal bridged elements were determined with the method presented in Section 6 of ISO 6946 (2007) and perfected by Gorgolewski (2007), since the first is only applicable if the insulation layer is not bridged by steel frames. The second method relies in the determination of two limits for the thermal 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. Whenever there is no thermal bridge in the element, then it is applied the method for homogenous layers, which takes into account the circuit of thermal resistances in series.

3.3.4 Calibration of the algorithm

In order to verify and improve the precision of the algorithm implement to predict the operational energy for space heating and cooling a building, based in the ISO 13790 monthly quasi-steady-state method, several verifications and calibration procedures were performed.

First the precision of the monthly algorithm is verified by applying it to twelve test cases prescribed in EN 15265 for a single office compartment. After, since real buildings are further complex having more than one compartment, the algorithm is calibrated for a multi-compartment residential building, making use of correction factors applied to the four main heat balance components of a building and also to the dimensionless dynamic parameters.

Finally, in Section 4.2 the obtained calibrated algorithm is validated by applying it to a case study (low-rise residential building) and comparing the obtained results with those obtained by advanced dynamic analysis using *DesignBuilder /EnergyPlus*.

3.3.4.1 Precision verification in the framework of EN 15265

This section presents some of the tests performed in order to verify the precision of the monthly algorithm, using the 12 test-cases (Table 3.21) prescribed in EN 15265 (2007) for a single office compartment (Fig. 3.13). This standard uses a reference room with a glazed element facing west and it is analysed under different boundary conditions, variations of the internal and solar gains and two types of heating/cooling modes: continuous and intermittent. For each of the twelve test cases considered, the standard provides reference results for heating and cooling energy needs for a specific location (Trappes, France), for which the climate data is also prescribed regarding hourly values of external air temperature and solar radiation.

Table 3.21: Test cases prescribed in EN 15265 (2007) to validate the calculation of energy needs for space heating and cooling using dynamic methods

Informative	**Normative**		**Normative**	
Test 1 Reference Case	**Test 5** = Test 1 +	**Intermittent HVAC** (only 8h00-18h00 from Monday to Friday)	**Test 9** = Test 5 +	**External Roof**
Test 2 Higher Thermal Inertia	**Test 6** = Test 2 +		**Test 10** = Test 6 +	
Test 3 No Internal Gains	**Test 7** = Test 3 +		**Test 11** = Test 7 +	
Test 4 No Solar Protection	**Test 8** = Test 4 +		**Test 12** = Test 8 +	

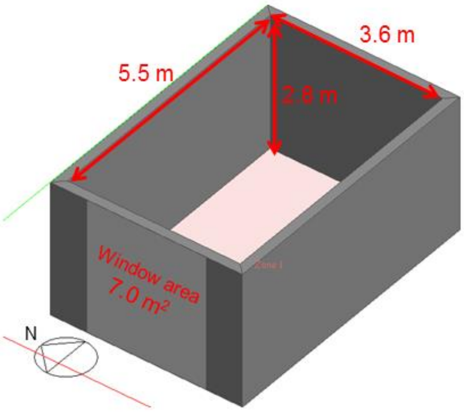
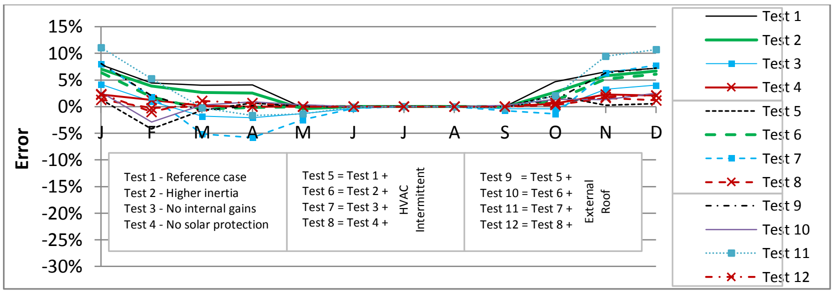
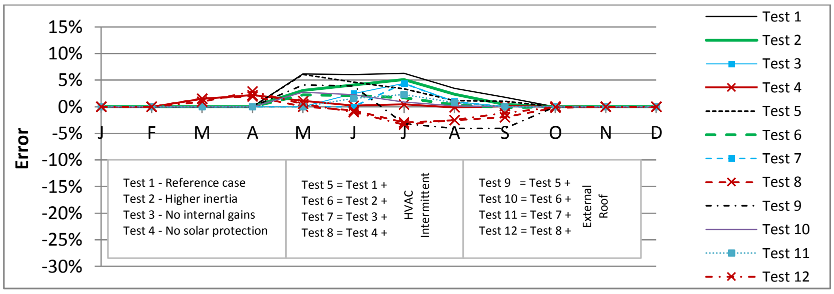


Fig. 3.13: Model of the single office compartment as prescribed in EN 15265

Since it was important to assess the accuracy of the terms that take part in the heat balance and these are not provided in the EN 15265 standard, the test cases were also calculated in the *DesignBuilder* advanced dynamic calculation software that make use of a the *EnergyPlus* energy simulation algorithm. The test-room was fully defined both in the dynamic software and in the monthly algorithm, in order to produce the energy need estimations. Fig. 3.14 illustrates the errors obtained with the quasi-steady-state approach presented on a monthly basis (with reference to the dynamic simulation results provided by *EnergyPlus* algorithm) and calculated as a percentage of the total yearly energy need. The maximum monthly error is lower than 12%, as shown in Fig. 3.14. The error is higher in summer and winter months for cooling and heating modes, respectively.



a) Heating mode



b) Cooling mode

Fig. 3.14: Monthly errors of the algorithm (monthly quasy-steady-state method) – reference results: EnergyPlus (hourly advanced dynamic method)

3.3.4.2 Calibration factors

The monthly quasi-steady-state approach includes several simplifications when compared to advanced dynamic simulations (based on hourly data). Several parameters contribute directly towards these differences:

(i) the dynamic monthly utilization factors, $\eta_{H,gn.m}$ and $\eta_{C,ls.m}$, assumed constant and independent of climatic data and occupancy schedule, within each climatic region;

(ii) the various energy terms, Q_{tr}, Q_{ve}, Q_{int} and Q_{sol}, are calculated for constant interior temperatures as defined by the set-points for heating and cooling seasons.

In addition, climatic data and occupancy schedule and the layout of the building also indirectly influence the above parameters.

Consequently, despite the good agreement of the monthly quasi-steady-state approach with respect to the test cases prescribed in EN 15265, the performance of real buildings with more complex layouts, operating conditions and different climates may significantly deviate from the results obtained with this simplified approach. This is recognized in ISO 13790, where possible differences ranging from 50% to 150% are quoted, thus providing a procedure for the derivation of the monthly utilization factors (Annex I of ISO 13790).

In order to minimize this possible scatter, new correction factors where defined and calibrated to improve the estimates of the various energy terms: (i) heat transfer by transmission; (ii) heat transfer by ventilation; (iii) internal heat gains; (iv) solar heat gains, as shown in equations (3.60)~~(3.60)~~ to (3.62)~~(3.62)~~,

$$H_{tr,adj,c} = f_{tr}.H_{tr,adj} \rightarrow Q_{tr,m} = H_{tr,adj,c}.\left(\theta_{int,sec,H} - \theta_e\right).t$$

Eq. (3.60)

$$H_{ve,adj,c} = f_{ve}.H_{ve,adj} \rightarrow Q_{ve,m} = H_{ve,adj,c}.\left(\theta_{int,sec,H} - \theta_e\right).t$$

Eq. (3.61)

$$Q_{gn} = f_{int}.Q_{int,m} + f_{sol}.Q_{sol,m}$$

Eq. (3.62)

where, $H_{tr,adj,c}$ is the corrected heat transfer by transmission; f_{tr} is the correction coefficient for the heat transfer by transmission; $H_{ve,adj,c}$ is the corrected heat transfer by ventilation; f_{ve} is the coefficient to correct the heat transfer by ventilation; f_{int} is the correction coefficient for the internal gains; and f_{sol} is the coefficient to correct the solar gains, excluding the thermal radiation to the sky. Notice that distinct correction factors were calibrated for each climatic region.

Besides the previously mentioned correction factors for the main four heat transfer components, the dimensionless parameters, a_{H0}, τ_{H0}, a_{C0} and τ_{C0}, were also calibrated for each climatic region.

Since the monthly algorithm aims at the prediction of the energy needs of buildings instead of focusing only on one building compartment as prescribed in EN 15265 (2007), all calibrations were carried out with a new set of test cases based on the typical building characteristics (apartment) as illustrated in Fig. 3.15.

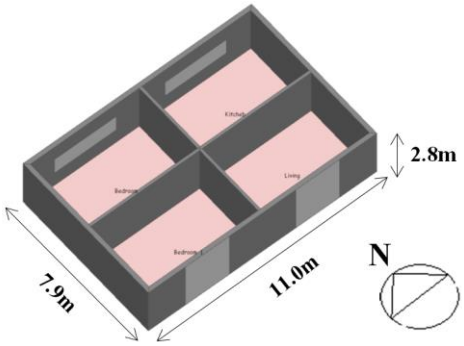


Fig. 3.15: Example of a building model used in the test cases to calibrate the monthly algorithm

These test cases use the same thermal properties as the envelope of the EN 15265 (2007) test cases (see Table 3.22~~Table 3.22~~), but with different boundary conditions (non-adiabatic walls and roof) and higher floor area (79.2 m²). The assumed airflow rate is 1.0 air changes per hour (constant).

Formatiert: Rechtschreibung und Grammatik prüfen

Table 3.22 – Envelope thermal properties of the calibration test cases

Element	U-value [W/m^2.K]	κ_m [J/m^2.K]
External wall	0.493	81297
Internal wall	-	9146
Roof	0.243	6697
Ground floor	-	63380

An important modification in the calibration models is related with the occupancy and systems operation schedule, since the EN 15265 (2007) test cases comprise offices compartments. Hence, the occupation schedules and respective heat flows were derived from the ISO 13790 (2008) for residential buildings as previously presented in Table 3.13~~Table 3.13~~.

Formatiert: Rechtschreibung und Grammatik prüfen

Given the importance of the glazing areas for the solar gains and heat losses by transmission, different wall to floor area ratios were studied, as presented in Table 3.23~~Table 3.23~~. Also, the scenarios with and without shading devices was studied in the calibration process.

Table 3.23 – Main variables of the test cases used to calibrate the tool

Test case	GFR [%]	NGWR [%]	SGWR [%]	Shading devices
T1	35	36	54	ON
T2				OFF
T3	25	20	40	ON
T4				OFF
T5	15	12	24	ON
T6				OFF

GFR: glazing to floor ratio;
NGWR: north-oriented glazed to wall ratio;
SGWR: south-oriented glazed to wall ratio.

All test cases were run in five different climatic regions: (i) Csa; (ii) Csb; (iii) Cfb; (iv) Dfb; and (v) Dfc. The correction factors were derived by minimizing the error for each sub-set of the test cases for each climatic region that, in some cases, reached 500 cases. Fig. 3.16 illustrates the accuracy improvements without and with the correction factors for the Dfb climate zone, showing average improvements from 43% absolute error to less than 2%.

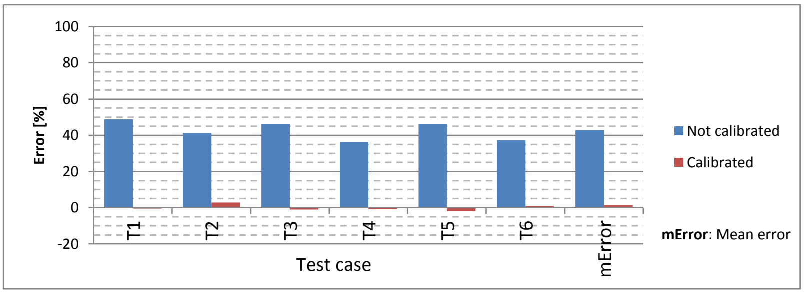


Fig. 3.16: Improvement of the accuracy of the monthly ISO 13790 method for the Dfb climate: total annual energy for space heating and cooling

Fig. 3.17 summarizes the improvements for five climatic regions addressed here. It is interesting to note that, without corrections, the precision of the method is lower for colder climates, the highest error occurring for the Dfc climatic region and the lowest for Csb climatic region. The monthly method presented lower accuracy in estimating the energy needs for the coldest months, since the comparisons with dynamic method proved that the gains are used in a more efficient way to heat the space than considered in the simplified method. This effect is even more relevant and evident when the solar gains are lower. Globally, with the correction factors, all the errors are lower than 10%.

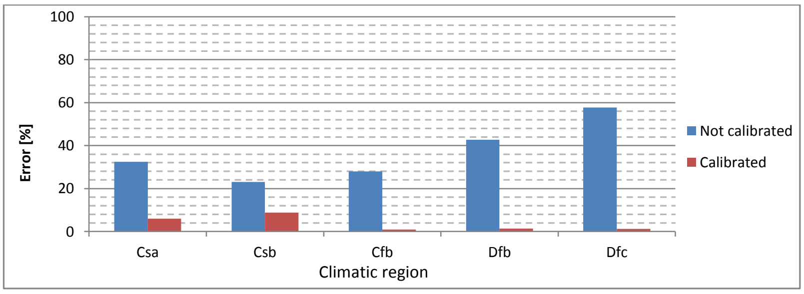


Fig. 3.17: Mean error of the monthly method with and without calibration factors

Notice that there was a different error trend with and without shading devices. For this reason, the calibration factors were distinguished for these two cases. Table 3.24~~Table 3.24~~ and Table 3.25~~Table 3.25~~ present the various correction factors, parted in terms of the use of a movable shading device.

Table 3.24 – Obtained calibration factors when solar shading devices are activated

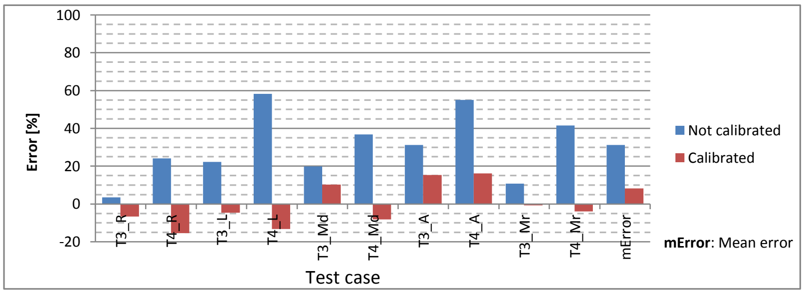
Shading devices ON												
	Heating mode						Cooling mode					
Region	a_{H0}	τ_{H0}	***Qtr***	***Qve***	***Qsol***	***Qint***	a_{C0}	τ_{C0}	***Qtr***	***Qve***	***Qsol***	***Qint***
Csa	1.00	15.67	1.00	1.00	0.90	0.93	1.20	15.00	1.07	1.00	0.83	0.90
Csb	1.33	15.00	1.00	1.07	0.97	0.93	1.10	15.00	1.03	1.10	0.97	1.00
Cfb	1.33	15.00	0.93	0.83	1.10	1.07	1.30	15.00	1.00	1.00	1.00	1.03
Dfb	1.30	14.67	0.83	0.90	1.25	1.25	1.00	15.00	1.07	1.07	0.97	1.00
Dfc	1.25	14.33	0.83	0.83	1.17	1.50	1.00	15.00	1.00	1.00	1.00	1.00

Table 3.25 – Obtained calibration factors when solar shading devices are not activated

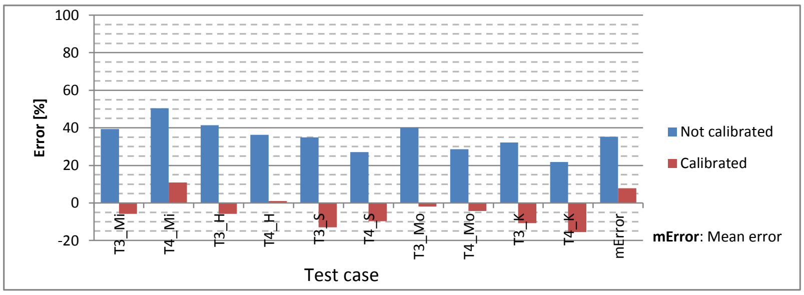
	Shading devices OFF											
Region	a_{H0}	τ_{H0}	***Qtr***	***Qve***	***Qsol***	***Qint***	a_{C0}	τ_{C0}	***Qtr***	***Qve***	***Qsol***	***Qint***
Csa	0.93	15.00	1.00	1.00	1.03	1.03	1.25	15.00	1.17	1.33	0.83	0.90
Csb	1.13	15.00	1.00	0.97	1.03	1.00	0.93	15.00	1.08	1.17	0.87	0.87
Cfb	1.17	15.00	1.00	0.93	1.00	1.03	1.08	15.00	1.08	1.33	0.90	0.87
Dfb	1.33	15.00	0.93	0.87	1.17	1.10	1.20	15.00	1.00	1.00	0.83	0.90
Dfc	1.50	14.00	0.80	0.80	1.07	1.20	1.00	15.00	1.17	1.17	0.92	0.90

Since the monthly algorithm allows to consider different shading devices activation modes in the winter and summer, the calibration factors of Table 3.24~~Table 3.24~~ were implemented in the cooling mode and the ones of Table 3.25~~Table 3.25~~ in the heating mode.

The calibration factors were applied to case tests 3 and 4 (25% glazing to floor ratio, Table 3.23~~Table 3.23~~) located in five cities of the climatic regions Csa and Dfb, in order to assess the error produced when using the climate of each location. In Fig. 3.18 it is shown that the error produced varies with the location, as expected. The highest errors occur for the city of Athens (16.2%) and for Kiev (15.5%), for the Csa and Dfb climatic regions, respectively. Nevertheless, the mean error is lower than 10% for the two climatic regions (Csa: 8.2% and Dfb: 7.9%).



a) R:Rome; L: Lisbon; Md: Madrid; A: Athens; Mr: Marseille



b) Mi: Minsk; H: Helsinki; S: Stockholm; Mo: Moscow; K: Kiev

Fig. 3.18: Verification of the calibration precision when applied to various cities of the climatic regions: a) Csa; b) Dfb

4 VALIDATION OF ADOPTED METHODOLOGIES

The validation of the adopted approaches described in the previous sections is herein presented. In both case, a case study is performed by the use of the simplified approach and the results are compared with the results provided by an advanced approach. The advanced analyses are made by the use of commercial software *GaBi 6* (2012) and *DesignBuilder* (2012), for life cycle assessment and energy quantification, respectively.

4.1 Validation of the macro-components approach

The validation of the macro-components approach is based on a case study referring to a low-rise residential building in Portugal. The results given by the adopted approach are compared with those obtained by an advanced analysis using GaBi software. The analysis is performed at the building level.

4.1.1 Description of the case study

The building is a two-storey residential house, for a single family, located in Coimbra (Portugal). The façades and the horizontal plans of the building are provided in Fig. 4.1 and Fig. 4.2, respectively.

Fig. 4.1: Building's façades

The total area of construction is about 202.00 m^2, with 100.8 m^2 on the ground floor and 100.8 m^2 on the first floor (20.2 m^2 in terrace). The total height of the building is 6 m.

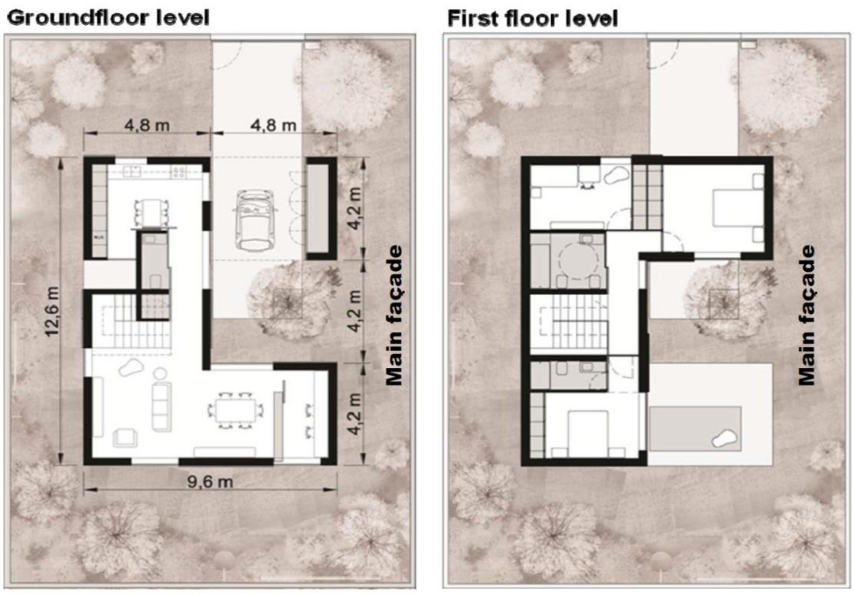


Fig. 4.2: Building's floors

The glazing areas of each façade are also provided in the plans of the building. Table 4.1 summarizes the areas of the building envelope.

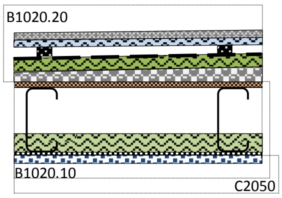
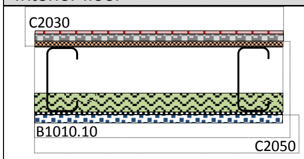
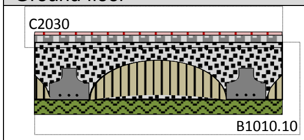
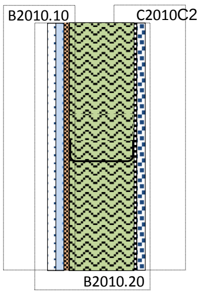
Table 4.1: Walls and glazing areas in the preliminary stage

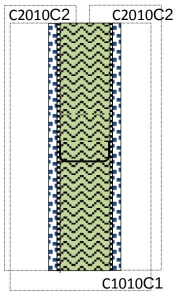
	North [m^2]	East [m^2]	South [m^2]	West [m^2]	Sum [m^2]
Walls	41.3	49.9	38.3	60.4	189.9
Glazing	13.0	17.3	15.6	4.3	50.2

4.1.2 Macro-components selection

To enable the life cycle assessment of the building, macro-components are selected for the main components of the building, namely, the superstructure, the exterior vertical enclosure and the interiors, which are indicated in Table 4.2.

Table 4.2: Macro-components selection

	Macro-component reference	Material layers	Thickness [mm] Density [kg/m^2]	U-value [W/m^2. K]	K_m [J/m^2. K]
Roof floor					
	B1020.20 Roof deck deck, slabs and sheathing	Cement slab	30 mm	0.37$^{(*)}$	13435
		XPS slab	30 mm		
		Air cavity	30 mm		
		Waterproof film	1.63 kg/m^2		
		XPS	0 mm		
		Concrete screed	40 mm		
	B1020.10 Roof structural frame	OSB	18 mmm		
		Air cavity	80 mm		
		Rock wool	120 mm		
		Light weight steel	17 kg/m^2		
		Gypsum board	15 mm		
	C2050 Ceiling finishes	Painting	0.125 kg/m^2		
Interior floor					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	-	61062
		Concrete screed	13 mm		
	B1010.10 Floor structural frame	OSB	18 mm		
		Air cavity	160 mm		
		Rock wool	40 mm		
		Light weight steel	14 kg/m^2		
		Gypsum board	15 mm		
	C2050 Ceiling finishes	Painting	0.125 kg/m^2		
Ground floor					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	0.599	65957
		Concrete screed	13 mm		
	B1010.10 Floor structural frame	Precast concrete slab	180 mm		
		XPS	40 mm		
Exterior wall					
	B2010.10 Exterior wall veneer	ETICS	13.8 kg/m^2	0.29$^{(*)}$	13391
	B2010.20 Exterior wall construction	OSB	13 mm		
		Rock wool	120 mm		
		Light weight steel	15 kg/m^2		
		Gypsum board	15 mm		
	C2010 Interior wall finishes	Painting	0.125 kg/m^2		
Interior wall					

	C2010 Interior wall finishes	Painting	0.125 kg/m^2	-	26782
	C1010 Interior partitions	Gypsum board	15 mm		
		Rock wool	60 mm		
		Light weight steel	10 kg/m^2		
		Gypsum board	15 mm		
	C2010 Interior wall finishes	Painting	0.125 kg/m^2		

(*) Corrected values for thermal bridging

4.1.3 Application of the macro-components approach

According to the building geometry and by the use of the selected macro-components (indicated in Table 4.2), the environmental calculations are undertaken for the complete building and for a life span of 50 years. The results are indicated in Fig. 4.3, considering the modules defined in EN 15978. This graph represents the contribution of each module per impact category. As observed from this graph, the stage of material production (modules A1-A3) dominates all impact categories (with contributions higher than 60%).

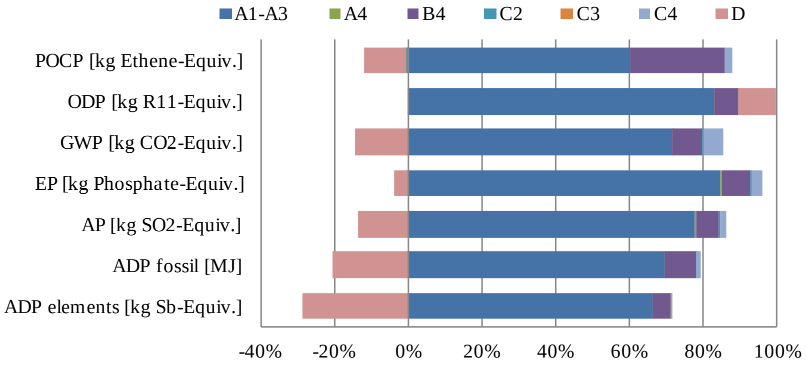


Fig. 4.3: Contribution of each module per environmental category

The stage of operation (module B4) and the recycling and recover of materials (module D) have a significant contribution to most impacts categories, followed by the demolition stage (modules C2 – C4). It is noted in Fig. 4.3 that negative values are obtained for module D indicating that for this particular solution credits are obtained due to the recycling and/or recovering of materials after building demolition. The results for each environmental category are summarized in Table 4.3.

Table 4.3: Life cycle environmental analysis of the building

Environmental category	TOTAL
ADP elements [kg Sb-Equiv.]	1.11E-01
ADP fossil [MJ]	4.38E+05
AP [kg SO2-Equiv.]	1.35E+02
EP [kg Phosphate-Equiv.]	1.53E+01
GWP [kg CO2-Equiv.]	3.54E+04
ODP [kg R11-Equiv.]	1.00E-03
POCP [kg Ethene-Equiv.]	3.71E+01

4.1.4 Comparison with detailed life cycle analysis

In this section, the single family house is analysed taking into account full building details and life cycle stages. The life-cycle analysis herein presented fills the gaps in the macro-component approach described previously, namely the foundations of the building and the construction stage (module A5). The full life cycle analysis was performed by *GaBi 6* software (2012).

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

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

The results of the life cycle analysis, taken into account all the life cycle stages, are represented in Fig. 4.4.

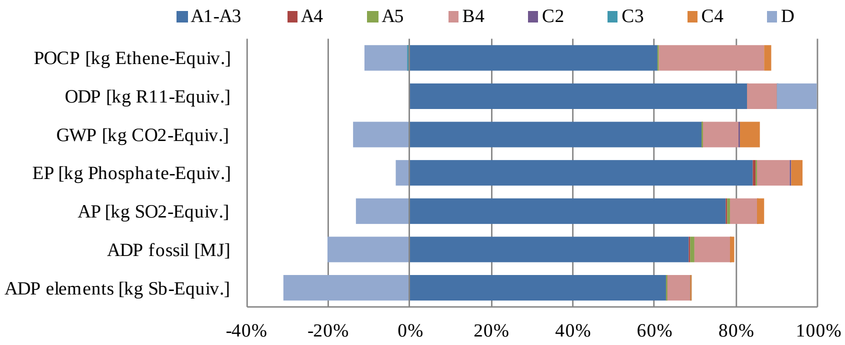


Fig. 4.4: Life cycle analysis of the full building

The stage of material production (modules A1-A3) dominates all impact categories (with contributions higher than 60%). The construction stage (modules A4-A5) has a negligible importance, varying from 0%, for the categories of ODP, POCP and $ADP_{elements}$ to about 2.1% for the environmental category of ADP_{fossil}. The stage of operation (module B4) and the recycling and recover of materials (module D) have a significant contribution to most impacts categories, followed by the demolition stage (modules C2 – C4). It is noted that these conclusion were already achieved in the simplified approach, despite its limitations.

Finally, the relative error in each impact category, of the simplified approach in relation to the full analysis is indicated in Table 4.4.

Table 4.4: Error (%) in each impact category by the use of the macro-components approach

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

For most environmental categories the error is negligible. Naturally, the consideration of other construction systems may lead to a higher relevance of the construction stage.

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

4.2 Validation of the approach for the calculation of energy needs

The validation of the adopted approach for energy calculation is based in same case study. In the following sections, all additional input data and calculation procedure are described.

The results given by the adopted approach are compared with those obtained by an advanced dynamic analysis using *DesignBuilder/EnergyPlus* (2012).

4.2.1 Climate data and ground thermal characteristics

The building is located in Coimbra, belonging to the climatic region Csb. The respective monthly values of air temperature and global solar radiation are presented in Fig. 4.5.

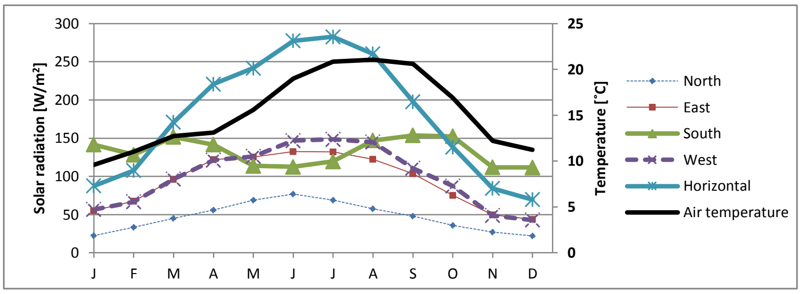


Fig. 4.5: Climate data of Coimbra: solar radiation and outside air temperature

The thermal characteristics of the ground were considered by default, as provided in Table 3.10.

4.2.2 Occupancy related data

The schedule of occupancy and heat flow due to internal loads (occupants activity, appliances and lighting) were considered by the default values provided by ISO 13790 and previously presented in Table 3.13~~Table 3.13~~. The comfort temperatures considered 20˚C and 25˚C for winter and summer seasons, respectively.

4.2.3 Building services

Likewise, for the technical information and schedule of the building services (heating, cooling, ventilation and DHW production) the set of default values, indicated in Table 4.5, were considered.

Table 4.5: Building systems' input data (default values)

Building Services	**Values**
Air conditioning (Set-point 20ºC – 25ºC) (1)	COP Heating = 4.0 COP Cooling = 3.0
Domestic hot water production [2]	Efficiency: 0.9
Ventilation + infiltration rate (3) (Constant values)	0.6 ac/h (Heating mode) 1.2 ac/h (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.

4.2.4 Glazed envelope and shading operational specifications

The characteristics and properties of the glazed elements are indicated in Table In this case, double-pane glazed windows, with a PVC frame, were considered.

Table 4.6: 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

The thermal properties of the shading devices were considered from Table 4.7~~Table 4.7~~.

Table 4.7: Thermal and optical properties of the shading devices

Element	**Solar transmittance**	**Solar reflectance**	**R** [m^2.K/W]	g_{gl+sh}
Shutters	0.02	0.80	0.260*	0,04**

*shutter and air space included (ISO 10077, 2006); **EN 13363-1, 2007.

4.2.5 Opaque envelope

The characteristics and properties of the opaque elements of the façades are taken from the macro-components (see Table 4.2).

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

4.2.6 Results of the energy performance of the building

In this case, the energy need, computed with monthly algorithm, is 651.3 kWh and 2195.0 kWh, per year, for space heating and cooling, respectively. Thus, the energy need, per year, for space heating and cooling is 2846.3 kWh (23.0 kWh/m^2) and for the DHW production is 2642 kWh (21.3 kWh/m^2).

The energy needs for space cooling and space heating, per month, is provided in Fig. 4.6.

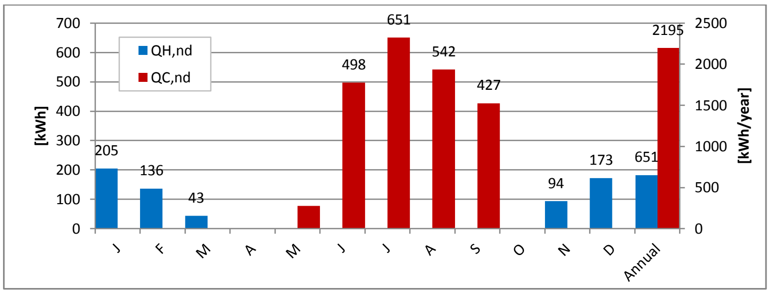


Fig. 4.6: Energy needs for space cooling and heating (based on the monthly algorithm)

4.2.7 Comparison with numerical advanced simulation

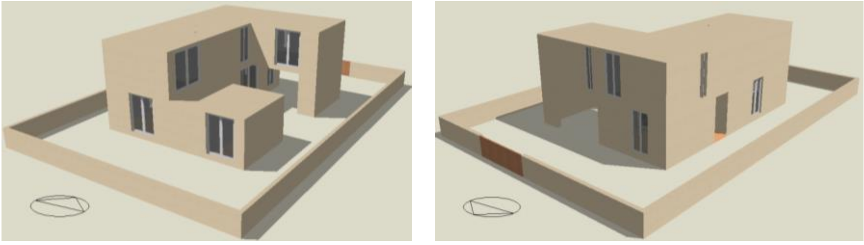
A comparison between the results provided by the monthly algorithm and the results of advanced dynamic simulations was performed in order to evaluate the accuracy of the results provided by the former.

4.2.7.1 Model for dynamic simulation

The advanced dynamic simulation of the thermal behaviour of the building was performed using the DesignBuilder (2012) software. The source of weather data used in the simulation was the same as in the simplified approach. However, in this case, instead of monthly values for dry bulb temperature and solar radiation, hourly values are used for all the weather parameters.

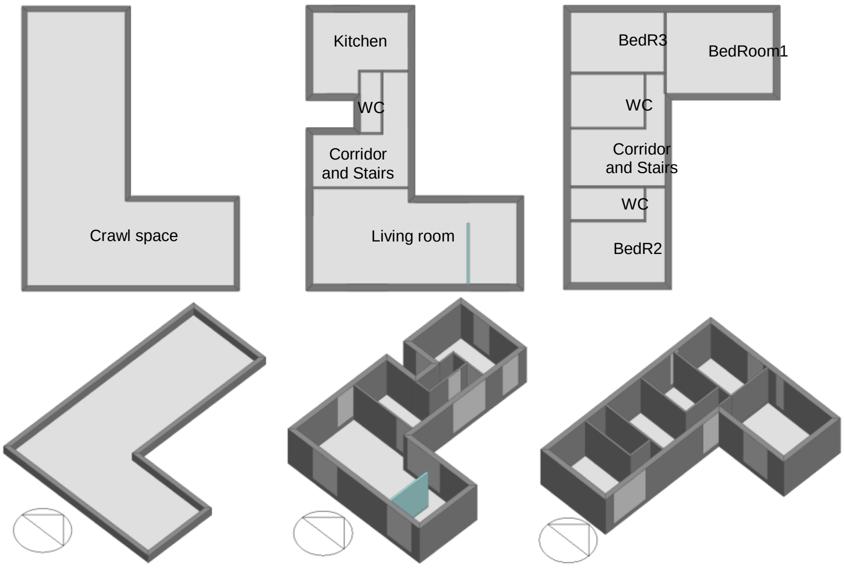
The three-dimensional advanced modelling allows simulating the full building architecture illustrated in Fig. 4.1 and Fig. 4.2. Hence, Fig. 4.7 illustrates two exterior elevation views of the DesignBuilder model used in the dynamic simulation. The building model was assembled using ten different thermal zones, corresponding to the internal partitions of the building (Fig. 4.8):

- (i) the crawl space on the basement, which was modelled as an unconditioned space;
- (ii) the ground floor, which has three thermal zones;
- (iii) the first floor with five zones;
- (iv) the area that is common to both floors, which includes the corridors and the stairways.



a) Southern and western views b) Northern and eastern views

Fig. 4.7: Elevation views of the building model



a) Basement b) Ground floor c) First floor

Fig. 4.8: Layout of the floors

The construction elements considered in the model are the same as described previously for the macro-components approach (see Table 4.2, Table 4.6~~Table 4.6~~ and Table 4.7~~Table 4.7~~, respectively for opaque, glazed components and shading devices). Likewise, the same strategy for windows shading control was considered. In addition, the occupancy schedule, the ventilation and infiltration rates, the efficiency and the schedule of the air-conditioning equipment are taken from the previous analysis.

A graphical comparison between the monthly and annual energy needs, for heating and cooling, computed by both approaches, is displayed in Fig. 4.9. The energy needs, per year, for space heating and cooling, provided by dynamic simulations, are 932.4 kWh and 2133.3 kWh, respectively; leading to a total energy need of 3065.7 kWh per year (24.8 kWh/m^2).

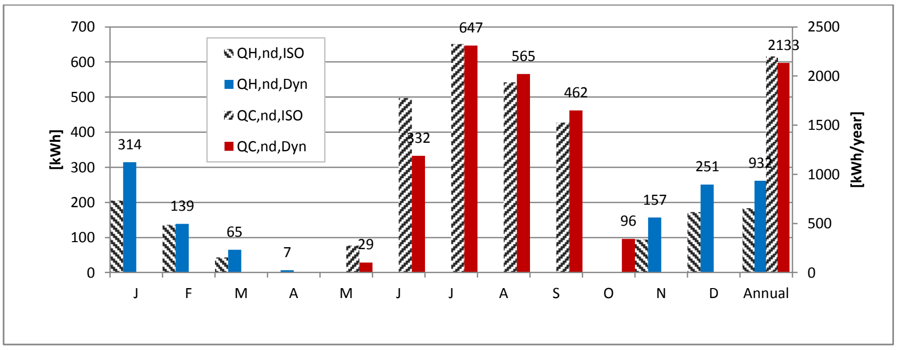


Fig. 4.9: Building energy need for space cooling and heating: dynamic simulations (Dyn) *versus* monthly algorithm (ISO)

As observed from Fig. 4.9, the energy need calculated with the simplified approach (monthly method) shows a good agreement with the results obtained from dynamic calculations. When comparing the total energy needs (heating and cooling) of the developed stage (2846.3 kWh/year) with the dynamic calculation, the error is -7.2%.

4.3 FINAL REMARKS

The two simplified approaches presented in this document avoid the use of complex tools such as LCA that usually requires some expertise in the field and provides substantial reduction in the time usually needed to perform such analysis.

The validation of both approaches was based on the comparison with advanced analyses performed by the use of commercial software *GaBi 6* (2012) and *DesignBuilder* (2012), for life cycle assessment and energy quantification, respectively.

The comparison of the results, from both types of analyses, enables to conclude that the accuracy of both approaches is very reasonable.

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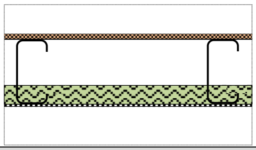
APPENDIX 1 – DATABASE OF MACRO-COMPONENTS

B1010.10 Floor structural frame				
B1010.10.1a	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	18	Incineration	80
	Air cavity (mm)	160		
	Rock wool (mm)	40	Recycling	80
	Gypsum board (mm)	15	Recycling	80
	LWS (kg/m2)	14	Recycling	90

B1010.10.1a - LCA

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	2,83E-05	1,76E-09	1,54E-09	3,37E-08	-1,96E-04
ADP fossil [MJ]	5,48E+02	6,54E-01	5,72E-01	1,31E+00	-3,35E+02
AP [kg SO2-Equiv.]	1,70E-01	2,11E-04	1,83E-04	5,74E-04	-4,45E-02
EP [kg Phosphate-Equiv.]	1,41E-02	4,86E-05	4,20E-05	8,79E-05	-1,01E-03
GWP [kg CO2-Equiv.]	5,12E+01	4,71E-02	4,12E-02	3,86E-01	-1,46E+01
ODP [kg R11-Equiv.]	7,65E-07	8,25E-13	7,21E-13	7,21E-11	1,76E-07
POCP [kg Ethene-Equiv.]	2,53E-02	-6,89E-05	-5,95E-05	1,49E-04	-1,07E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
Rock wool	PE International	Europe	2011

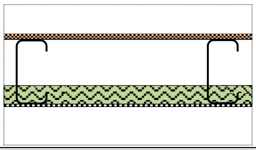
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B1010.10 Floor structural frame

B1010.10.1b	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	18	Incineration	80
	Air cavity (mm)	160	-	-
	EPS (mm)	40	Incineration	80
	Gypsum board (mm)	15	Recycling	80
	LWS (kg/m2)	14	Recycling	90

B1010.10.1b - LCA

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	2,75E-05	1,53E-09	1,34E-09	3,80E-08	-1,96E-04
ADP fossil [MJ]	5,36E+02	5,70E-01	5,00E-01	1,37E+00	-3,57E+02
AP [kg SO2-Equiv.]	1,30E-01	1,84E-04	1,60E-04	6,24E-04	-5,26E-02
EP [kg Phosphate-Equiv.]	9,54E-03	4,24E-05	3,68E-05	1,00E-04	-1,48E-03
GWP [kg CO2-Equiv.]	4,68E+01	4,11E-02	3,60E-02	2,48E+00	-1,63E+01
ODP [kg R11-Equiv.]	8,21E-07	7,19E-13	6,31E-13	6,98E-11	1,76E-07
POCP [kg Ethene-Equiv.]	3,55E-02	-6,01E-05	-5,20E-05	1,42E-04	-1,12E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

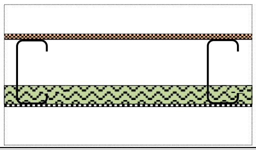
Process - LCA	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
EPS	PE International	Europe	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Incineration EPS	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B1010.10 Floor structural frame				
B1010.10.1c	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	18	Incineration	80
	Air cavity (mm)	160		
	XPS (mm)	40	Incineration	80
	Gypsum board (mm)	15	Recycling	80
	LWS (kg/m2)	14	Recycling	90

B1010.10.1c - LCA

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	2,81E-05	1,56E-09	1,37E-09	4,42E-08	-1,96E-04
ADP fossil [MJ]	5,75E+02	5,78E-01	5,07E-01	1,54E+00	-3,70E+02
AP [kg SO2-Equiv.]	1,33E-01	1,87E-04	1,62E-04	7,16E-04	-5,74E-02
EP [kg Phosphate-Equiv.]	9,73E-03	4,30E-05	3,73E-05	1,17E-04	-1,77E-03
GWP [kg CO2-Equiv.]	4,79E+01	4,16E-02	3,65E-02	3,78E+00	-1,72E+01
ODP [kg R11-Equiv.]	7,64E-07	7,29E-13	6,40E-13	7,61E-11	1,75E-07
POCP [kg Ethene-Equiv.]	2,49E-02	-6,09E-05	-5,28E-05	1,54E-04	-1,15E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

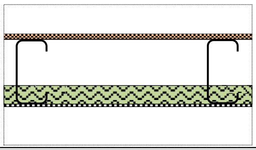
Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
XPS	PE International	Germany	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Incineration XPS	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B1010.10 Floor structural frame				
B1010.10.1d	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	18	Incineration	80
	Air cavity (mm)	160		
	PUR (mm)	40	Incineration	80
	Gypsum board (mm)	15	Recycling	80
	LWS (kg/m2)	14	Recycling	90

B1010.10.1d - LCA

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	4,65E-05	1,56E-09	1,37E-09	4,48E-08	-1,96E-04
ADP fossil [MJ]	6,19E+02	5,78E-01	5,07E-01	1,76E+00	-3,57E+02
AP [kg SO2-Equiv.]	1,37E-01	1,87E-04	1,62E-04	1,43E-03	-5,26E-02
EP [kg Phosphate-Equiv.]	1,09E-02	4,30E-05	3,73E-05	3,06E-04	-1,48E-03
GWP [kg CO2-Equiv.]	5,18E+01	4,16E-02	3,65E-02	2,59E+00	-1,63E+01
ODP [kg R11-Equiv.]	7,65E-07	7,29E-13	6,40E-13	8,46E-11	1,76E-07
POCP [kg Ethene-Equiv.]	2,37E-02	-6,09E-05	-5,28E-05	1,90E-04	-1,12E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
PUR	PE International	Germany	2011

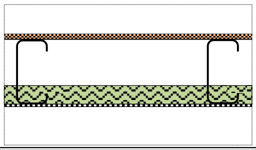
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Incineration PUR	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B1010.10 Floor structural frame

B1010.10.1e	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	18	Incineration	80
	Air cavity (mm)	160		
	Cork (mm)	40	Recycling	80
	Gypsum board (mm)	15	Recycling	80
	LWS (kg/m2)	14	Recycling	90

B1010.10.1e - LCA

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	2,72E-05	1,64E-09	1,43E-09	3,09E-08	-1,96E-04
ADP fossil [MJ]	5,04E+02	6,09E-01	5,32E-01	1,21E+00	-3,35E+02
AP [kg SO2-Equiv.]	1,35E-01	1,97E-04	1,70E-04	5,26E-04	-4,45E-02
EP [kg Phosphate-Equiv.]	1,13E-02	4,53E-05	3,91E-05	8,06E-05	-1,01E-03
GWP [kg CO2-Equiv.]	4,75E+01	4,38E-02	3,83E-02	3,54E-01	-1,46E+01
ODP [kg R11-Equiv.]	7,64E-07	7,68E-13	6,71E-13	6,61E-11	1,76E-07
POCP [kg Ethene-Equiv.]	2,27E-02	-6,42E-05	-5,54E-05	1,37E-04	-1,07E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

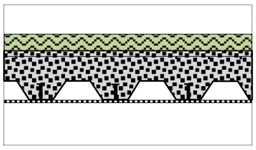
Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
Cork	PE International	Germany	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B1010.10 Floor structural frame				
B1010.10.2a	Materials	Thickness/ density	End-of-life scenario	RR (%)
	PE (mm)	20	Incineration	80
	Concrete (kg/m2)	410	Recycling	70
	Rebars (kg/m2)	8.24	Recycling	70
	Steel sheet (kg/m2)	11.10	Recycling	70
	Gypsum board (mm)	15	Recycling	80
	Steel structure (kg/m2)	40	Recycling	90
B1010.10.2a - LCA				

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	-4,61E-04	2,08E-08	1,81E-08	1,26E-06	-3,32E-04
ADP fossil [MJ]	1,56E+03	7,71E+00	6,74E+00	4,90E+01	-3,44E+02
AP [kg SO2-Equiv.]	3,93E-01	2,49E-03	2,16E-03	2,14E-02	-9,22E-02
EP [kg Phosphate-Equiv.]	3,65E-02	5,73E-04	4,96E-04	3,28E-03	-2,77E-03
GWP [kg CO2-Equiv.]	1,51E+02	5,56E-01	4,86E-01	1,58E+01	-3,67E+01
ODP [kg R11-Equiv.]	1,88E-06	9,73E-12	8,51E-12	2,68E-09	1,04E-06
POCP [kg Ethene-Equiv.]	6,27E-02	-8,13E-04	-7,01E-04	5,54E-03	-1,90E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

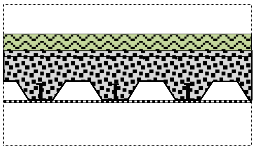
Process	Data source	Geographical coverage	Date
Concrete	PE International	Germany	2011
Reinforcement rebars	Worldsteel	World	2007
Steel sheet	Worldsteel	World	2007
Structural steel	Worldsteel	World	2007
Gypsum board	PE International	Europe	2008
PE	PE International	Germany	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration PE	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

<table>
<tr><th colspan="5">B1010.10 Floor structural frame</th></tr>
<tr><td>B1010.10.2b</td><td>Materials</td><td>Thickness/ density</td><td>End-of-life scenario</td><td>RR (%)</td></tr>
<tr><td rowspan="6"></td><td>EPS (mm)</td><td>20</td><td>Incineration</td><td>80</td></tr>
<tr><td>Concrete (kg/m2)</td><td>410</td><td>Recycling</td><td>70</td></tr>
<tr><td>Rebars (kg/m2)</td><td>8.24</td><td>Recycling</td><td>70</td></tr>
<tr><td>Steel sheet (kg/m2)</td><td>11.10</td><td>Recycling</td><td>70</td></tr>
<tr><td>Gypsum board (mm)</td><td>15</td><td>Recycling</td><td>80</td></tr>
<tr><td>Steel structure (kg/m2)</td><td>40</td><td>Recycling</td><td>90</td></tr>
</table>

B1010.10.2b - LCA

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	-4,62E-04	2,08E-08	1,81E-08	1,26E-06	-3,32E-04
ADP fossil [MJ]	1,54E+03	7,71E+00	6,74E+00	4,89E+01	-3,37E+02
AP [kg SO2-Equiv.]	3,92E-01	2,49E-03	2,16E-03	2,13E-02	-8,94E-02
EP [kg Phosphate-Equiv.]	3,64E-02	5,73E-04	4,96E-04	3,27E-03	-2,61E-03
GWP [kg CO2-Equiv.]	1,50E+02	5,55E-01	4,86E-01	1,54E+01	-3,62E+01
ODP [kg R11-Equiv.]	1,91E-06	9,73E-12	8,50E-12	2,68E-09	1,04E-06
POCP [kg Ethene-Equiv.]	6,92E-02	-8,13E-04	-7,01E-04	5,53E-03	-1,88E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
Concrete	PE International	Germany	2011
Reinforcement rebars	Worldsteel	World	2007
Steel sheet	Worldsteel	World	2007
Structural steel	Worldsteel	World	2007
Gypsum board	PE International	Europe	2008
EPS	PE International	Europe	2011

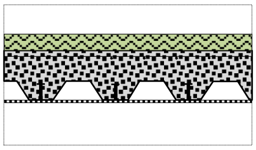
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration EPS	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B1010.10 Floor structural frame

B1010.10.2c	Materials	Thickness/ density	End-of-life scenario	RR (%)
	XPS (mm)	20	Incineration	80
	Concrete (kg/m2)	410	Recycling	70
	Rebars (kg/m2)	8.24	Recycling	70
	Steel sheet (kg/m2)	11.10	Recycling	70
	Gypsum board (mm)	15	Recycling	80
	Steel structure (kg/m2)	40	Recycling	90

B1010.10.2c - LCA

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	-4,62E-04	2,08E-08	1,82E-08	1,26E-06	-3,32E-04
ADP fossil [MJ]	1,56E+03	7,71E+00	6,74E+00	4,90E+01	-3,43E+02
AP [kg SO2-Equiv.]	3,94E-01	2,49E-03	2,16E-03	2,14E-02	-9,19E-02
EP [kg Phosphate-Equiv.]	3,65E-02	5,74E-04	4,96E-04	3,28E-03	-2,75E-03
GWP [kg CO2-Equiv.]	1,51E+02	5,56E-01	4,86E-01	1,60E+01	-3,66E+01
ODP [kg R11-Equiv.]	1,88E-06	9,73E-12	8,51E-12	2,68E-09	1,04E-06
POCP [kg Ethene-Equiv.]	6,39E-02	-8,13E-04	-7,01E-04	5,54E-03	-1,89E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

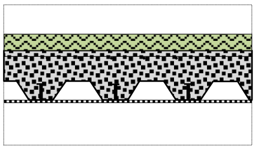
Process	Data source	Geographical coverage	Date
Concrete	PE International	Germany	2011
Reinforcement rebars	Worldsteel	World	2007
Steel sheet	Worldsteel	World	2007
Structural steel	Worldsteel	World	2007
Gypsum board	PE International	Europe	2008
XPS	PE International	Germany	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration XPS	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B1010.10 Floor structural frame				
B1010.10.2d	Materials	Thickness/ density	End-of-life scenario	RR (%)
	Cork (mm)	20	Recycling	80
	Concrete (kg/m2)	410	Recycling	70
	Rebars (kg/m2)	8.24	Recycling	70
	Steel sheet (kg/m2)	11.10	Recycling	70
	Gypsum board (mm)	15	Recycling	80
	Steel structure (kg/m2)	40	Recycling	90
B1010.10.2d - LCA				

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	-4,62E-04	2,08E-08	1,82E-08	1,25E-06	-3,32E-04
ADP fossil [MJ]	1,52E+03	7,73E+00	6,76E+00	4,88E+01	-3,26E+02
AP [kg SO2-Equiv.]	3,95E-01	2,50E-03	2,16E-03	2,13E-02	-8,54E-02
EP [kg Phosphate-Equiv.]	3,73E-02	5,75E-04	4,97E-04	3,26E-03	-2,37E-03
GWP [kg CO2-Equiv.]	1,51E+02	5,57E-01	4,87E-01	1,43E+01	-3,53E+01
ODP [kg R11-Equiv.]	1,88E-06	9,75E-12	8,53E-12	2,68E-09	1,04E-06
POCP [kg Ethene-Equiv.]	6,28E-02	-8,15E-04	-7,03E-04	5,53E-03	-1,86E-02

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
Concrete	PE International	Germany	2011
Reinforcement rebars	Worldsteel	World	2007
Steel sheet	Worldsteel	World	2007
Structural steel	Worldsteel	World	2007
Gypsum board	PE International	Europe	2008
Cork	PE International	Germany	2011

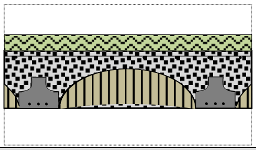
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B1010.10 Floor structural frame

B1010.10.3a	Materials	Thickness/ density	End-of-life scenario	RR (%)
	PE (mm)	20	Incineration	80
	Concrete (kg/m2)	455.4	Recycling	70
	Rebars (kg/m2)	21.17	Recycling	70

B1010.10.3a

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	-5,27E-05	2,07E-08	1,81E-08	1,36E-06	-1,09E-05
ADP fossil [MJ]	6,37E+02	7,68E+00	6,71E+00	5,31E+01	-4,99E+01
AP [kg SO2-Equiv.]	1,62E-01	2,48E-03	2,15E-03	2,32E-02	-1,80E-02
EP [kg Phosphate-Equiv.]	2,12E-02	5,71E-04	4,94E-04	3,55E-03	-7,25E-04
GWP [kg CO2-Equiv.]	7,42E+01	5,53E-01	4,84E-01	1,70E+01	-5,44E+00
ODP [kg R11-Equiv.]	2,64E-07	9,69E-12	8,47E-12	2,91E-09	3,61E-08
POCP [kg Ethene-Equiv.]	2,23E-02	-8,09E-04	-6,98E-04	6,00E-03	-2,31E-03

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

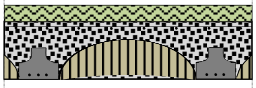
Process	Data source	Geographical coverage	Date
Concrete	PE International	Germany	2011
Reinforcement rebars	Worldsteel	World	2007
PE	PE International	Germany	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007
Incineration PE	PE International	Europe	2011

<table>
<tr><th colspan="5">B1010.10 Floor structural frame</th></tr>
<tr><td>B1010.10.3b</td><td>Materials</td><td>Thickness/ density</td><td>End-of-life scenario</td><td>RR (%)</td></tr>
<tr><td rowspan="3"></td><td>EPS (mm)</td><td>20</td><td>Incineration</td><td>80</td></tr>
<tr><td>Concrete (kg/m2)</td><td>455.4</td><td>Recycling</td><td>70</td></tr>
<tr><td>Rebars (kg/m2)</td><td>21.17</td><td>Recycling</td><td>70</td></tr>
</table>

B1010.10.3b

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	-5,38E-05	2,07E-08	1,81E-08	1,36E-06	-1,09E-05
ADP fossil [MJ]	6,18E+02	7,68E+00	6,71E+00	5,30E+01	-4,24E+01
AP [kg SO2-Equiv.]	1,61E-01	2,48E-03	2,15E-03	2,31E-02	-1,52E-02
EP [kg Phosphate-Equiv.]	2,11E-02	5,71E-04	4,93E-04	3,55E-03	-5,61E-04
GWP [kg CO2-Equiv.]	7,36E+01	5,53E-01	4,83E-01	1,66E+01	-4,87E+00
ODP [kg R11-Equiv.]	2,93E-07	9,68E-12	8,46E-12	2,90E-09	3,61E-08
POCP [kg Ethene-Equiv.]	2,87E-02	-8,09E-04	-6,98E-04	6,00E-03	-2,14E-03

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
Concrete	PE International	Germany	2011
Reinforcement rebars	Worldsteel	World	2007
EPS	PE International	Europe	2011

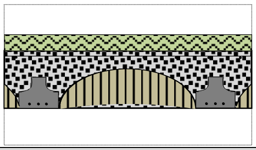
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007
Incineration EPS	PE International	Europe	2011

B1010.10 Floor structural frame

B1010.10.3c	Materials	Thickness/ density	End-of-life scenario	RR (%)
	XPS (mm)	20	Incineration	80
	Concrete (kg/m2)	455.4	Recycling	70
	Rebars (kg/m2)	21.17	Recycling	70

B1010.10.3c

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	-5,35E-05	2,07E-08	1,81E-08	1,36E-06	-1,09E-05
ADP fossil [MJ]	6,37E+02	7,68E+00	6,71E+00	5,31E+01	-4,89E+01
AP [kg SO2-Equiv.]	1,63E-01	2,48E-03	2,15E-03	2,32E-02	-1,77E-02
EP [kg Phosphate-Equiv.]	2,12E-02	5,71E-04	4,94E-04	3,56E-03	-7,04E-04
GWP [kg CO2-Equiv.]	7,42E+01	5,53E-01	4,84E-01	1,72E+01	-5,37E+00
ODP [kg R11-Equiv.]	2,64E-07	9,69E-12	8,47E-12	2,91E-09	3,61E-08
POCP [kg Ethene-Equiv.]	2,35E-02	-8,09E-04	-6,98E-04	6,01E-03	-2,28E-03

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

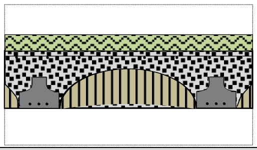
Process	Data source	Geographical coverage	Date
Concrete	PE International	Germany	2011
Reinforcement rebars	Worldsteel	World	2007
XPS	PE International	Europe	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007
Incineration XPS	PE International	Europe	2011

B1010.10 Floor structural frame				
B1010.10.3d	Materials	Thickness/ density	End-of-life scenario	RR (%)
	Cork (mm) Concrete (kg/m2) Rebars (kg/m2)	20 455.4 21.17	Recycling Recycling Recycling	80 70 70

B1010.10.3d

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	-5,40E-05	2,07E-08	1,83E-08	1,36E-06	-1,09E-05
ADP fossil [MJ]	6,02E+02	7,69E+00	6,80E+00	5,29E+01	-3,17E+01
AP [kg SO2-Equiv.]	1,64E-01	2,49E-03	2,18E-03	2,31E-02	-1,12E-02
EP [kg Phosphate-Equiv.]	2,19E-02	5,72E-04	5,00E-04	3,54E-03	-3,22E-04
GWP [kg CO2-Equiv.]	7,40E+01	5,54E-01	4,90E-01	1,55E+01	-4,05E+00
ODP [kg R11-Equiv.]	2,64E-07	9,71E-12	8,58E-12	2,90E-09	3,62E-08
POCP [kg Ethene-Equiv.]	2,24E-02	-8,11E-04	-7,07E-04	6,00E-03	-1,91E-03

Functional equivalent:

1 m^2 of a structural slab of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
Concrete	PE International	Germany	2011
Reinforcement rebars	Worldsteel	World	2007
Cork	PE International	Germany	2011

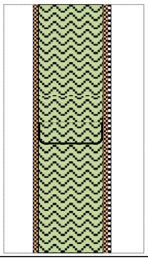
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B2010.20 Exterior wall construction

B2010.20.1a	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	13	Incineration	80
	Rock wool (mm)	120	Recycling	80
	Gypsum board (mm)	15	Landfill	
	LWS (kg/m2)	15	Recycling	90

B1010.20.1a

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	3,06E-05	2,19E-09	1,92E-09	4,32E-08	-2,10E-04
ADP fossil [MJ]	7,09E+02	8,14E-01	7,12E-01	1,68E+00	-3,05E+02
AP [kg SO2-Equiv.]	2,65E-01	2,63E-04	2,28E-04	7,35E-04	-4,81E-02
EP [kg Phosphate-Equiv.]	2,41E-02	6,05E-05	5,23E-05	1,13E-04	-1,17E-03
GWP [kg CO2-Equiv.]	6,50E+01	5,86E-02	5,13E-02	4,94E-01	-1,73E+01
ODP [kg R11-Equiv.]	6,43E-07	1,03E-12	8,98E-13	9,24E-11	3,41E-07
POCP [kg Ethene-Equiv.]	3,27E-02	-8,58E-05	-7,40E-05	1,91E-04	-1,13E-02

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
Rock wool	PE International	Europe	2011

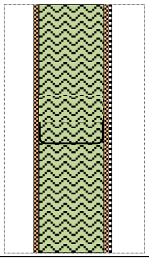
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B2010.20 Exterior wall construction

B2010.20.1b	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	13	Incineration	80
	EPS (mm)	120	Incineration	80
	Gypsum board (mm)	15	Landfill	
	LWS (kg/m2)	15	Recycling	90

B1010.20.1b

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	2,82E-05	1,93E-09	1,62E-09	5,61E-08	-2,10E-04
ADP fossil [MJ]	6,75E+02	7,18E-01	6,00E-01	1,84E+00	-3,70E+02
AP [kg SO2-Equiv.]	1,44E-01	2,32E-04	1,92E-04	8,87E-04	-7,24E-02
EP [kg Phosphate-Equiv.]	1,03E-02	5,34E-05	4,41E-05	1,50E-04	-2,60E-03
GWP [kg CO2-Equiv.]	5,18E+01	5,17E-02	4,33E-02	6,79E+00	-2,22E+01
ODP [kg R11-Equiv.]	8,13E-07	9,05E-13	7,57E-13	8,54E-11	3,41E-07
POCP [kg Ethene-Equiv.]	6,33E-02	-7,57E-05	-6,24E-05	1,70E-04	-1,27E-02

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
EPS	PE International	Europe	2011

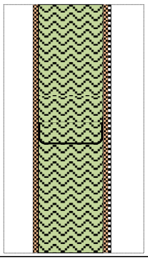
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Incineration EPS	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B2010.20 Exterior wall construction

B2010.20.1c	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	13	Incineration	80
	XPS (mm)	120	Incineration	80
	Gypsum board (mm)	15	Landfill	
	LWS (kg/m2)	15	Recycling	90

B1010.20.1c

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	2,99E-05	2,24E-09	1,84E-09	7,46E-08	-2,10E-04
ADP fossil [MJ]	7,89E+02	8,33E-01	6,85E-01	2,36E+00	-4,08E+02
AP [kg SO2-Equiv.]	1,53E-01	2,69E-04	2,19E-04	1,16E-03	-8,70E-02
EP [kg Phosphate-Equiv.]	1,09E-02	6,20E-05	5,04E-05	2,01E-04	-3,46E-03
GWP [kg CO2-Equiv.]	5,52E+01	6,00E-02	4,94E-02	1,07E+01	-2,52E+01
ODP [kg R11-Equiv.]	6,41E-07	1,05E-12	8,65E-13	1,04E-10	3,41E-07
POCP [kg Ethene-Equiv.]	3,16E-02	-8,79E-05	-7,13E-05	2,06E-04	-1,36E-02

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

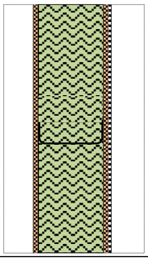
Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
XPS	PE International	Germany	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Incineration XPS	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B2010.20 Exterior wall construction				
B2010.20.1d	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	13	Incineration	80
	PUR (mm)	120	Incineration	80
	Gypsum board (mm)	15	Landfill	
	LWS (kg/m2)	15	Recycling	90

B1010.20.1d

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	8,52E-05	2,24E-09	1,84E-09	7,64E-08	-2,10E-04
ADP fossil [MJ]	9,22E+02	8,33E-01	6,85E-01	3,02E+00	-3,70E+02
AP [kg SO2-Equiv.]	1,66E-01	2,69E-04	2,19E-04	3,30E-03	-7,23E-02
EP [kg Phosphate-Equiv.]	1,43E-02	6,20E-05	5,04E-05	7,68E-04	-2,60E-03
GWP [kg CO2-Equiv.]	6,70E+01	6,00E-02	4,94E-02	7,11E+00	-2,22E+01
ODP [kg R11-Equiv.]	6,44E-07	1,05E-12	8,65E-13	1,30E-10	3,41E-07
POCP [kg Ethene-Equiv.]	2,81E-02	-8,79E-05	-7,13E-05	3,15E-04	-1,27E-02

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

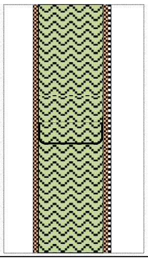
Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
PUR	PE International	Germany	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Incineration PUR	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B2010.20 Exterior wall construction				
B2010.20.1e	Materials	Thickness/ density	End-of-life scenario	RR (%)
	OSB (mm)	13	Incineration	80
	Cork (mm)	120	Recycling	80
	Gypsum board (mm)	15	Landfill	
	LWS (kg/m2)	15	Recycling	90

B1010.20.1e

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	2,72E-05	3,49E-09	1,60E-09	3,48E-08	-2,10E-04
ADP fossil [MJ]	5,78E+02	1,30E+00	5,94E-01	1,36E+00	-3,05E+02
AP [kg SO2-Equiv.]	1,60E-01	4,19E-04	1,90E-04	5,92E-04	-4,81E-02
EP [kg Phosphate-Equiv.]	1,55E-02	9,64E-05	4,37E-05	9,07E-05	-1,17E-03
GWP [kg CO2-Equiv.]	5,39E+01	9,34E-02	4,28E-02	3,98E-01	-1,73E+01
ODP [kg R11-Equiv.]	6,40E-07	1,64E-12	7,49E-13	7,44E-11	3,41E-07
POCP [kg Ethene-Equiv.]	2,50E-02	-1,37E-04	-6,17E-05	1,54E-04	-1,13E-02

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
OSB	PE International	Germany	2008
Gypsum board	PE International	Europe	2008
Light-weight steel (LWS)	Worldsteel	World	2007
Cork	PE International	Germany	2011

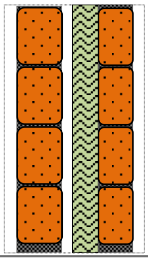
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration OSB	PE International	Germany	2008
Landfill of inert materials	PE International	Germany	2011
Recycling steel	Worldsteel	World	2007

B2010.20 Exterior wall construction

B2010.20.2a	Materials	Thickness/ density	End-of-life scenario	RR (%)
	Brick wall (mm)	11	Landfill	
	Air cavity (mm)	0		
	Rock wool (mm)	60	Recycling	80
	Brick wall (mm)	11	Landfill	

B1010.20.2a

	A1-A3	A4	C2	C4
ADP elements [kg Sb-Equiv.]	4,00E-06	1,37E-08	1,20E-08	1,55E-06
ADP fossil [MJ]	6,11E+02	5,10E+00	4,46E+00	6,05E+01
AP [kg SO2-Equiv.]	1,33E-01	1,65E-03	1,43E-03	2,64E-02
EP [kg Phosphate-Equiv.]	1,58E-02	3,79E-04	3,28E-04	4,04E-03
GWP [kg CO2-Equiv.]	8,12E+01	3,67E-01	3,21E-01	1,78E+01
ODP [kg R11-Equiv.]	3,62E-09	6,43E-12	5,62E-12	3,32E-09
POCP [kg Ethene-Equiv.]	1,21E-02	-5,37E-04	-4,64E-04	6,86E-03

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

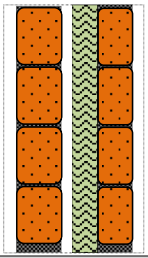
Process	Data source	Geographical coverage	Date
Brick	PE International	Germany	2011
Rock wool	PE International	Europe	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Landfill of inert materials	PE International	Germany	2011

B2010.20 Exterior wall construction				
B2010.20.2b	Materials	Thickness/ density	End-of-life scenario	RR (%)
	Brick wall (mm)	11	Landfill	
	Air cavity (mm)	0		
	EPS (mm)	60	Incineration	80
	Brick wall (mm)	11	Landfill	

B1010.20.2b

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	2,81E-06	1,34E-08	1,17E-08	1,56E-06	-4,49E-08
ADP fossil [MJ]	5,94E+02	4,97E+00	4,35E+00	6,06E+01	-3,21E+01
AP [kg SO2-Equiv.]	7,23E-02	1,61E-03	1,39E-03	2,65E-02	-1,22E-02
EP [kg Phosphate-Equiv.]	8,96E-03	3,70E-04	3,20E-04	4,06E-03	-7,17E-04
GWP [kg CO2-Equiv.]	7,46E+01	3,58E-01	3,13E-01	2,09E+01	-2,46E+00
ODP [kg R11-Equiv.]	8,86E-08	6,27E-12	5,48E-12	3,31E-09	-4,97E-11
POCP [kg Ethene-Equiv.]	2,74E-02	-5,24E-04	-4,52E-04	6,85E-03	-7,02E-04

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
Brick	PE International	Germany	2011
EPS	PE International	Europe	2011

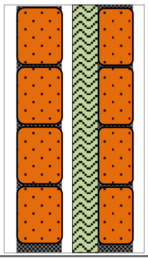
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration EPS	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011

B2010.20 Exterior wall construction

B2010.20.2c	Materials	Thickness/ density	End-of-life scenario	RR (%)
	Brick wall (mm)	11	Landfill	
	Air cavity (mm)	0		
	XPS (mm)	60	Incineration	80
	Brick wall (mm)	11	Landfill	

B1010.20.2c

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	3,64E-06	1,34E-08	1,17E-08	1,57E-06	-7,18E-08
ADP fossil [MJ]	6,51E+02	4,98E+00	4,36E+00	6,08E+01	-5,14E+01
AP [kg SO2-Equiv.]	7,67E-02	1,61E-03	1,39E-03	2,66E-02	-1,95E-02
EP [kg Phosphate-Equiv.]	9,23E-03	3,71E-04	3,20E-04	4,09E-03	-1,15E-03
GWP [kg CO2-Equiv.]	7,63E+01	3,59E-01	3,14E-01	2,29E+01	-3,94E+00
ODP [kg R11-Equiv.]	3,00E-09	6,29E-12	5,50E-12	3,32E-09	-7,96E-11
POCP [kg Ethene-Equiv.]	1,15E-02	-5,25E-04	-4,53E-04	6,87E-03	-1,12E-03

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
Brick	PE International	Germany	2011
XPS	PE International	Germany	2011

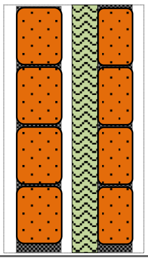
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration XPS	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011

B2010.20 Exterior wall construction

B2010.20.2d	Materials	Thickness/ density	End-of-life scenario	RR (%)
	Brick wall (mm)	11	Landfill	
	Air cavity (mm)	0		
	PUR (mm)	60	Incineration	80
	Brick wall (mm)	11	Landfill	

B1010.20.2d

	A1-A3	A4	C2	C4	D
ADP elements [kg Sb-Equiv.]	3,13E-05	1,34E-08	1,17E-08	1,57E-06	-4,52E-08
ADP fossil [MJ]	7,17E+02	4,98E+00	4,36E+00	6,12E+01	-3,22E+01
AP [kg SO2-Equiv.]	8,33E-02	1,61E-03	1,39E-03	2,77E-02	-1,21E-02
EP [kg Phosphate-Equiv.]	1,09E-02	3,71E-04	3,20E-04	4,37E-03	-7,15E-04
GWP [kg CO2-Equiv.]	8,22E+01	3,59E-01	3,14E-01	2,11E+01	-2,46E+00
ODP [kg R11-Equiv.]	4,11E-09	6,29E-12	5,50E-12	3,34E-09	-4,99E-11
POCP [kg Ethene-Equiv.]	9,80E-03	-5,25E-04	-4,53E-04	6,92E-03	-7,02E-04

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 $W/m^2.K$ and a thermal inertia (κ_m) of 61060 $J/m^2.K$.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
Brick	PE International	Germany	2011
PUR	PE International	Germany	2011

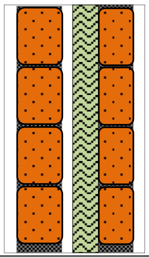
List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Incineration PUR	PE International	Europe	2011
Landfill of inert materials	PE International	Germany	2011

B2010.20 Exterior wall construction

B2010.20.2e	Materials	Thickness/ density	End-of-life scenario	RR (%)
	Brick wall (mm)	11	Landfill	
	Air cavity (mm)	0		
	Cork (mm)	60	Recycling	80
	Brick wall (mm)	11	Landfill	

B1010.20.2e

	A1-A3	A4	C2	C4
ADP elements [kg Sb-Equiv.]	2,27E-06	1,35E-08	1,18E-08	1,55E-06
ADP fossil [MJ]	5,46E+02	5,03E+00	4,40E+00	6,03E+01
AP [kg SO2-Equiv.]	8,06E-02	1,63E-03	1,41E-03	2,63E-02
EP [kg Phosphate-Equiv.]	1,16E-02	3,74E-04	3,23E-04	4,03E-03
GWP [kg CO2-Equiv.]	7,57E+01	3,62E-01	3,17E-01	1,77E+01
ODP [kg R11-Equiv.]	2,30E-09	6,35E-12	5,55E-12	3,31E-09
POCP [kg Ethene-Equiv.]	8,25E-03	-5,30E-04	-4,57E-04	6,84E-03

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

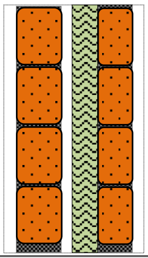
Process	Data source	Geographical coverage	Date
Brick	PE International	Germany	2011
Cork	PE International	Germany	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Landfill of inert materials	PE International	Germany	2011

B2010.20 Exterior wall construction				
B2010.20.2f	Materials	Thickness/ density	End-of-life scenario	RR (%)
	Brick wall (mm)	11	Landfill	
	Air cavity (mm)	0		
	Glass wool (mm)	60	Landfill	
	Brick wall (mm)	11	Landfill	

B1010.20.2f

	A1-A3	A4	C2	C4
ADP elements [kg Sb-Equiv.]	6,07E-04	1,35E-08	1,18E-08	1,55E-06
ADP fossil [MJ]	6,13E+02	5,01E+00	4,38E+00	6,05E+01
AP [kg SO2-Equiv.]	9,80E-02	1,62E-03	1,40E-03	2,67E-02
EP [kg Phosphate-Equiv.]	1,33E-02	3,73E-04	3,22E-04	5,07E-03
GWP [kg CO2-Equiv.]	7,81E+01	3,61E-01	3,16E-01	1,83E+01
ODP [kg R11-Equiv.]	3,81E-09	6,32E-12	5,53E-12	-3,92E-09
POCP [kg Ethene-Equiv.]	8,60E-03	-5,28E-04	-4,56E-04	7,01E-03

Functional equivalent:

1 m^2 of an exterior wall of a building, designed for a service life of 50 years, with a thermal transmittance (U) of 0.92 W/m^2.K and a thermal inertia (κ_m) of 61060 J/m^2.K.

Additional information:

List of datasets used in Modules A1-A3

Process	Data source	Geographical coverage	Date
Brick	PE International	Germany	2011
Glass wool	PE International	Europe	2011

List of datasets used in Modules A4 and C2 (assuming distances of 20 km)

Process	Data source	Geographical coverage	Date
Transportation by truck	PE International	World	2011

List of datasets used in Module C4-D

Process	Data source	Geographical coverage	Date
Landfill of inert materials	PE International	Germany	2011
Landfill of glass wool	PE International	Germany	2010