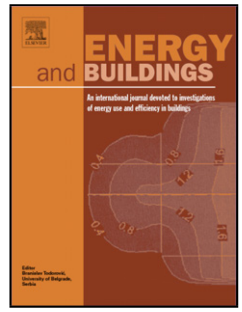


Title: Assessment of building operational energy at early stages of design – a monthly quasi-steady-state approach

Author: P. Santos R. Martins H. Gervásio L. Simõ es da Silva

PII: S0378-7788(14)00363-6
DOI: http://dx.doi.org/doi:10.1016/j.enbuild.2014.02.084
Reference: ENB 5017

To appear in: *ENB*

Received date: 29-9-2013
Revised date: 28-1-2014
Accepted date: 19-2-2014

Please cite this article as: P. Santos, R. Martins, H. Gervásio, L.S. Silva, Assessment of building operational energy at early stages of design ndash a monthly quasi-steady-state approach, *Energy and Buildings* (2014), http://dx.doi.org/10.1016/j.enbuild.2014.02.084

ASSESSMENT OF BUILDING OPERATIONAL ENERGY AT EARLY STAGES OF DESIGN – A MONTHLY QUASI-STEADY-STATE APPROACH

P. Santos [a], **R. Martins** [a], **H. Gervásio** [a] **and L. Simões da Silva** [a]

[a] *ISISE, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal*

AUTHOR FOR CORRESPONDENCE:

Paulo Santos

Department of Civil Engineering, University of Coimbra, Pólo 2, Rua Luís Reis Santos

3030-788 COIMBRA, PORTUGAL

e-mail: pfsantos@dec.uc.pt tel: +351 239 797199 fax: +351 239 797190

ABSTRACT

In this paper a new numerical tool to estimate the operational energy of buildings, in early design stages, is presented. This tool is part of a novel approach for life-cycle analysis based on macro-components developed in the European research project *SB_Steel – Sustainable Buildings in Steel*. Two early design stages are considered in the scope of the methodology: the concept stage and the preliminary stage. This numerical tool enables to estimate the energy use for space heating, space cooling and domestic hot water production, taking into account (i) the climate; (ii) the use type of the building (e.g. residential, offices and commercial/industrial); (iii) the building envelope characteristics; and (iv) the building services.

The developed algorithm is based on a monthly quasi-steady-state approach, modified for improved accuracy through the calibration of correction factors that depend on the climatic region and the type of building. Good results were achieved, with errors lower than 10% when compared to performance–based approaches such as the use of advanced dynamic methods.

Finally, the case study of a low-rise residential building is presented, in which the results obtained from the simplified methodology are compared with the results from the simulation program *EnergyPlus*, showing a good agreement between them.

Keywords: Early design, Buildings, Operational energy assessment, Quasi-steady-state method, Monthly approach.

Contents

Nomenclature

A	area [m^2]
a	numerical parameter in utilization factor, reduction factor
C	internal heat capacity of a conditioned space [J/K]
f	correction factor, fraction
g	total solar energy transmittance
H	heat transfer coefficient [W/K]
n	number of days of the month [d]
P	electrical power density [W/m^2]
Q	quantity of heat [MJ], [kWh]
q_v	volumetric airflow rate [m^3/s], [ac/h]
R	thermal resistance [m^2·K/W]
r	ratio
t	period of time [Ms]
U	thermal transmittance [W/(m^2·K)]
V	volume [m^3]
ΔT	temperature difference [ºC]
ε	emissivity of a surface for long-wave thermal radiation
ϕ	heat flow rate, thermal power [W]
γ	heat-balance ratio
η	efficiency, utilization factor
κ	heat capacity per area [J/(m^2·K)]
θ	celsius temperature [ºC]
τ	time constant [h]

Subscript

adj	adjusted
cont	continuous
conv	conversion
C	cooling
corr	corrected

D	direct
f	floor
gn	gains
gl	glazing, glazed element
g	ground
H	heating
int	internal (heat gains)
L	lighting (heat gains)
ls	loss
LW	long wavelength radiation
m	month, mass-related
nd	need (heating and/or cooling energy)
oc	occupants (heat gains)
red	reduced
sh	shading
sol	solar (heat gains)
SW	short wavelength radiation
t	tapping point
T	thermal radiation
tot	total
tr	transmission (heat transfer)
ve	ventilation (heat transfer)
V	visible
z	zone number
ref , *0*	reference
W , *DHW*	water (domestic hot)

1 INTRODUCTION

The energy used for the operation of buildings represents 40% of the total energy consumption in the European Union (Gervásio et al., 2010). This has motivated all European countries to reduce up to 20% its value in order to comply with the Kyoto Protocol (Directive 2010/31/EU, 2010). To meet this goal, the design process of a building should be based on life cycle criteria in order to enhance the thermal performance of the building. Additionally, buildings should be able to contribute to a significant extent with the production of renewable energies, in order to achieve another EU target: "nearly zero-energy" buildings (Directive 2010/31/EU, 2010). The effect of these measures is supported by the fact that nearly two-thirds of the world's new solar panels were installed in Europe in 2011 (Jager-Waldau, 2012). In a broader spectrum than limiting the environmental concerns to technical solutions, it is the entire concept of the building that should be revised and improved, in order to meet the targets set by the EU. This holistic approach is of higher effectiveness if applied at early stages of building design (UNEP, 2003). As the design process of the building design advances, changing design options becomes more onerous and time consuming (Balcomb & Curtner, 2000). This demonstrates the importance of an accurate estimation of energy needs and optimization of building solutions in early stages of design. However, due to the lack of data at early design stages, current methodologies and tools to assess the energy performance of buildings under these conditions failed to fulfil this task.

This paper presents the energy module (EM) of a new early stage sustainability assessment tool (ESSAT) aiming for the evaluation of the life cycle environmental performance of a building, which will be freely available online as the outcome of the European research project *SB_Steel: Sustainable Building Project in Steel* (SB_Steel, 2010). In the first part of this paper, the main variables influencing the building thermal calculations are introduced and their availability in early stages of design is discussed. Then, the framework for energy calculation is presented, followed by the determination of climate-dependent correction factors, which were calibrated in order to provide a higher accuracy of the results. Finally, a case-study is presented and discussed, in order to illustrate the application of the proposed approach and to verify the accuracy of its outcomes.

2 ASSESSMENT OF THE ENERGY PERFORMANCE OF BUILDINGS

The normative framework for the sustainability assessment of buildings in the European Union is provided by the CEN-TC 350 series of standards, covering environmental, economic and social aspects (EN 15643-1, 2010). In case of the environmental performance of buildings, EN 15978 (2011) considers potential environmental impacts, in all life cycle stages (materials production, use, end-of-life and reuse/recovery/recycling potential), in a modular system. According to this system, Module B6 corresponds to the operational energy use, i.e., the building energy consumption. It comprehends the consumption of energy for space cooling, space heating and domestic hot water (DHW) production.

In order to perform the assessment of the thermal behaviour of a building, in terms of its cooling and heating energy needs, a monthly quasi-steady-state approach was developed, following the guidance provided by ISO 13790 (2008). This standard covers all aspects involved in the thermal calculations and provides correlation factors to take dynamic thermal effects into account. The energy needs for DHW production is calculated according to EN 15316-3-1 (2007).

The calculation of the building's energy needs relies on a three step procedure: i) definition of input data; ii) quantification of the building energy needs based on the developed algorithm, in accordance with ISO 13790 and EN 15316-3-1; iii) the output of the assessment. The complete algorithm was implemented into a user friendly tool based on an excel-sheet. The proposed approach is fully detailed in Section 3.

2.1 Availability of data in early stages of design

The design process of a building comprises several stages (Gervásio et al., 2014) as illustrated in Figure 1: (i) the first stage, the **Project Start-Up** whereby the project brief is developed by identifying the requirements of the building through consultation with stakeholders, (ii) the second stage, the **Concept Design**, in which the building concept is developed and schematic drawings are produced, (iii) the third stage, the **Preliminary Design** whereby schematic diagrams are refined enabling to estimate the main quantities for the building project, and (iv) the **Developed Design**, which contains all the information required to execute the building and all data necessary for a sustainability assessment.

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

Figure 1 – Stages of design: availability of data vs. degree of accuracy of results

Therefore, a methodology aiming for the assessment of the energy performance of buildings, in the early stages of design, has to address the scarcity of data.

2.2 Available energy quantification approaches

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

Most available software for the energy quantification relies on the former, enabling to accurately quantify energy on a hourly basis, through a series of iterations taking into account different heat transfer mechanisms and phenomena (Crawley, 1994). However, these tools are usually time consuming, require a good knowledge about heat transfer and other subjects involved, and are not user friendly. Furthermore, they require the complete knowledge of the finished building design (Attia et al., 2012).

On the other hand, simplified methods are usually based on quasi-steady-state approaches. Some works claiming to assess the building in the early stages of design are provided by Nielsen (2005), Petersen and Svendsen (2010) and Carlos and Nepomuceno (2012). However, they really only address the finished project and do not provide any indication on the level of approximation for early design stages, with incomplete data. Additionally, they present other drawbacks, such as: they do not help the user to estimate envelope areas, the user must compute and provide the properties of the envelope (e.g. thermal transmittance or U-values, thermal inertia of the envelope, solar heat gain coefficient - SHGC, reduction factors due to shading provisions) and only calculates heating loads (Carlos and Nepomuceno, 2012). Thus, the user must be an expert in energy efficiency. Finally, none of them calculates the energy use for DHW production.

3 EARLY STAGE SUSTAINABILITY ASSESSMENT TOOL - ENERGY MODULE (ESSAT-EM)

3.1 Assumptions

As already referred the proposed approach aims at the assessment of the energy performance of a building in early stages of design when data availability is scarce. In order to cope with this problem, simplified assumptions were adopted in relation to the building shape, the structural system, the building envelope and the building finishes.

Concerning the building shape, data input is distinguished between the concept stage and the preliminary stage. In the former, the building is assumed to be of a rectangular shape. Therefore only the length, the width and the height of each floor are needed. The glazing areas of each façade are computed automatically according to the building orientation and the climatic zone.

For the preliminary stage, the input of the building geometric characteristics is more detailed since building plans already exist. In this case, a few pre-defined solutions are provided, as indicated in Figure 2.

Figure 2 – Pre-defined building solutions in the preliminary stage of design

The lack of other building details is overcome by the use of macro-components (see (Gervásio et al., 2014), which are pre-assembled construction solutions, integrating materials and respective life cycle impacts, for the main components of the building. A database of macro-components is organized into three main categories: (A) Substructure, (B) Shell and (C) Interior. Furthermore, macro-components enable the automatic calculation of the required thermal properties, such as the U-value and the heat capacity.

In addition, for the quantification of the energy needs of the building for cooling and heating, data is needed in relation to the use of mechanical equipment, shading devices, etc. Again, the input distinguishes between the concept stage and the preliminary stage. In the former, a representative value for each parameter is provided; in the latter, the designer may select the parameters according to the availability of information. The input of these parameters is further detailed in the following sub-sections.

3.2 Framework

The complete tool integrates two modules for: i) energy calculation (ESSAT-EM) and ii) assessment of potential life cycle environmental impacts (ESSAT-PI). It was developed with the aim to assist designers in the early process of building design and aid in the decision-making process.

This paper only addresses the module for energy calculation, for further details on the module for life cycle assessment see Gervásio et al. (2014).

The ESSAT-EM module is able to calculate energy needs, on a monthly basis, for: (i) the heating mode; (ii) the cooling mode; and (iii) DHW production. Different standards are used for the calculation of the different parameters involved in the calculation, as indicated in Figure 3.

Figure 3 – Flowchart of the ESSAT-EM algorithm and the reference standards for space conditioning

As observed in Figure 3, ISO 13790 provides the general framework for the energy calculation. In order to compute the heat transfer by transmission through the building envelope (e.g. windows, roofs, walls and ground floor) and by ventilation, several international standards were taken into account. To calculate the heat gains (e.g. solar and internal) the prescriptions given in other international standards were followed. Subsequently, using these values for the heat gains and heat losses, the heat balance is performed taking into account appropriate dynamic parameters (e.g. the gain utilization factor) and assuming continuous operation of the HVAC systems. The effect of intermittency of the working schedule of the systems is taken into account by using a reduction factor for intermittent heating/cooling. Finally the energy use of the HVAC systems is computed by applying the systems' efficiency in the previous value of the energy need.

Besides the energy for space heating and cooling, and given the importance of the DHW production in the building's energy consumption, it is also essential to estimate its contribution. In this case, the guidance provided by EN 15316-3-1 (2007) is taken into account. Further details may be obtained in EN 13790 (2008).

3.3 Energy needs calculation method

The estimation of the energy needs for space heating and cooling is based on a monthly quasi-steady-state approach, which relies in gains utilization factors to simulate dynamic effects. The algorithm is implemented in a modular system as shown in Figure 4. Two main modules are considered: (i) space heating/cooling, that includes the calculation of additional parameters in separate modules (sub-modules); and (ii) DHW production.

Figure 4 – Flowchart of the calculation of the energy consumption of the building

Sub-modules 1 and 2 correspond, respectively, to the calculation of the U-value and heat capacity of the envelope elements, and are provided from the macro-components selected by the user. Whenever applicable, the U-value is corrected to account for thermal bridging in accordance to ISO 6946 (2007) and Gorgolewski (2007). Sub-module 3 covers the heat transfer through the ground, according to ISO 13370 (2007). Sub-modules 4, 5 and 6 address the calculation of the effects of shading devices and shading by external obstacles. The shading coefficients (F_{sh}) were obtained for different latitudes (35º, 45º, 55º, and 65º) and the algorithm performs an interpolation depending on the latitude of the building location.

The energy calculation is based on the heat balance equations (1) and (2), respectively, for the energy needs for space heating and cooling (ISO 13790):

$$Q_{H,nd,cont,m} = (Q_{H,tr,m} + Q_{H,ve,m}) - \eta_{H,gn,m} \cdot Q_{H,gn,m} \quad (1)$$

$$Q_{C,nd,cont,m} = Q_{C,gn,m} - \eta_{C,ls,m} \cdot (Q_{C,tr,m} + Q_{C,ve,m}) \quad (2)$$

where subscripts H and C denote heating and cooling modes, respectively; *cont* means continuous heating/cooling; and m denotes monthly. The parameters $\eta_{H,gn,m}$ and $\eta_{C,ls,m}$, are the monthly utilization factors used in the heating and cooling modes, respectively. When the HVAC system operates in an intermittent mode, reduction factors for the energy needs ($a_{H,red}$ and $a_{C,red}$) are taken into account.

The energy needs for DHW production is influenced by the type of building, its floor area and the temperature difference between the inlet water ($\theta_{w,0}$) and the one desired at the tapping point ($\theta_{w,t}$), according to EN 15316-3-1 (2007):

$$Q_{DHW,nd,m} = 4{,}182 . V_{W,m} . (\theta_{W,t} - \theta_{W,0}) \quad (3)$$

where $V_{W,m}$ is the monthly DHW volume need.

3.4 Key input data for building assessment

The tool takes into account the most influencing parameters in the thermal behaviour and energy efficiency of the building (Santos et al., 2012a): the climate, the building geometry and orientation, ventilation and airtightness, building envelope characteristics, shading devices, building services and human factors.

The climate depends essentially on the location of the building and it is of vital importance regarding thermal behaviour calculations(Santos et al., 2011a). The Köppen-Geiger climate classification is the most worldwide used climate classification (Kottek et al., 2006). The ESSAT-EM tool provides climate data for different locations (cities), although user-defined values may be introduced for specific locations. This data was gathered from the *International Weather for Energy Calculation* (IWEC, 2013) database. Based in those values, the mean monthly values of temperature and solar incident radiation, on a given surface, were determined using *EnergyPlus* (2011). The tool is currently calibrated for the five most relevant climatic regions in Europe (Csa, Csb, Cfb, Dfb and Dfc), according to the Köppen-Geiger classification (Kottek et al., 2006).

The definition of the building geometry depends of the stage of design and it is currently limited to the building shapes referred in sub-section 3.1.

The building geometry and orientation have a major importance for solar gains. In the proposed approach, solar gains are taken into account by shading coefficients, computed for different latitudes according to ISO 13790, and for three types of external obstructions: (i) overhangs; (ii) fins; (iii) obstructions from the horizon.

Airtightness and ventilation control is taken into account by allowing different airflow rates for the heating and cooling modes. Additionally, the tool assesses the effect of a mechanical heat recovery system by defining its technical characteristics and the fraction of the airflow that goes through the heat recovery unit.

Likewise, the adequate design of the opaque and glazed elements of the building envelope is vital to enhance the thermal behaviour and energy performance of buildings (Santos et al., 2012b). In this case, the key-parameters are: (i) U-values; (ii) absorption coefficient for solar radiation; (iii) internal heat capacity; (iv) solar heat gain coefficient (SHGC); and (v) heat losses through ground. These parameters are considered as follows:

- The characteristics of opaque and glazed elements, including the U-value, are taken from macro-components (Gervásio at al., 2014);
- The internal heat capacity is calculated according to the simplified procedure in ISO 13786 (2007);
- The default values for the solar heat gain coefficients of different glazing systems were obtained from EN 15193 (2007) and ISO 13790 (2008);
- The heat losses through the ground are computed for three ground floor solutions (slab on ground floor, suspended ground floor and heated basement) according with ISO 13370 (2007). In addition, the default values adopted for thermal characteristics of the ground, indicated in Table 1, are provided from the same standard.

Table 1 – Default values of the thermal properties of the ground (ISO 13370, 2007)

Several types of movable shading devices are available in the tool and also the option to assign user defined values. The effect of automated shading devices is accounted for through the calculation of the fraction of the day in which the solar incident radiation on a given orientation exceeds a predefined set-point. Furthermore, the effect of night window protection device activation is taken into account by a correction of the U-value of the window, according to ISO 13790.

Regarding the building services, the tool allows the user to select the systems' efficiency and their working schedule. However, typical values of these systems are provided by default, which are indicated in Table 2. Additionally, the conversion factor from delivered energy to primary energy should be selected or defined by the user.

Table 2 – Building systems' input data (default values)

In relation to human factors, the tool enables different operation schedules and internal heat gains, depending on the type of use of the building. These values are taken by default (values given in Table 3) or defined by the user.

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

4 CORRECTION FACTORS

4.1 Introduction

When compared to advanced dynamic simulations (based on hourly data), the monthly quasi-steady-state approach includes several simplifications, leading to different results with a lower accuracy when compared to real measured results (Santos et al., 2011b). Several factors contribute directly towards these differences: (i) the dynamic monthly utilization factors, $\eta_{H,gn,m}$ and $\eta_{C,ls,m}$, which are assumed constant and independent of climatic data and occupancy schedule, within each climatic region; and (ii) the various heat balance terms indicated in Figure 4 (Q_{tr}, Q_{ve} and Q_{gn}), which are calculated for constant interior temperatures defined by the set-points for heating and cooling seasons.

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

Thus, in order to improve the accuracy of the monthly quasi-steady-state approach, correction factors were calibrated for each climatic region and a specific building type. This section presents the calibration procedures used for the determination of the correction factors and the corresponding validation.

4.2 Assessment of the monthly quasi-steady-state approach in the framework of EN 15265

EN 15265 (2007) provides twelve test cases for the validation of the calculation of energy needs for space heating and cooling using dynamic methods. This standard uses a reference room with internal dimensions: 3.6 m length; 5.5 m depth; 2.8 m height; and a glazed element (7.0 m^2) facing west, which is analyzed under different boundary conditions: (i) all internal partitions and slabs (floor and ceiling) are adiabatic; and (ii) all internal partitions and floor slab are adiabatic. Additionally, variations of internal and solar heat gains, two different heat capacities of the slabs and two types of heating/cooling modes (continuous and intermittent) are considered. Table 4 provides an overview of the twelve test-cases prescribed in the standard. The first four initial tests are informative, while the remaining eight are normative.

Table 4 – Test cases prescribed in EN 15265 (2007) to validate the calculation of energy needs for space heating and cooling using dynamic methods

For each of the twelve test cases considered, the standard provides reference annual results for heating ($Q_{\mathrm{H,ref}}$) and cooling energy needs ($Q_{\mathrm{C,ref}}$) in kWh/yr, for a specific location (Trappes, France). The accuracy of a given algorithm is obtained by calculating the following ratios:

$$\mathrm{r}Q_{\mathrm{H}} = \mathrm{abs}\left(Q_{\mathrm{H}} - Q_{\mathrm{H,ref}}\right) / Q_{\mathrm{tot,ref}} \quad (4)$$

$$\mathrm{r}Q_{\mathrm{C}} = \mathrm{abs}\left(Q_{\mathrm{C}} - Q_{\mathrm{C,ref}}\right) / Q_{\mathrm{tot,ref}} \quad (5)$$

where, Q_{H} and Q_{C} are the estimated values for annual energy needs for space heating and cooling, respectively (in kWh/yr); and $Q_{\mathrm{tot,ref}}$ is the reference value for the total annual energy needs for space heating and cooling (in kWh/yr). The standard specifies three levels of accuracy: A, B and C when both ratios $\mathrm{r}Q_{\mathrm{H}}$ and $\mathrm{r}Q_{\mathrm{C}}$ are lower than or equal to 5%, 10% and 15%, respectively.

Since the aim of the verification process was to assess the accuracy of monthly energy need values and also the terms that take part in the heat balance (e.g. heat losses by transmission/ventilation and solar/internal heat gains), and these are not given in the standard, the test cases indicated in Table 4 were calculated in the dynamic software *EnergyPlus* (2011), using a previously calibrated model (Santos et al., 2011a). Therefore, the reference annual values, for heating and cooling, indicated in expressions were obtained from this dynamic analysis. Notice that the weather data file used by *EnergyPlus* requires some additional climatic hourly values (not provided in Annex A of EN 15265), such as atmospheric pressure, dew point temperature, relative humidity, wind direction and wind velocity. Therefore, this missing data were obtained from an *EnergyPlus* weather data file (FRA_PARIS_ORLY_IWEC.epw) for the closest location to Trappes (Paris-Orly).

All test cases were calculated in ESSAT-EM and compared with the reference values calculated using EnergyPlus. Figure 5 illustrates the errors, per month, obtained with the quasi-steady-state approach ESSAT-EM, using expressions (4) and (5), for the heating and cooling modes, respectively. As observed in Figure 5, the error is higher for the heating mode than for the cooling mode. The maximum monthly error, in the heating mode, is lower than 12%; in the cooling mode the maximum error is lower than 7%.

Figure 5 – Errors of the monthly quasi-steady-state approach ESSAT-EM

4.3 Methodology for the derivation of the correction factors

Despite the good agreement of the ESSAT-EM approach with respect to the test cases of EN 15265 (2007), the performance of real buildings with more complex layouts, different operating conditions and different climates may significantly deviate from the results obtained with a monthly quasi-steady-state approach. This is acknowledged in ISO 13790, where possible deviations, ranging from 50% to 150%, are referred. Therefore, correction factors were calculated in order to minimize these deviations.

Since ESSAT-EM aims at the prediction of the energy needs of buildings instead of a single building compartment, calibration analyses were carried out based on a reference building with four compartments and a floor area equal to 79.2 m^2, as illustrated in Figure 6a. The thermal properties (e.g. thermal transmittance and heat capacity) were the same as in EN 15265 (see Figure 6b) but with different boundary conditions (non-adiabatic walls and roof). The airflow rate was considered constant and equal to 1.0 air changes per hour [ac/h].

Figure 6 – Reference building used to calibrate the correction factors

Given the importance of the glazing areas, different wall to floor area ratios were analyzed. Also, the option of shading devices was taken into account in the calibration procedure, as presented in Table 5.

Table 5 – Test cases used to calibrate the correction factors

In the calibration models, the occupation schedules and respective heat flows were derived from ISO 13790 for residential buildings.

The correction factors were calibrated in order to improve the computation of the following energy terms: (i) heat transfer by transmission; (ii) heat transfer by ventilation; (iii) internal heat gains; (iv) solar heat gains, as shown in equations (6) to (8).

$$H_{tr,adj,corr} = f_{tr}.H_D \rightarrow Q_{tr,m} = H_{tr,adj,corr}.(\theta_{int,sec,H} - \theta_e).t \tag{6}$$

$$H_{ve,adj,corr} = f_{ve}.H_{ve,adj} \rightarrow Q_{ve,m} = H_{ve,adj,corr}.(\theta_{int,sec,H} - \theta_e).t \tag{7}$$

$$Q_{gn} = f_{int}.Q_{int,m} + f_{sol}.Q_{sol,m} \tag{8}$$

where $H_{tr,adj,corr}$ is the corrected value of heat transfer by transmission [W/K]; f_{tr} is the correction coefficient for the heat transfer by transmission; $H_{ve,adj,corr}$ is the corrected value of heat transfer by ventilation [W/K]; 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 correction coefficient for the solar gains, excluding the thermal radiation to the sky.

Additionally, the reference dimensionless parameters (a_{H0}, a_{C0}) and the reference time constants (τ_{H0}, τ_{C0}), indicated in the ISO 13790, were also calibrated.

In the calibration analysis, all test cases indicated in Table 5 were run for five different climatic regions: Csa; Csb; Cfb; Dfb; and Dfc. The correction factors were derived by minimizing the error for each sub-set of the test cases, for each climatic region, which in some cases, reached 500 runs.

The resulting set of correction factors is presented in Table 6.

Table 6 – Correction factors for each climatic region

4.4 Assessment of the accuracy of the proposed procedure using correction factors

Figure 7 compares the ESSAT-EM monthly quasi-steady-state approach, with and without correction factors, for the Dfb climatic zone. Average improvements, in the absolute error, from 43% to less than 2% are noted.

Figure 7 – Improvement of the accuracy of the proposed approach for the Dfb climate: total annual energy for space heating and cooling

Figure 8 summarizes the improvements for the five climatic regions addressed in this paper. It is interesting to note that, without correction factors, the precision of the method is lower for colder climates (Dfb and Dfc), while, after calibration, the accuracy is higher. As observed in the advanced dynamic results, the calibrated approach makes use of the gains in a more efficient way to heat the space, than the original ISO approach. This effect is more relevant and evident when the solar gains are lower. Globally, with the correction factors, all errors are lower than 10%.

Figure 8 – Mean error of the proposed approach for five climatic regions

In addition, the correction factors were applied to test cases 3 and 4, assuming that the building was located in five different cities of the climatic regions Csa (warmest) and Dfb (coldest). The aim of this analysis was to assess the error obtained when using the climate of each location instead of the mean values of the respective climatic region. As expected, the error obtained varies with the location, as observed from Figure 9. The highest errors occur for the cities of Athens (16.2%) and 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%).

Figure 9 – Verification of the calibration factors when applied to various cities of the climatic regions: a) Csa; b) Dfb.

5 CASE STUDY: LOW RISE RESIDENTIAL BUILDING

In order to illustrate the application of ESSAT-EM and to assess its accuracy for early stages of design, a case-study of a low-rise residential building is herein presented. The building under study is located in Coimbra, Portugal. It is a two-storey single family house with about 120 m^2 of conditioned floor area. The building has a lightweight steel frame (LSF) structure, with flat roof and suspended ground floor (with unventilated crawl space).

In the following sections, all input data and calculation procedure are described. The case study focuses on the concept stage of design. However, the results obtained from the conceptual stage are compared with the results obtained for the same case study but assuming that full details of the building are known, i.e., in the developed stage of design. Additionally, the results given by the developed approach are compared with those obtained by a dynamic analysis using *EnergyPlus* (2011), which is the computation engine of the *DesignBuilder* (2011) software.

5.1 Common data for all design stages

5.1.1 Climate data and ground thermal characteristics

The building is located in the Csb climatic region. The corresponding monthly values of air temperature and global solar radiation are presented in Figure 10.

Figure 10 – Climate data of Coimbra (IWEC): solar radiation and outside air temperature

The thermal characteristics of the ground were considered by default, as provided in Table 1.

The heat transfer to the sky was calculated considering a temperature difference between the air temperature and the sky apparent temperature of 11˚C, as given in ISO 13790 (2008), Clause 11.4.6. The radiative heat transfer coefficient was assumed to be five times the surface emissivity (ε), as recommended in this standard (common construction materials present an emissivity of 0.9).

5.1.2 Occupancy related data

The schedule of occupancy and heat flow due to internal loads (occupants activity, appliances and lighting) were considered according to the default values provided in Table 3.

Given that ISO 13790 (2008) does not provide a method to calculate the effect of heat gains due to lighting, the methodology provided by *EnergyPlus* (US DoE, 2011) was adopted. It assumes that part of the visible radiation is absorbed by the surfaces and the rest is directly transmitted to the air. The monthly heat gain (in *kWh*) is obtained from,

$$Q_{gn,L,z,m} = \left(P_{tot,z} \cdot A_{f,z} \cdot f_{L,On,z} \cdot \left(f_{SW,V} \cdot \alpha_{s,z} + f_{SW,T} + f_{LW}\right)\right) \cdot n \cdot \frac{24}{1000} \quad (9)$$

where $P_{tot,z}$ is the total power installed in zone z (W/m^2); $A_{f,z}$ is the floor area of zone z (m^2); $f_{L,0n,z}$ represents the fraction of the number of hours per day in operation in zone z; $f_{SW,V}$ is the fraction of visible radiation (short wavelength); $f_{SW,T}$ is the fraction of thermal radiation (short wavelength); f_{LW} is the fraction of convection (long wavelength); n is the number of days of the month. Since, in this case, the lighting gains were modelled as a constant convective heat source, the terms $f_{SW,V}$ and $f_{SW,T}$ in Equation (9) were taken as zero and f_{LW} as 1.

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

5.1.3 Building services

Similarly, for the technical information and schedule of the building services (heating, cooling, ventilation and DHW production) the set of default values indicated in Table 2, were considered.

5.1.4 Glazed envelope and shading operational specifications

The characteristics and properties of the glazed elements are taken from macro-components of glazed elements. In this case, double-pane glazed windows, with a PVC frame, were considered with the characteristics indicated in Table 7.

Table 7 – Optical and thermal properties of the glazing (glass + frames)

The thermal properties of the shading devices were considered according to Table 8. The solar passive technique used in this case study assumes a radiation set- point (300 W/m^2) that activates the shading devices in order to prevent overheating. The positive effect that the shading devices develop when activated during the night was also taken into account by correcting the U-value of the window, as indicated in ISO 13790 (2008).

Table 8 – Thermal and optical properties of the shading devices

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.

5.2 Concept stage of design

5.2.1 Geometry and envelope

In the concept stage of design, it is assumed that no plans of the building are available and therefore, the assessment is made based on the basis of a simplified rectangular floor plan.

It was considered that the building has two floors, with a total area of construction of 240 m^2 and with a height between floors of 2.7 m. In order to estimate the main envelope areas (external walls and windows), a rectangular plan with width-to-length ratio of 1:2 was considered. Following the guidelines for solar passive house (Inanici & Demirbilek, 2000; Farrar-Nagy et al., 2002; Milne et al., 2010), the glazing areas were estimated based on the following percentages for each façade: North-oriented, 20%; East-oriented, 10%; South-oriented, 25%; and West-oriented, 8%.

Table 9 presents the resulting wall and glazing areas.

Table 9 – Wall and glazing areas [m^2] assumed in the conceptual stage

For the definition of the building components, the macro-components presented in Table 10 (Gervásio et al., 2014) were adopted.

Table 10 – Macro-components adopted in the conceptual stage

5.2.2 Results of the conceptual stage

The energy needs for space heating yield a value of 355 kWh per year. Figure 11 illustrates the output for the space heating energy, which includes: (i) heat transfer by transmission (opaque and glazed elements); (ii) heat transfer by ventilation; (iii) heat gains (opaque elements, glazed elements and internal gains); (iv) the energy needs per month; and (v) the energy needs per year.

In addition, the total energy for heating is provided in terms of delivery energy and primary energy.

Figure 11 – Outputs of ESSAT-EM for the space heating energy (conceptual stage)

From the breakdown of the heat transfer contributions it is easy to identify the most critical processes. In this case, Figure 11 shows that the glazing areas are the main contributor to the heat loss of the building, followed by the walls. The heat transfer by ventilation also contributes significantly to the losses. This type of information helps to decide on the most effective changes to improve the performance of the building. For instance, it is easier to intervene in the envelope (by reducing the U-value of its elements, for example), than reducing the heat transfer by ventilation, as the air flow in the winter is already low (0.60 ac/h).

The energy for space cooling is presented in Figure 12. In this case, a value of 2261 kWh per year was obtained.

Figure 12 – Outputs of ESSAT-EM for the space cooling energy (conceptual stage)

From Figure 12, it is observed that the heat transfer is higher in the cooling mode due to a higher ventilation rate in the summer season (1.20 ac/h). The effect of changing, for example, the shading devices may be analysed in terms of energy needs but also by the value of the heat gains of the glazing areas.

In relation to the energy for DHW production, a value of 2605.0 kWh per year was obtained, highlighting the importance of this component to the total energy. The output of the DHW calculation is illustrated in Figure 13.

Figure 13 – Outputs of ESSAT-EM: energy for DHW production

The results of the energy for heating, cooling and DHW production are then compiled and the contribution of each component is compared, in order to quickly identify the main contributor for the energy consumption, which is reflected in the electricity bill (Figure 14).

Figure 14 – Output of the ESSAT-EM for the energy totals (conceptual stage)

Hence, the calculation of the total energy needs for the building, assuming the conceptual stage of design, lead to a value of 5222.0 kWh/year (43.5 kWh/year/m^2).

5.3 Developed stage of design

5.3.1 Geometry and envelope

In the developed stage of design, full details of the building are available. Hence, for this case study, the façades and the horizontal plans of the building are illustrated in Figure 15.

Figure 15 – Building's architecture

According to the definition of the architectural drawings, the total area of construction of the building is about 202.0 m^2. The height between floors remains 2.7 m. For the energy calculation, the total conditioned area is 123.8 m^2.

Table 11 presents the areas of other envelope elements, including the differences to the conceptual stage.

Table 11 – Wall and glazing areas [m^2] in the developed design stage

With the addition of an external slab for the terrace, not available in the conceptual stage, it was necessary to select an additional macro-component for this component, which is illustrated in Table 12.

Table 12 – Macro-component adopted for the external slab in the developed design

5.3.2 Results of the developed stage

In this case, the energy needs, computed with ESSAT-EM, is 651.3 kWh and 2195.0 kWh, per year, for space heating and cooling, respectively. Thus, the energy needs, 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).

A comparison of the energy calculated in the conceptual stage and in the developed stage of design, is provided in Figure 16, showing the same trend, as well as a good approximation for the total results. The building total energy needs for space cooling and heating is 8.8% higher in the developed stage of design. The energy needs for DHW production (not represented in the graph) shows a difference of -2%, which is only due to the estimation of the conditioned area in the concept stage.

Figure 16 – Comparison of the energy need (for space cooling and heating) between the concept and developed stages (ESSAT-EM results)

5.3.3 Comparison with advanced dynamic numerical simulations

A comparison between the results provided by ESSAT-EM (in the developed stage of design) and the results of advanced dynamic simulations using the *EnergyPlus* software was performed. This comparative analysis is illustrated in Figure 17.

Figure 17 – Building energy need for space cooling and heating: dynamic simulations (Dyn) *versus* ESSAT-EM tool

The energy needs, per year, for space heating and cooling, provided by dynamic simulations, are 826.1 kWh and 1931.3 kWh, respectively, leading to total energy needs of 2757.5 kWh per year (22.3 kWh/m^2). As observed from Figure 17, the energy needs calculated with the simplified approach (ESSAT-EM) 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 +3.2%.

6 CONCLUSIONS

In this paper, the energy module of a novel tool for the assessment of the sustainability performance of a building (ESSAT-EM), in early design stages was presented and applied to a case study.

The algorithm is based on the simplified quasi-steady-state monthly method provided by ISO 13790, for the quantification on the energy need for space heating and cooling, and in EN 15316-3-1, for the quantification of DHW production.

The simplifications of the monthly quasi-steady-state method result in significant deviations from the real thermal performance and operational energy needs of buildings. Within the scope of the parametric study performed in this paper, errors in the range of ±50% were recorded. Furthermore, there is poor correlation between the error and the climatic parameters for each individual location. The first important contribution of this paper was the development of a modified monthly quasi-steady-state method using calibrated correction factors that result in good results when compared to performance-based approaches such as the use of dynamic simulation methods. Errors lower than 10% were obtained. To achieve this, specific correction factors were calibrated for appropriate sub-sets of parameters:

- climatic region;
- type of building (building use and construction solution).

In this paper, correction factors were proposed for five different climatic regions: Csa; Csb; Cfb; Dfb; and Dfc, covering most of Europe, and low-rise residential buildings using light steel framing. Nevertheless, the methodology is completely general and further sets of correction factors could be calibrated for other climatic regions and building types (e.g. multi-storey buildings or commercial buildings).

The second important contribution of this paper relates to the development of a methodology that allows the calculation of the energy needs of buildings at early stages of design. Two early stages of design were considered: conceptual stage and preliminary stage (Gervásio et al., 2014). Focussing on the conceptual stage because it is the more complex as the available data is scarce (no floor plans are available), the methodology is able to achieve reasonable results (errors per m^2 of less than 10% when compared to the fully developed project). Given that the objective is to be able to compare alternative design options in the early stages of design, this methodology provides a simple way to rank alternatives or to optimize solutions. It is noted that the key factor to deal with incomplete information in the early stages of design was the definition of appropriate representative values of the missing input data according to appropriate sub-sets for each climatic region and type of building.

Finally, the methodology was implemented in a user-friendly web tool, ESSAT-EM, freely available at http://www.onesource.pt/sbsteel/site/. Current work is continuing on the extension of the tool to other building types and climatic regions.

7 ACKNOWLEDGEMENT

This research work has received funding from the European Community's Research Fund for Coal and Steel (RFCS) under grant agreement N. RFSR-CT-2010-00027.

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

8 REFERENCES

Attia, S., Gratia, E., De Herde, A., & Hensen, J. L. M. (2012). Simulation-based decision support tool for early stages of zero-energy building design. *Energy and Buildings*, *49*, 2–15.

Balcomb, J. D., & Curtner, A. (2000). Multi-Criteria Decision-Making Process for Buildings. In *American Institute of Aeronautics and Astronautics Conference* (pp. 1–8). Las Vegas, USA.

Carlos, J. S., & Nepomuceno, M. C. S. (2012). A simple methodology to predict heating load at an early design stage of dwellings. *Energy and Buildings*, *55*, 198–207.

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., … Glazer, J. (1994). EnergyPlus: Creating a new-generation building energy simulation program. *Energy and Buildings*, *33*(4), 443–457.

DesignBuilder. (2011). DesignBuilder software version 3.0.0.105. Available at: http://www.designbuilder.co.uk/.

Directive 2010/31/EU: On the energy performance of buildings. (2010). OJ L153/13.

EN 13363-1. (2007). Solar protection devices combined with glazing - Part 1: Simplified method. CEN - European Committee for Standardization.

EN 15193. (2007). Energy performance of buildings — Energy requirements for lighting Contents. CEN - European Committee for Standardization.

EN 15265. (2007). Energy performance of buildings - Calculation of energy needs for space heating and cooling using dynamic methods - General criteria and validation procedures. CEN - European Committee for Standardization.

EN 15316-3-1. (2007). Heating systems in buildings – Method for calculation of system energy requirements and system efficiencies – Part 3.1 Domestic hot water systems, characterisation of needs (tapping requirements). CEN – European Committee for Standardization.

EN 15643-1. (2010). Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework. CEN - European Committee for Standardization.

EN 15978. (2011). Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. CEN – European Committee for Standardization.

EnergyPlus. (2011). EnergyPlus energy simulation software version 7.0.0.036. United States Department of Energy. Available at: http://apps1.eere.energy.gov/buildings/energyplus.

Farrar-Nagy, S., J. Hayter, S., Larson, A., Torcellini, P. A., & Geet, O. Van. (2002). LANL Sustainable Design Guide (p. 252). Los Alamos National Laboratory, USA.

Gervásio, H., Santos, P., Martins, R., & Simões da Silva, L. (2014). A macro-component approach for the assessment of building sustainability in early stages of design. *Building and Environment*, *72*, 256–270.

Gervásio, H., Santos, P., Simões da Silva, L., & Lopes, A. M. G. (2010). Influence of thermal insulation on the energy balance for cold-formed buildings. *Advanced Steel Construction*, *6*(2), 742–766.

Gorgolewski, M. (2007). Developing a simplified method of calculating U-values in light steel framing. *Building and Environment*, *42*(1), 230–236.

Inanici, M. N., & Demirbilek, F. N. (2000). Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey. *Building and Environment*, *35*, 41–52.

ISO 10077. (2006). Thermal performance of windows, doors and shutters - Calculation of thermal transmittance - Part 1: General. ISO - International Organization for Standardization.

ISO 13370. (2007). Thermal performance of buildings - Heat transfer via the ground - Calculation methods. ISO - International Organization for Standardization.

ISO 13786. (2007). Thermal performance of building components - Dynamic thermal characteristics - Calculation methods. ISO - International Organization for Standardization.

ISO 13790. (2008). Energy performance of buildings - Calculation of energy use for space heating and cooling. ISO - International Organization for Standardization.

ISO 6946. (2007). Building components and building elements - Thermal resistance and thermal transmittance - Calculation method. ISO - International Organization for Standardization.

IWEC. (2013). International Weather for Energy Calculation. Available at: http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm.

Jager-Waldau, A. (2012). JRC Scientific and Policy Reports (European Comission, Jointe Research Centre, Institue for Energy and Transport) PV Status Report 2012.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263.

Nielsen, T. R. (2005). Simple tool to evaluate energy demand and indoor environment in the early stages of building design. *Solar Energy*, *78*(1), 73–83.

Petersen, S., & Svendsen, S. (2010). Method and simulation program informed decisions in the early stages of building design. *Energy and Buildings*, *42*(7), 1113–1119.

Reardon, C., Milne, G., Mcgee, C., & Downton, P. (2010). *Your Home, Technical manual: Australia's guide to environmentally sustainable homes*. (P. Downton, Ed.) (4th ed., p. 348). Camberra, AU: Sherrey Quinn – Libraries Alive.

Santos, P., Gervásio, H., Simões da Silva, L., & Gameiro, A. (2011). Influence of climate change on the energy efficiency of light-weight steel residential buildings. *Civil Engineering and Environmental Systems*, *28*(4), 325–352.

Santos, P., Martins, R., Simões da Silva, L., & Gervásio, H. (2012). Towards a numerical algorithm to evaluate energy performance of steel buildings at early design stages. In *SB_Steel – ECCS TC14 – ESTEP WG3, Concepts and Methods for Steel Intensive Building Projects* (pp. 37–54). Munich, Germany.

Santos, P., Simoes da Silva, L., Gervasio, H., & Gameiro Lopes, A. (2011). Parametric analysis of the thermal performance of light steel residential buildings in Csb climatic regions. *Journal of Building Physics*, *35*(1), 7–53.

Santos, P., Simões da Silva, L., & Ungureanu, V. (2012). *Energy Efficiency of Light-weight Steel-framed Buildings*. *Sustainability & Eco-Efficiency of Steel Construction*. ECCS-TC14.

SB_Steel. (2010). Sustainable Building Project in Steel. Research projetc suported by the Research Fund for Coal and Steel (RFCS) under grant agreement: RFSR-CT-2010-00027.

UNEP. (2003). Life-cycle analysis of the built environment, UNEP (United Nations Environment Programme), 17–21.

US DoE. (2011). *Engineering Reference: The Reference to EnergyPlus Calculations, US Department of Energy*.

List of Figures

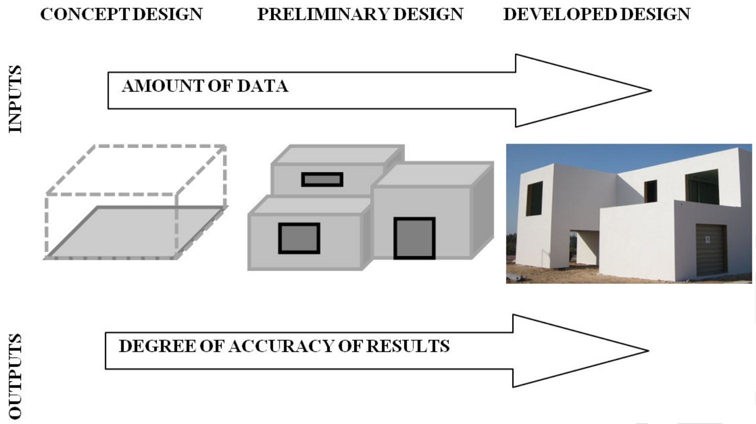


Figure 1 – Stages of design: availability of data vs. degree of accuracy of results

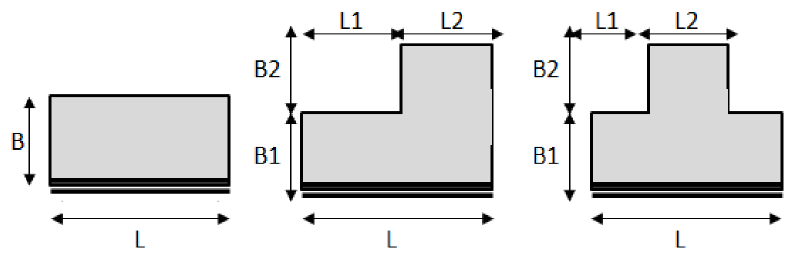


Figure 2 – Pre-defined building solutions in the preliminary stage of design

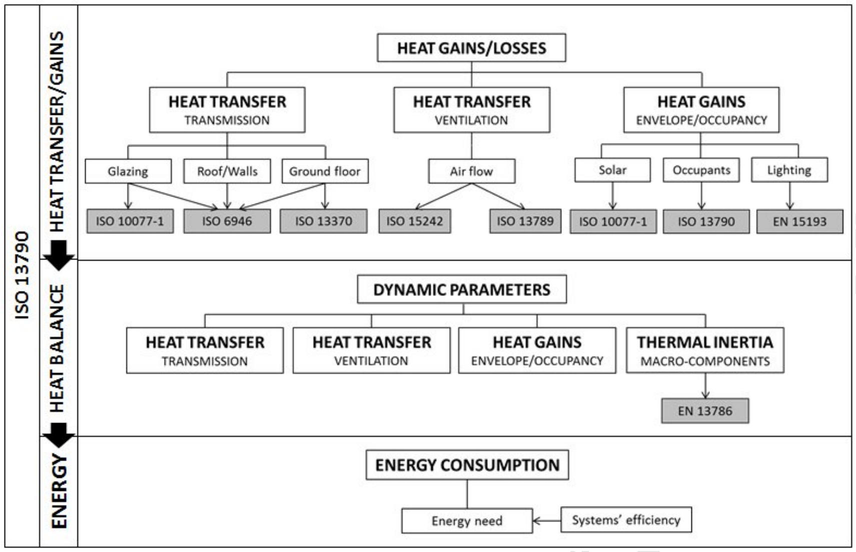


Figure 3 – Flowchart of the ESSAT-EM algorithm and the reference standards for space conditioning

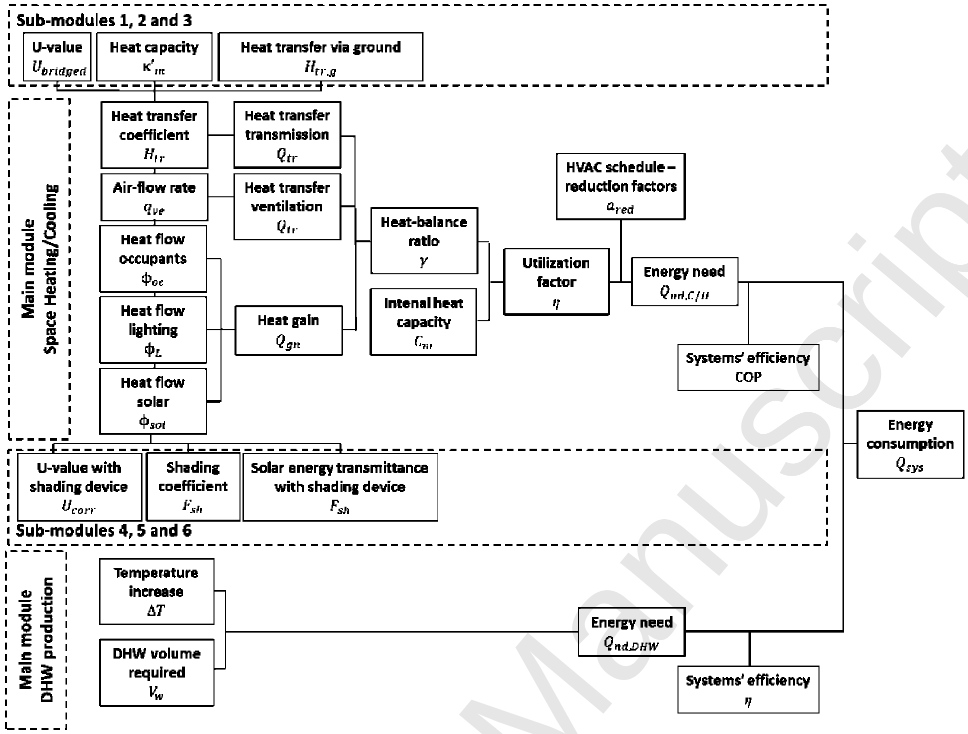
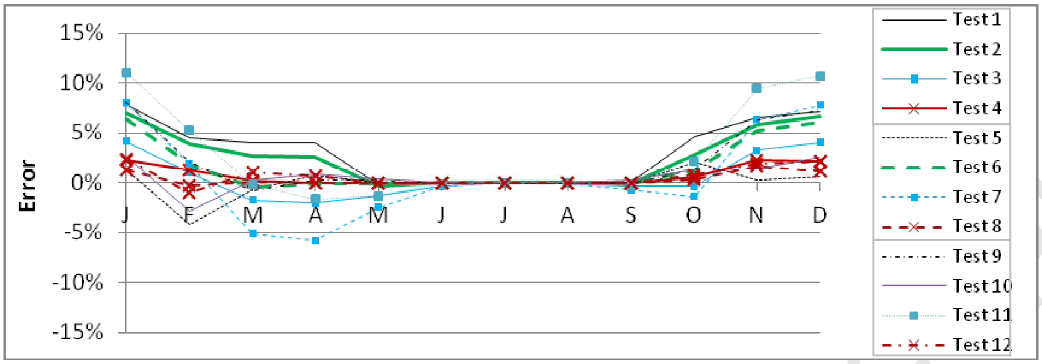
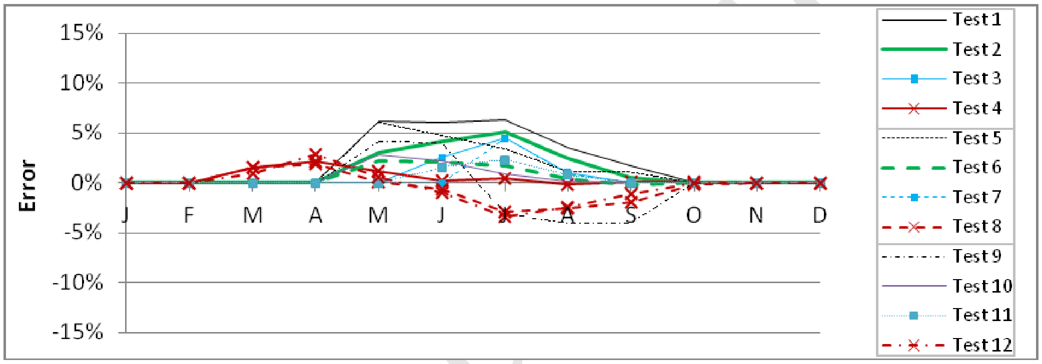


Figure 4 – Flowchart of the calculation of the energy consumption of the building

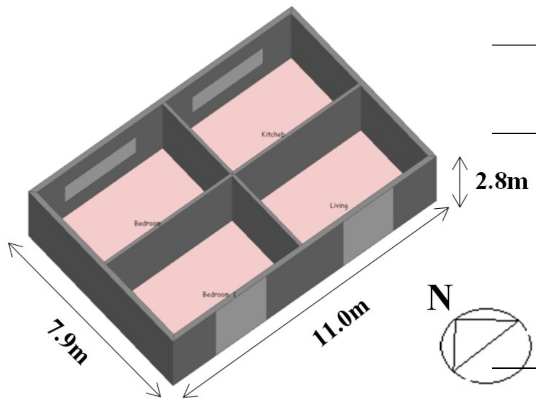


a) Heating mode



b) Cooling mode

Figure 5 – Errors of the monthly quasi-steady-state approach ESSAT-EM



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

a) Building model (internal dimensions)   b) Thermal properties of the envelope

Figure 6 – Reference building used to calibrate the correction factors

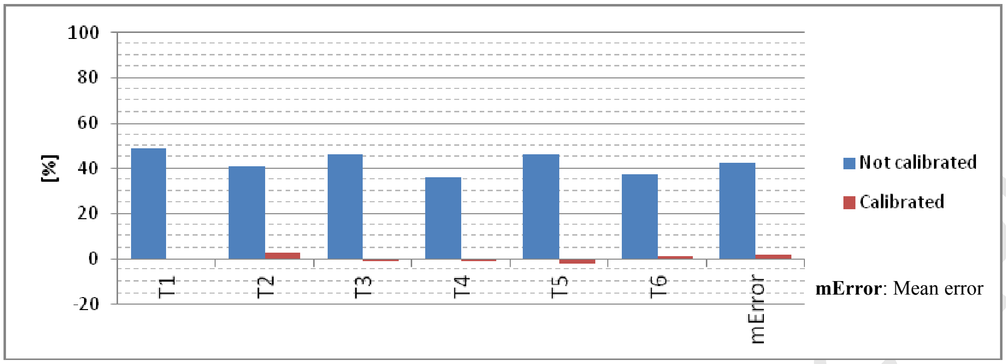


Figure 7 – Improvement of the accuracy of the proposed approach for the Dfb climate: total annual energy for space heating and cooling

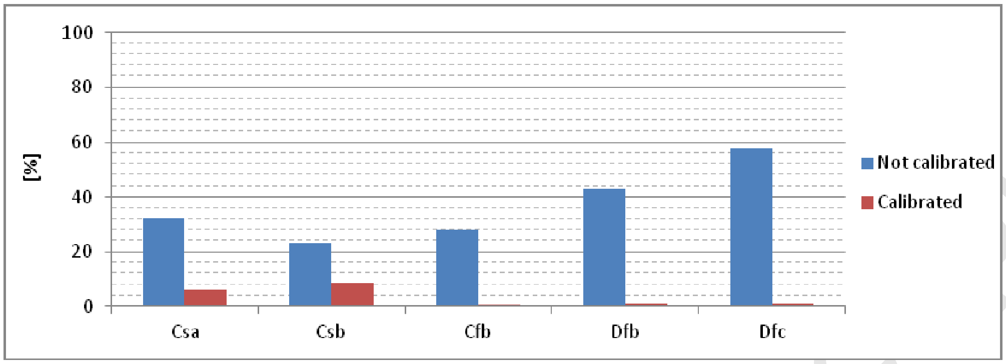
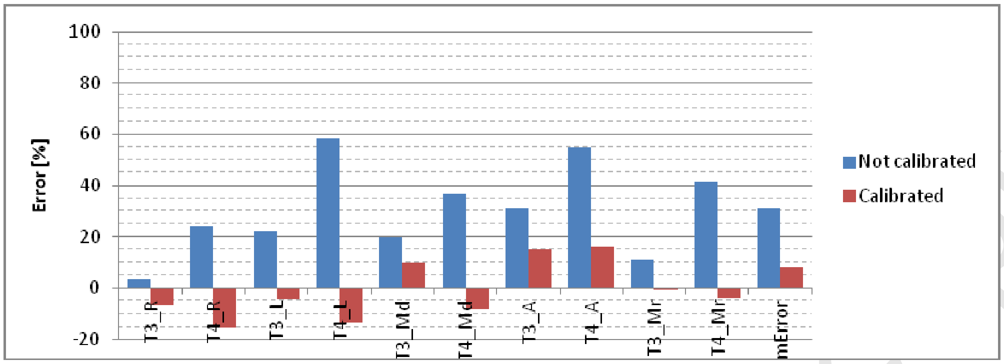
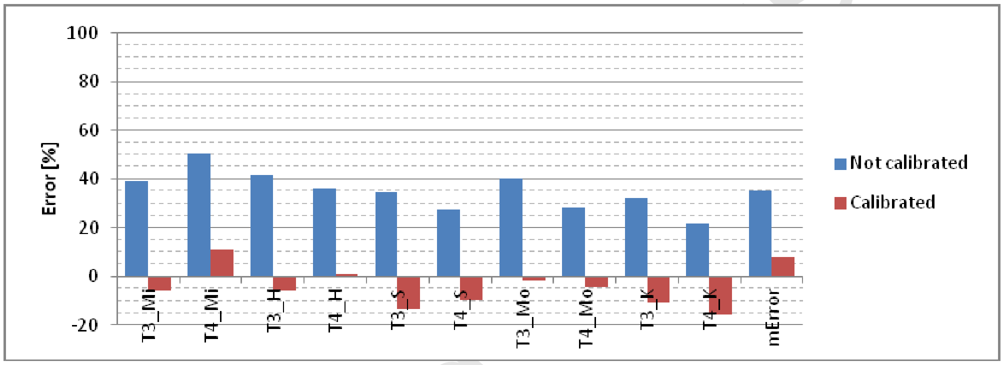


Figure 8 – Mean error of the proposed approach for five climatic regions



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



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

Figure 9 – Verification of the calibration factors when applied to various cities of the climatic regions: a) Csa; b) Dfb.

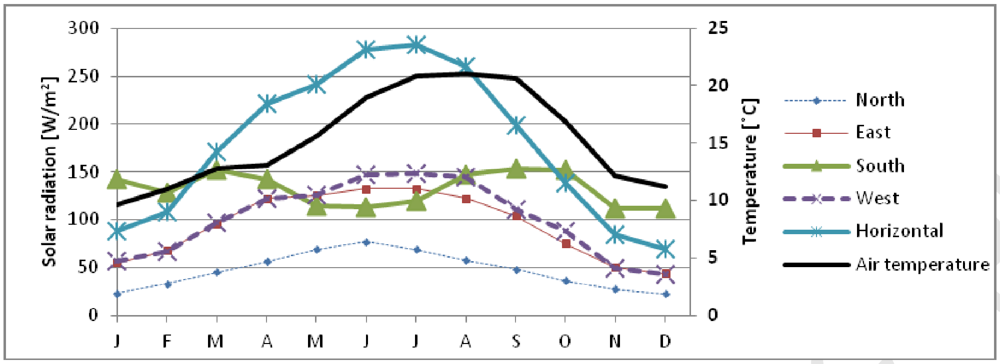


Figure 10 – Climate data of Coimbra (IWEC): solar radiation and outside air temperature

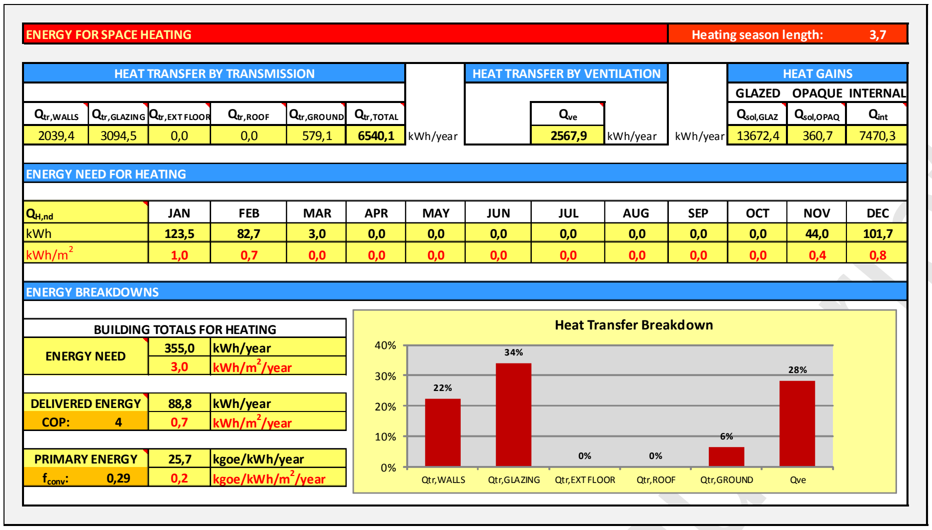
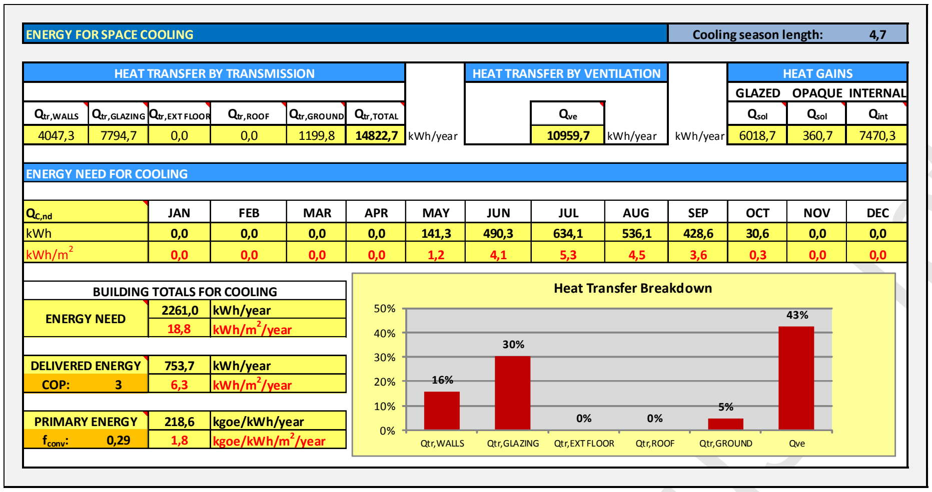


Figure 11 – Outputs of ESSAT-EM for the space heating energy (conceptual stage)



ENERGY FOR SPACE COOLING	Cooling season length:	4,7

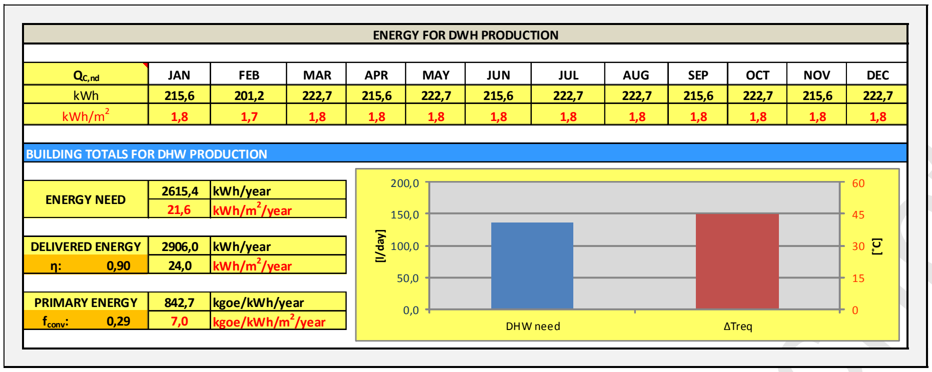
HEAT TRANSFER BY TRANSMISSION							HEAT TRANSFER BY VENTILATION			HEAT GAINS		
										GLAZED	OPAQUE	INTERNAL
$Q_{tr,WALLS}$	$Q_{tr,GLAZING}$	$Q_{tr,EXT FLOOR}$	$Q_{tr,ROOF}$	$Q_{tr,GROUND}$	$Q_{tr,TOTAL}$		Q_{ve}			Q_{sol}	Q_{sol}	Q_{int}
4047,3	7794,7	0,0	0,0	1199,8	14822,7	kWh/year	10959,7	kWh/year	kWh/year	6018,7	360,7	7470,3

ENERGY NEED FOR COOLING

$Q_{C,nd}$	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
kWh	0,0	0,0	0,0	0,0	141,3	490,3	634,1	536,1	428,6	30,6	0,0	0,0
kWh/m^2	0,0	0,0	0,0	0,0	1,2	4,1	5,3	4,5	3,6	0,3	0,0	0,0

BUILDING TOTALS FOR COOLING		
ENERGY NEED	2261,0	kWh/year
	18,8	$kWh/m^2/year$
DELIVERED ENERGY	753,7	kWh/year
COP: 3	6,3	$kWh/m^2/year$
PRIMARY ENERGY	218,6	kgoe/kWh/year
f_{conv}: 0,29	1,8	$kgoe/kWh/m^2/year$

Figure 12 – Outputs of ESSAT-EM for the space cooling energy (conceptual stage)



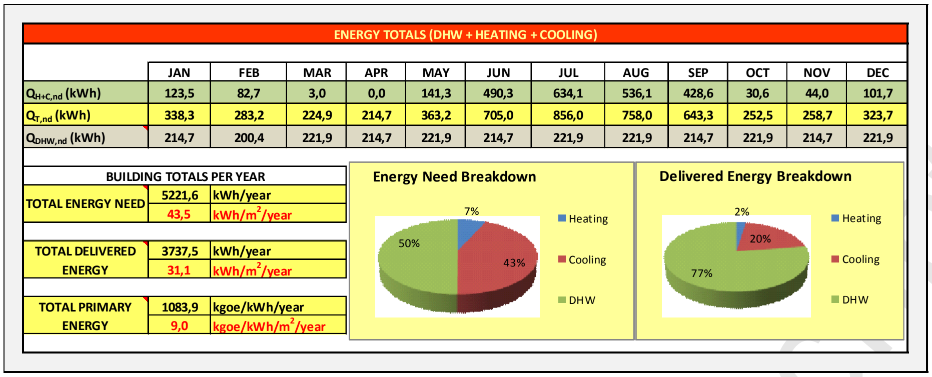
ENERGY FOR DWH PRODUCTION

$Q_{C,nd}$	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
kWh	215,6	201,2	222,7	215,6	222,7	215,6	222,7	222,7	215,6	222,7	215,6	222,7
kWh/m^2	1,8	1,7	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8

BUILDING TOTALS FOR DHW PRODUCTION

ENERGY NEED	2615,4	kWh/year
	21,6	kWh/m^2/year
DELIVERED ENERGY	2906,0	kWh/year
η: 0,90	24,0	kWh/m^2/year
PRIMARY ENERGY	842,7	kgoe/kWh/year
f_{conv}: 0,29	7,0	kgoe/kWh/m^2/year

Figure 13 – Outputs of ESSAT-EM: energy for DHW production

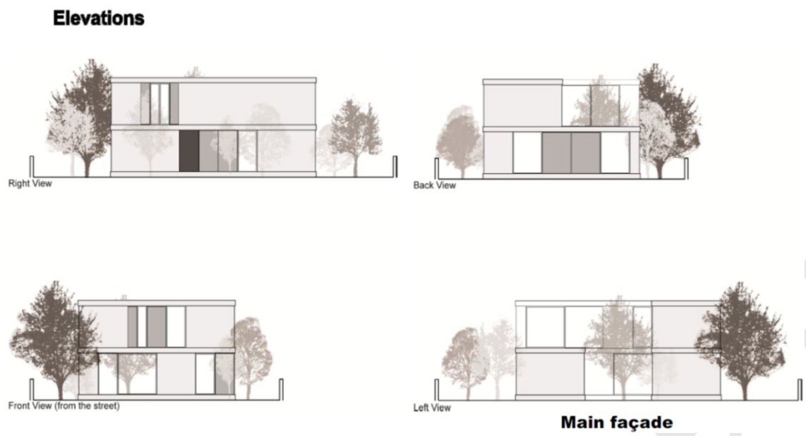


ENERGY TOTALS (DHW + HEATING + COOLING)

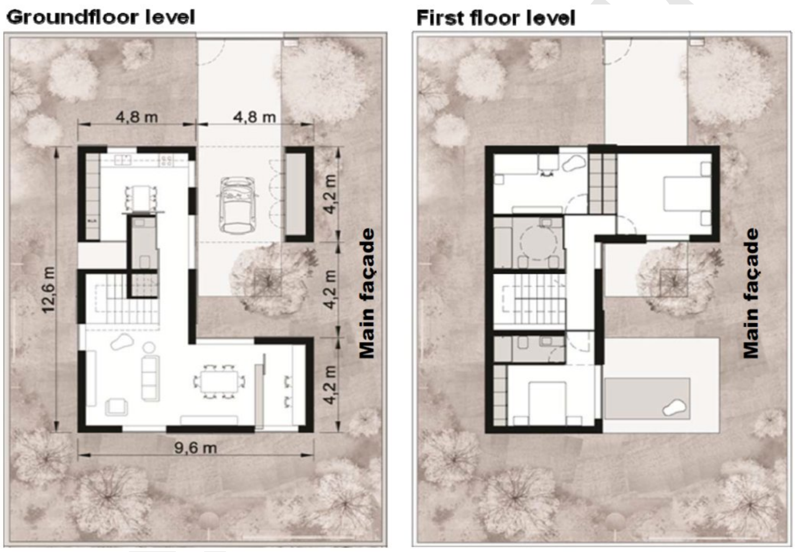
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
$Q_{H+C,nd}$ (kWh)	123,5	82,7	3,0	0,0	141,3	490,3	634,1	536,1	428,6	30,6	44,0	101,7
$Q_{T,nd}$ (kWh)	338,3	283,2	224,9	214,7	363,2	705,0	856,0	758,0	643,3	252,5	258,7	323,7
$Q_{DHW,nd}$ (kWh)	214,7	200,4	221,9	214,7	221,9	214,7	221,9	221,9	214,7	221,9	214,7	221,9

BUILDING TOTALS PER YEAR		
TOTAL ENERGY NEED	5221,6	kWh/year
	43,5	kWh/m²/year
TOTAL DELIVERED ENERGY	3737,5	kWh/year
	31,1	kWh/m²/year
TOTAL PRIMARY ENERGY	1083,9	kgoe/kWh/year
	9,0	kgoe/kWh/m²/year

Figure 14 – Output of the ESSAT-EM for the energy totals (conceptual stage)



a) Façades layouts



b) Floor layouts

Figure 15 – Building's architecture

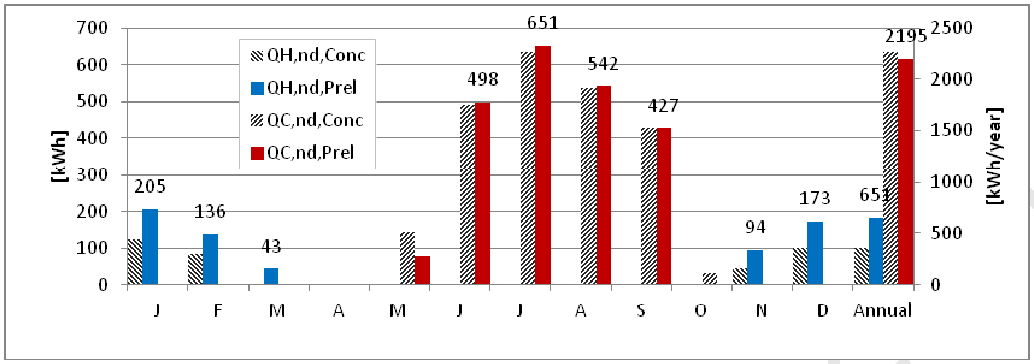


Figure 16 – Comparison of the energy need (for space cooling and heating) between the concept and developed stages (ESSAT-EM results)

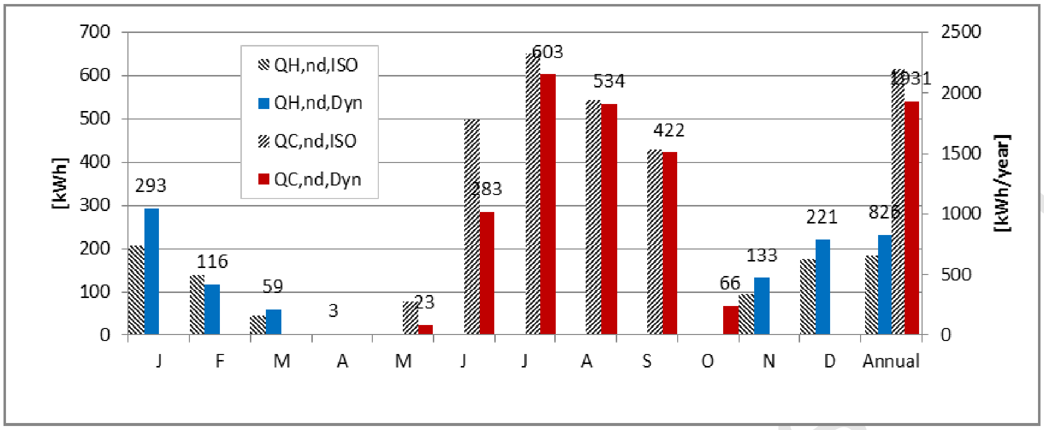


Figure 17 – Building energy need for space cooling and heating: dynamic simulations (Dyn) *versus* ESSAT-EM tool

List of Tables

Table 1 – Default values of the thermal properties of the ground (ISO 13370, 2007)

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

Table 2 – Building systems' input data (default values)

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

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

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

Table 4 – Test cases prescribed in EN 15265 (2007) to validate the calculation of energy needs for space heating and cooling using dynamic methods

<table>
<tr><th>Informative</th><th colspan="2">Normative</th><th colspan="2">Normative</th></tr>
<tr><td>Test 1 Reference Case</td><td>Test 5 = Test 1 +</td><td rowspan="4">Intermittent HVAC (only 8h00-18h00 from Monday to Friday)</td><td>Test 9 = Test 5 +</td><td rowspan="4">External Roof</td></tr>
<tr><td>Test 2 Higher Thermal Inertia</td><td>Test 6 = Test 2 +</td><td>Test 10 = Test 6 +</td></tr>
<tr><td>Test 3 No Internal Gains</td><td>Test 7 = Test 3 +</td><td>Test 11 = Test 7 +</td></tr>
<tr><td>Test 4 No Solar Protection</td><td>Test 8 = Test 4 +</td><td>Test 12 = Test 8 +</td></tr>
</table>

Table 5 – Test cases used to calibrate the correction factors

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.

Table 6 – Correction factors for each climatic region

	Heating mode						Cooling mode					
	Shading devices ON											
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
	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

Table 7 – 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

Table 8 – Thermal and optical properties of the shading devices

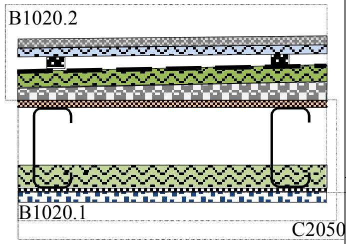
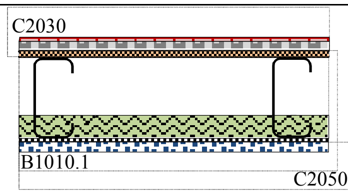
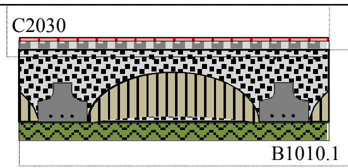
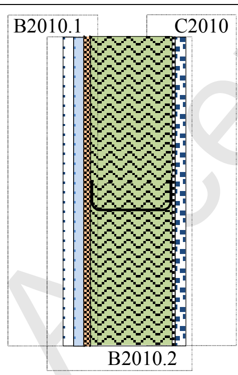
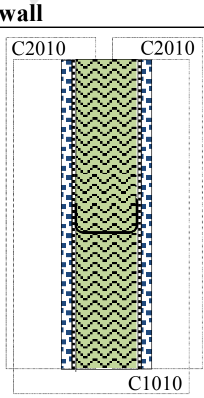
Element	Solar transmittance	Solar reflectance	R [m^2.K/W]	g_{gl+sh}
Shutters	0.02	0.80	0.260*	0,04**

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

Table 9 – Wall and glazing areas [m^2] assumed in the conceptual stage

Envelope	North	East	South	West	Roof	Floor
Opaque	52.6	29.6	49.3	30.2	60.0	60.0
Glazed	13.2	3.3	16.4	2.6	-	n.a.

Table 10 – Macro-components adopted in the conceptual stage

	Macro-component reference	**Material layers**	**Thickness** [mm] **Density** [kg/m²]	**U-value** [W/m².K]	**κm** [J/m².K]
Roof floor					
	B1020.20 Roof deck deck, slabs and sheathing	Cement slab	30 mm	0.373^(*)	13435
		XPS slab	30 mm		
		Air cavity	30 mm		
		Waterproof film	1.63 kg/m²		
		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/m²		
		Gypsum board	15 mm		
	C2050 Ceiling finishes	Painting	0.125 kg/m²		
Interior floor					
	C2030 Flooring	Ceramic tiles	31 kg/m²	0.962^(*)	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/m²		
		Gypsum board	15 mm		
	C2050 Ceiling finishes	Painting	0.125 kg/m²		
Ground floor					
	C2030 Flooring	Ceramic tiles	31 kg/m²	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/m²	0.296^(*)	13391
	B2010.20 Exterior wall construction	OSB	13 mm		
		Rock wool	120 mm		
		Light weight steel	15 kg/m²		
		Gypsum board	15 mm		
	C2010 Interior wall finishes	Painting	0.125 kg/m²		
Interior wall					
	C2010 Interior wall finishes	Painting	0.125 kg/m²	1.069^(*)	26782
	C1010 Interior partitions	Gypsum board	15 mm		
		Rock wool	60 mm		
		Light weight steel	10 kg/m²		
		Gypsum board	15 mm		
	C2010 Interior wall finishes	Painting	0.125 kg/m²		

^(*)corrected values for thermal bridging; XPS – Extruded PolyStyrene foam; OSB – Oriented Strand

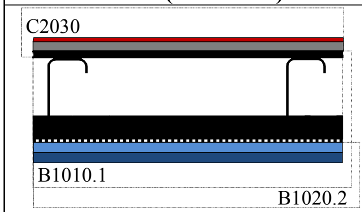
Board; ETICS – External Thermal Insulation Composite System.

Table 11 – Wall and glazing areas [m^2] in the developed design stage

	North	East	South	West	Roof	Floor	External Floor
Opaque	41.3	49.9	38.3	60.3	83.7	63.9	21.0
(difference)*	(+21.5%)	(+68.6%)	(-77.7%)	(-99.7%)	(+40%)	(+7%)	n.a.
Glazing	13.0	17.3	15.6	4.6	n.a.	n.a.	n.a.
(difference)*	(-1.5%)	(+424%)	(-4.9%)	(+76.9%)			

* Difference to conceptual stage

Table 12 – Macro-component adopted for the external slab in the developed design

	Macro-component reference	**Material layers**	**Thickness** [mm] **Density** [kg/m^2]	**U-value** [W/m^2.K]	**κ_m** [J/m^2.K]
External floor (solution 1)					
	C2030 Flooring	Ceramic tiles	31 kg/m^2	0.345$^{(*)}$	47627
		Concrete screed	13 mm		
	B1010.10 Floor structural frame	OSB	18 mm		
		Air cavity	140 mm		
		Rock wool	60 mm		
		Gypsum board	15 mm		
		Light weight steel	14 kg/m^2		
	B1020.20 Roof deck, slab and sheathing	ETICS	13.8 kg/m^2		

*corrected values for thermal bridging;
ETICS – External Thermal Insulation Composite System; OSB – Oriented Strand Board.

HIGHLIGHTS

- Numerical tool to predict operational energy of buildings at early design stages
- Part of a new approach to perform life-cycle analysis based on macro-components
- Two early design stages are considered: the concept stage and the preliminary stage
- The algorithm is based in prescriptions obtained from international standards
- An average error lower than 10% was obtained taking into account five climates